MISCELLANEOUS GENERAL MAINTENANCE VOLUMES I

FIST VOLUMES 4 - 3 THROUGH 4 - 5

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*The Appearance of the Internet Version of This Manual
May Differ From the Original, but the Contents Do Not*

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

MISCELLANEOUS GENERAL MAINTENANCE VOLUMES I

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BUREAU OF RECLAMATION

FACILITIES INSTRUCTIONS, STANDARDS, & TECHNIQUES

Volume 4 - 3

ECONOMIC ANALYSIS OF MAINTENANCE PROBLEMS

September 1992

FOREWORD

Economic analysis is a systematic and well-defined study of alternatives. It is a concept, a way of thought-life, that:

- Analyzes available resources
- Identifies alternative ways of handling a problem
- Compares results of alternative solutions
- Recommends a solution based on well-defined data

Maintenance managers are well-advised to learn when and how to use economic analysis to guide their thoughts and verify their recommendations.

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1. INTRODUCTION AND PURPOSE

1.1. Maintenance can be expensive, particularly around powerplants and switchyards where valuable equipment is located. It is worthwhile to make an economic analysis of some maintenance programs, especially those that: run into large amounts of money (over $50,000, for example); extend over several years time; and where there are alternatives to consider to gain the desired results.

1.2. Economic analysis should *not be used* in situations where it is expected to:

- Produce results more valid than input data (garbage in, garbage out)
- Make final decisions
- Be applied with exact precision
- Provide relevant solutions to irrelevant problems
- Predict political, social, and other non-economic impacts
- Substitute for sound judgment, management, or control

A well-prepared economic analysis requires considerable though, research, and effort. Do *not make* an economic analysis when:

- The analytical effort is not worth the benefits
- Legislative directives or management decisions govern
- Other studies have already been made (usually by another name)

1.3. This bulletin is designed to show maintenance managers, by example, how to make an economic analysis of alternate ways to accomplish maintenance, thus giving them key information to arrive at the best decisions. Readers are shown how to analyze typical maintenance situations by using "discount factors" to determine the "present value" of benefits and costs, a very powerful tool to determine the value of future payments. However, economic analysis is but one of many factors that maintenance managers must consider; other Items such as Reclamation policies and social and environmental impacts may influence the decision more. Remember the advice in paragraph 1.2.; the economic analysis is no substitute for sound Judgment, management, or control. Although other factors may override economic considerations, maintenance managers should be familiar with, and frequently use, economic analysis to help guide their Judgments. This bulletin is for them.

2. THE THREE BASIC STEPS OF ANALYSIS

2.1. Economic analysis of a problem Involves three basic steps: (1) examine all alternatives; (2) determine costs and benefits of each alternative; and (3) compare costs and benefits of the alternatives.

2.2. *Examine all alternatives.-* For example, the alternatives of performing maintenance on power circuit breakers include: (1) perform periodic routine maintenance and major overhauls by force account labor, (b) perform periodic routine maintenance by force account labor but contract for performance of major overhauls, and (c) lengthen intervals between periodic maintenance to the point that occasional repairs are required and depend primarily on major overhauls every 5th (or 10th) year, etc. The list is limited only by one's Ingenuity and judgment of prudent actions. Consideration of alternatives usually involves one or more of the following:

- To do maintenance or to do nothing and accept occasional breakdowns
- To repair or replace damaged equipment
- To buy or lease special services or equipment such as communication circuits, computers, and test/inspection services
- To do manually or by machine (is the program labor intensive or capital intensive?)

- To manufacture equipment (spare parts, test sets, etc.) in-house or to buy from commercial sources

- To contract for services or to direct-hire required personnel

- To centralize or decentralize operations and/or maintenance crews and facilities (stores, warehouses, etc.)

Examples of the broad range of applications Include analysis of a turbine runner replacement or a generator rewind. As a maintenance manager, analyze your own facilities and programs with the thought of improving productivity, safety, and reliability. Stretch your thinking beyond the conventional, accepted norms; seek new solutions. Chances are the programs you Inherited are running on their own Inertia. Compare your existing programs with non-Reclamation programs In your area. Look at the old and keep what is good - what still makes sense - then evaluate alternatives for needed new programs.

2.3. *Determine costs and benefits.-* Set up a "discounting table" showing costs and/or benefits and their present values (P) for each year of the proposed program in the following format:

Program year	**Discount factor**	**Alternative A**		**Alternative B**	
		Costs (P)	**Benefits (p)**	**Costs (P)**	**Benefits (p)**
1 **2** **3** **4** **etc.**					

Once you understand this format and the examples given later on, you will be in a position to make rational economic decisions on an amazing variety of matters. The discounting table is the heart of the economic analysis, and, when properly applies, becomes a powerful tool. Now consider costs and benefits.

2.3.1. Costs typically Include such items as:

- Land

- Labor

- Material

- Leasing charges

- Contractor services

- Research and development

- Planning, design, and construction

- O&M expenses

The determination of costs is basic to economic analysis; it provides the decision maker with the economic facts that are available, so the economic sot of a decision is known before the program is started. Failure to determine economic costs is perhaps the greatest single cause of program failures. Cost information requires proper documentation to provide a trail for validation of the analysis. In giving cost data, four principles apply:

- State all assumptions

- State all sources

- Use full disclosure of all elements of the study

- Be consistent in the analysis

2.3.2. Benefits typically include such items as:

- Performance (productivity, safety, reliability)

- Output (capacity, volume, plant factor)

- Results (program accomplishment, Income, repayment)

- Reduced costs (must be real, not transferred elsewhere)

Anticipated benefits are, of course, the reasons any activity is undertaken in the first place. It is easy, and often dangerous, to become overly optimistic on benefits. Like costs, benefits are basic to economic analysis. They provide the decision maker with the economic facts available.

2.4. *Compare costs and benefits.-* It was great to be able to send men to the moon, but was it worth it? Such a difficult question defies economic answers since many noneconomic factors (such as political and social) are involved. Economic answers too many difficult questions can, however, be obtained by comparing costs and benefits. This can be done by using a discounting table similar to that shown in section 2.3, comparing the total present values (P) of costs and benefits for each alternative considered. To select the best alternative, use these rules:

- If benefits are equal, choose the least costly alternative.

- If costs are equal, choose the most productive alternative.

- If costs are unequal and benefits are unequal, use the alternative with the highest benefit/cost ratio.

3. THE TIME VALUE OF MONEY

3.1. Present value formula.- The following basic economic formula, relating time to money, defines the present value of money that will be spent in the future. This formula will be used in practically all of our economic comparisons.

$$P = \frac{F}{(1+1)^{N}}$$

where:

P = Present value of F dollars to be spent in a future year

F = Future dollars to be spent in year N
N = Number of years, after start of the study, that F dollars will be spent

I = Interest rate per year, expressed in decimal form

Table A shows present values calculated from this formula for a wide range of years and Interest rates. Using this formula, wherein the value of F is assumed to be $1, it is a simple matter to use a packet calculator to quickly develop your own table of present values for any interest rate. This present value formula provides the foundation for the basic economic principle:

- To enhance economic feasibility, attempt to delay payment of costs and accelerate accrual of benefits.

Using table A, solve the following "present value" problem:

- *Problem.-* You will need a supply of make-up insulating oil for transformers in about 8 years. You can buy insulating oil today for $50 a barrel. You guess that in 8 years, the same oil will cost $100 a barrel. If the annual interest rate is 10 percent, should you buy now or wait?.

$$P = \frac{F}{(1+1)^{N}}$$

$$= 100/(1 + 0.10)^{8}$$

= $46.65 per barrel

- *Solution.-*

Since the present value of the cost to buy oil in the future is lower than today's cost ($46.65 vs. $50 per barrel), you should not buy the oil today. In this example, we have assumed zero storage costs, which, if included, would have reinforced our decision not to buy today.

Table A. - *Present value of $1*

Spent Years hence (n)	*4% (0.04)*	*6% (0.06)*	*7% (0.07)*	*8% (0.08)*	*9% (0.09)*	*10% (0.10)*	*12% (0.12)(1)*
1	0.962	0.943	0.935	0.926	0.917	0.909	0.893
2	.925	.890	.873	.857	.842	.826	.797
3	.889	.IMO	.816	.794	.772	.751	.712
4	.855	.792	.763	.735	.708	.683	.636
5	.822	.747	.713	.681	.650	.621	.567
6	.790	.705	.666	.630	.596	.564	.507
7	.760	.665	.623	.583	.547	.513	.452
8	.731	.627	.582	.540	.502	.467	.404
9	.703	.592	.544	.500	.460	.424	.361
10	.676	.558	.508	.463	.422	.386	.322
11	.650	.527	.475	.429	.386	.350	.287
12	.625	.497	.444	.397	.356	.319	.257
13	.601	.409	.415	.368	.326	.290	.229
14	.577	.442	.388	.340	.299	.263	.205
15	.555	.417	.362	.315	.275	.239	.183
16	.534	.394	.339	.292	.252	.218	.163
17	.513	.371	.317	.270	.231	.198	.146
18	.404	.350	.296	.250	.212	.180	.130
19	.475	.331	.277	.232	.194	.164	.116
20	.456	.312	.258	.215	.178	.149	.104
21	.439	.294	.242	.199	.164	.135	.093
22	.422	.278	.226	.184	.150	.123	.083
23	.406	.262	.211	.170	.138	.112	.074
24	.390	.247	.197	.158	.126	.102	.066
25	.375	.233	.184	.146	.116	.092	.059
26	.361	.220	.172	.135	.106	.084	.053
27	.347	.207	.161	.125	.098	.076	.047
28	.333	.196	.150	.116	.090	.069	.042
29	.321	.185	.141	.107	.082	.063	.037
30	.308	.174	.131	.099	.075	.057	.033
40	.208	.097	.067	.046	.032	.022	.011
50	.141	.054	.034	.021	.013	.009	.003

The interest rate assumed is a critical item in the analysis. How does a maintenance manager decide what value to use? Long-term treasury bond yields are often used (see the example in part 5.1.), but we suggest you contact the Operation and Maintenance Engineering Branch, D-5850, Denver Office, for the proper rate for your problem.

3.2. *Sunk costs.-* Funds that have been spent are called "sunk costs." In economic analysis, always disregard sunk costs (except possibly to learn and moan) as they are now financially irrelevant. Economic analysis is for the purpose of examining expenditure of funds for future alternatives. Therefore, when a project is being built, an economic analysis that is performed in successive years during construction would show declining project costs, since funds already spent for construction are "sunk" and are no longer evaluated. If the benefits of such a project remain constant, or increase, the B/C (benefit/cost) ratio would increase for each new year in which the economic analysis is performed. With zero base budgeting concepts, economic analyses are often performed each year for a particular project, and if the project develops as expected, the successive analyses show increasing B/C ratios.

An example of a maintenance problem involving sunk costs is:

- *Problem.-* $1,000,000 have been spent on procurement and installation of airblast power circuit breakers. After 3 years of service, it has been found that the breakers are totally unreliable and will have to be replaced. The salvage value of the breakers for scrap metal is $10,000 net, Including removal costs. The cost of suitable new oil breakers is $1,500,000; should they be purchased?

- *Solution.-* The only relevant costs for economic analysis are: $1,500,00 (new breakers) - $10,000 (salvage) = $1,490,000 (net). The decision to spend a net of $1,490,000 for new breakers is independent of the $1,000,000 sunk cost.

4. ECONOMIC LIFE AND TERMINAL VALUE

An economic analysis extending over several years must recognize that equipment wears out and must be replaced. Usually it is not obvious what equipment life to assume, and we must rely on what experience has shown from operating similar equipment. Reclamation engineers have made detailed studies of equipment operating histories and have been able to establish statistical "service life" values for a wide variety of equipment and structures. A summary of these studies may be found in "Replacements-Units, Service Lives, Factors," Bureau of Reclamation, pages III-1 through III-11, May, 1989.

4.1. *Economic life.-* The service life, or economic life, of a class of equipment is the time in which savings (benefits) gained through using the equipment accrue to the organization. There are three ways to determine whether equipment has reached the end of its useful service life:

- Physical life - Determined to be over when the machine is no longer repairable

- Technological life - Determined to be over when the machine is made obsolete by availability of improved models.

- Product life - Determined to be over when there is limited production of an item, and the life ends with production of the last unit.

In evaluating these three methods, the shortest life from among the three should be used in the economic analysis.

4.2. *Terminal value.-* The selvage value, or terminal value, of equipment is determined, at the end of the equipment life, to be the sale value minus the cost of disposal. Terminal values are usually determined by making straight-line or percentage projections of equipment resale data. The most familiar source of terminal value data is the "Blue Book" used by automotive dealers in determining used car trade-in allowances for new car purchases. The terminal value is used in an economic study as a "benefit" which accrues to the organization in the study year that it is salvaged. When in doubt, assume a zero salvage value at the end of the service life. Salvage value, when used, is discounted for the appropriate future year in order to determine its real economic benefit. Example:

- *Problem.-* An office computer has been purchased and installed for $5,000,000. Its terminal value 8 years later is estimated to be $50,000. What economic benefit does this value have? Assume an 8-percent interest rate.

- *Solution.-* The present worth of the computer salvage value is:

$$\mathbf{P} = \frac{\$50{,}000}{(1+0.08)^8}$$

$$= \$27{,}013$$

5. EXAMPLES AND SOLUTIONS OF MAINTENANCE PROBLEMS

We will now make economic analyses of actual problems which are typical of those which are faced by Reclamation maintenance managers. Only the names are fictitious. Complete solutions are shown to illustrate the basic concepts discussed above.

5.1. *Replacement of the telephone cord board at Glen Echo Powerplant.-*

- *Problem.-* The maintenance manager is considering replacing the existing leased Type 555 cord board at Glen Echo Powerplant. This unit is old, obsolete, and cumbersome to operate. Also, the local telephone company has stated that the Type 555 is no longer in production and maintenance is difficult due to lack of parts. Clearly, the useful life of this equipment is over. The manager intends to replace it with a modern 40-line PABS switchboard and has asked for price quotations both from the telephone company and a private equipment supplier. The manager must now prepare a cost comparison, using rules defined in Treasury Department Circular A-76, to determine which of the following alternatives will produce the greatest savings to the Government: Alternative 1 - Lease the new PABS from the telephone company; or Alternative 2 - Reclamation purchase, Install, and maintain the equipment.

- *Solution.- Alternative* 1 - Leased service option from the telephone company. The company offers leased service under the following conditions.

  Tier A, full rent. - Five-year period $650 monthly recurring charge.

  Tier B, reduced rent.- After 5 years, the rent will reduce to $250 per month until terminated by Reclamation. On termination, there will be a one-time charge of $1,000 to remove the company's equipment.

  Main station charge. - $2.20 per main station per month. Maximum of 40 stations at $2.20 each = $88 monthly recurring charge for the duration of the lease.

  Contract administration charge.- $620 annual recurring charge.

  Installation charge.- One-time nonrecurring charge: $2,000.

Summary of costs by year- Alternative 1. -

Year 1:2,000 + 12 x (650 + 88) + 620 = $11,476

Years 2, 3, 4, 5:12(650 + 88) + 620 = $9,476

Year 6 to termination year: 12(250 + 88) + 620 = $4,676

Termination year: 1,000 + 12(250 + 88) + 620 = $5,676

Alternatives 1 and 2 will be designed to provide identical service; hence the benefits are assumed to be equal.

Table B. - *Discounting table for telephone cord board problem*

Year	Discount factor (8.91%)	Alternative 1		Alternative 2	
		Cost	(P)	Cost	(P)
1	**0.981**	**$11,476**	**410,535**	**$20,465**	**$18,787**
2	**.843**	**9,476**	**7,988**	**1,500**	**1,264**
3	**.774**	**9,476**	**7,334**	**1,500**	**1,161**
4	**.711**	**9,476**	**6,737**	**1,500**	**1,066**
5	**.653**	**9,476**	**6,188**	**1,500**	**980**
6	**.599**	**4,676**	**2,801**	**1,044**	**625**
7	**.550**	**4,676**	**2,572**	**1,044**	**574**
8	**.505**	**4,676**	**2,361**	**1,044**	**527**
9	**.464**	**4,676**	**2,170**	**1,044**	**484**
10	**.426**	**4,676**	**1,992**	**1,044**	**445**
11	**.391**	**4,676**	**1,828**	**1,044**	**408**
12	**.359**	**4,676**	**1,679**	**1,044**	**375**
13	**.330**	**4,676**	**1,543**	**1,044**	**344**
14	**.303**	**4,676**	**1,417**	**1,044**	**316**
15	**.278**	**5,676**	**1.578**	**245**	**68**
Total present value			**$58,723**		**$27,424**

Therefore, this economic analysis will compare only costs to determine the most favorable alternative.

Alternative 2. - Reclamation ownership. Reclamation personnel determine that equivalent telephone switching equipment can be purchased from a commercial supplier and installed and maintained by force account labor. A tabulation of the costs involved is:

Equipment cost from private supplier: $15,980

Installation and testing of new system at 3 percent of equipment cost: $479

Indirect costs covering Reclamation procurement and finance office costs: $2,397.

Estimated Federal tax credit on contract procurement, 2 percent x $15,980: $230. (Amount of Federal tax the contractor will pay on equipment procurement. Rate computed from Quarterly Financial Report of Manufacturing Corporations.)

Interest during construction; 2 months at 8.91 percent on $15,980: $237.

(Amount of interest Reclamation pays on the estimated contract cost during construction. Construction period estimated at 2 months and interest rate at 8.91 percent is the yield on long-term treasury bonds taken from Treasury Bulletin for January 1979.)

Operation and maintenance annual costs based on experience with similar systems: $600.

Annual allowance of 9.5 percent for Federal income tax calculated using the telephone company's 1979 expense report and computed on the yearly costs of the leased system: (0.095 x yearly cost of leased system).

Net scrap value at end of service life, at 5 percent of new equipment cost (005 x $15,980):-$799

The estimated service life of telephone switching equipment is 15 years.

Summary of costs by year - Alternative 2. -

Year 1:$15,980 + 479 + 2,397- 320 + 237 + 600 + 0.095 x 11,496 = $1,500

Years 2, 3, 4, 5:600 + 0.095 x 9,476 = $1,500

Years 6 to 15: 600 + 0.095 x 4,676 = $1,044

Year 15:600 + 0.095 x 4,676- 799 = $245

Use an interest rate of 8.91 percent (current yield on long-term treasury bonds) to determine the present worth (P) of the costs of the two alternatives.

Cost Comparison, Conclusions, and Recommendations

The analysis shown on the discounting table (table B) can be used to tell several important economic facts about alternatives 1 and 2.

a. The present value of costs of alternative 1 ($58,723) is more than twice that of alternative 2 ($27,424). Since the benefits (services) of the two alternatives are the same, alternative 2 (Government ownership of the switchboard) is the most economical scheme.

b. Circular A-76 comparison criteria (section 7b-3) require that Government costs be at least 10 percent less than leased circuit costs before a Government-owned system can be installed. The ratio of leased circuit costs to adjusted Government-owned costs is therefore

$$\frac{58{,}723}{27{,}424 \times 1.10} = 1.95$$

Clearly, alternative 2 meets the economic test for being the preferred system.

c. What would happen if the projected 15-year service life for the equipment is too long? Note that the total present value of costs for alternative 1 exceeds those of alternative 2 in the 3rd year of the study. This indicates that should obsolescence or other factors make switchboard replacement desirable after only 4 years (for example), alternative 2 is still the preferred economic scheme. This is a comfortable margin for error in service-life estimation.

We conclude that the economic analysis shows considerable savings for Reclamation ownership of the switchboard. However, our final recommendations must depend upon other factors as well. Are Government maintenance forces adequately staffed and training to provide this service? Do management policies permit installation of a Government-owned system? If the answers to such questions are yes, one can strongly recommend that alternative 2 be Implemented.

5.2. Justification for warehouse docking facilities at the Big Water Project Headquarters. -

- Problem.- The maintenance manager is evaluating the feasibility of building loading docks for the warehouse at Big Water Project Headquarters. The building does not have docks and warehousing activities are tedious and expensive. The manager evaluates the lost time and concludes that these docks will save $10,000 annually. The docks will cost $50,000 and take 1 year to complete. The new docks are estimated to have a service life of 7 years. The current annual interest rate is 10 percent. The maintenance manager determines that adequate funds can be programmed for the docks, but wants to ensure the expenditure can be economically justified. The following study is performed.

Benefit/Cost Comparisons, Conclusions, and Recommendations

See the discounting table (table C). The present value of costs ($45,450) exceeds that of benefits ($44,230) over the study period. Therefore, it would not be economical to build the dock facilities. Other factors such as safety, anticipated staff cuts, etc., will also have a significant influence on the decision. Note the following from the discounting table:

a. The 1-year delay in accruing savings (study year 2 rather than study year 1) caused the adverse economic study result, if a way could be found to shorten the construction time, the

Table C. - Discounting table for warehouse docking facility problem

Program year	**Discount factor (10%)**	**Costs**	**(P)**	**Benefits**	**(P)**
I	**0.909**	**$50,000**	**$45,450**	**$ 0**	**$ 0**
2	**.826**	**0**	**(Docks in use)**	**10,000**	**8,260**
3	**.751**	**0**	**0**	**10,000**	**7,510**
4	**.683**	**0**	**0**	**10,000**	**6,830**
5	**.620**	**0**	**0**	**10,000**	**6,200**
6	**.620**	**0**	**0**	**10,000**	**5,640**
7	**.513**	**0**	**0**	**10,000**	**5,130**
8	**.466**	**0**	**0**	**10,000**	**4,660**
Total present value			**$45,450**		**$44,230**

docks would become more economically feasible.

b. If the service life of the docks could be extended from 7 to 8 years, they could be economically Justified.

Perhaps the service life could be extended through use of concrete instead of wood. Other alternatives should be considered.

The maintenance manager concludes that the docks cannot be economically justified as proposed. However, other alternatives or modifications may be developed which prove economically feasible. No firm recommendations on the docks can be made until further studies are completed.

6. FURTHER HELP

You have been exposed to several basic economic principles in this bulletin, and by following and understanding the examples, you have an insight on use of economic analysis. The economic principles discussed were selected in the belief that they will be of most use to you, the maintenance manager. No attempt is made to cover all important economic principles; to do so would require the services of a professional economist. Assistance on analysis of maintenance problems is available from the Operation and Maintenance Engineering Branch, Attention D-5850, Denver Office.

For those wishing further study of principles and practices as applied in the Bureau of Reclamation, the following publication is recommended: "A Guide to Using Interest Factors in Economic Analysis of Water Projects." This publication may be ordered from the Denver Office, Attention D-7923A.

BUREAU OF RECLAMATION

FACILITIES INSTRUCTIONS, STANDARDS, & TECHNIQUES

Volume 4 - 4

TEST EQUIPMENT AVAILABLE FOR LOAN FROM THE DENVER OFFICE

September 1992

TEST EQUIPMENT AVAILABLE FOR LOAN FROM THE DENVER OFFICE

A stock of test Instruments and equipment is maintained by the Research and Laboratory Services Division, Electric Power Branch, at the Denver Office, Denver, Colorado, for loan to project or regional offices. Some specialized test equipment is also available from certain project offices. Requests for the use of this equipment should be sent to the Bureau of Reclamation, Attention: D-3770, RO. Box 25007, Denver, CO 80225-0007. The equipment requested will be packed and shipped to the project or regional office immediately or as soon as it becomes available. Each project or regional office using equipment is responsible for its maintenance and its return in complete and good condition. Equipment instruction books must be returned in good condition with the equipment so that the next user will have all the necessary operating instructions. Ensure that the equipment is properly packed to prevent damage during the return shipment. Since most test equipment is delicate, attach a conspicuous tag marked “FRAGILE-DELICATE INSTRUMENT”, or similar warning, to the shipping container. Shipping costs will be charged to the project or regional office using the equipment.

A list of the test equipment available for loan from the Denver Office, and certain project offices, is contained in "Spare and Specialized Equipment for Loan," periodically updated by the General Sciences Division, Operation and Maintenance Engineering Branch. Some additional specialized laboratory equipment not listed in the above document may also be available for loan from the Electric Power Branch, D-3770. The project or regional offices should contact the Electric Power Branch or the Operation and Maintenance Engineering Branch for equipment needs not shown in the equipment for loan document.

BUREAU OF RECLAMATION

FACILITIES INSTRUCTIONS, STANDARDS, & TECHNIQUES

Volume 4 - 5

USE OF CATHODIC PROTECTION OF BURIED AND SUBMERGED METALS IN CORROSION PREVENTION IN ELECTRIC POWER SYSTEMS

PURPOSE AND SCOPE

The intent of this volume is to provide basic information concerning corrosion of submerged and buried metals encountered in electric power installations and the application of cathodic protection or other methods as a means of protection. The protection of metallic structures against corrosion damage is considered important from an operating standpoint and from the financial aspect of replacement of structural components. A few of the considerations of this cost are shortened structure life, equipment or system out-of-service time, and increased maintenance. The dollar cost is not the only concern as the loss of critical material and human effort are also items of considerable importance. Protection against corrosion by cathodic protection is one method of curtailing this loss.

The principles and methods discussed herein will provide field personnel with the necessary basic information for a clearer understanding of the action involved in corrosion. Further, it will delineate the simple situations in which a cathodic protection system might be installed by project forces and other circumstances where the assistance of specialists would be advisable.

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1. General

1.1. Types of corrosion.- Corrosion is an electrochemical phenomenon; that is, it involves chemical reactions and the flow of current. The two most common types are corrosion caused by stray currents from external sources and galvanic-type corrosion caused by different metals in an electrolyte or the same metal in different electrolytes. These will be discussed separately and possible remedial measures given.

1.2. Description of corrosion terms.- Several corrosion terms frequently used in this bulletin and in corrosion work are described more in terms of practical corrosion concepts rather than as formal definitions.

Anion.- Negatively charged ions in the electrolyte. Anions are attracted to and move toward the anode under influence of a potential gradient. Some may react at the anode.

Anode.- The metal which corrodes, considered as being at the higher potential or positive terminal of the current source.

Cathode.- The metal which is protected by the anode and does not corrode, considered as the lower potential or negative terminal of the current source.

Cation.- Positivity charged ion in electrolyte. cations are attracted to and move toward the cathode under influence of a potential gradient. Some may react at the cathode.

Concentration cell.- A corrosion cell whose voltage is the result of inhomogeneities or differential chemical conditions within the electrolyte.

Corrosion.- The process of oxidation of a metal due to the interaction of the metal and its environment.

Corrosion cell.- Consists of an anode and a cathode which are both metallically connected and immersed in an electrolyte. Dry and wet cell batteries are common exampies (when shorted across the terminals).

Electrical resistivity.- The resistance offered to the passage of current by a unit volume of the material. Units are ohm-centimeters or ohm-feet.

Electrolyte.- The medium (such as water or moist soil or solution of special chemicals) through which the internal circuit current or a corrosion cell flows from the anode to the cathode by migration of anions and cations.

Electron flow.- Is in the opposite direction to "conventional" current flow.

External circuit.- The part of a corrosion cell circuit in which the current flows through the metal of the anode, cathode, and metallic conductor between them (the metallic part of the circuit).

Internal circuit.- The part of a corrosion cell circuit in which the current flows through the electrolyte (the solution part of the circuit).

Galvanic cell.- A corrosion cell in which the anode is of a different metal than the cathode.

Galvanic-type corrosion.- Corrosion similar to that produced by a galvanic cell.

Galvanic series.- A listing of metals and alloys arranged in increasing order of their resistance to corrosion when any two of them are the electrodes of a complete cell (table 1).

Ion.- An electrically charged atom or group of atoms.

Local cell corrosion.- Corrosion caused by local inhomogeneities in a metal surface which creates small anode and cathode areas.

Long-line corrosion.- Corrosion occurring where the anode and cathode are widely separated, sometimes by several hundred feet. It is usually caused by inhomogeneity in the electrolyte or metal at these locations.

Mill scale.- A heavy oxide layer formed on steel and iron during hot fabrication or heat treatment of the metal.

Noble metals.- Those metals having the greatest tendency to remain in the uncombined or free state. The more noble of two metals in a corrosion cell will be the cathode and will not corrode.

Polarization.- Production of a back EMF (electromotive force) or countervoltage in a corrosion cell as a result of chemical changes at the electrode produced by the flow of current. This acts as resistance in the internal circuit of a corrosion cell.

Stray current corrosion.- Corrosion caused where current from an extraneous source is discharged into the electrolyte (i.e., ground return from a street, railway system, etc.).

Tuberculation.- The formation of knob-like mounds of corrosion products due to local corrosion.

2. Galvanic-type corrosion

2.1. Description.- Galvanic-type corrosion occurs as the result of the tendency of metals to revert to their natural state. If this is to occur, the metals must be so arranged as to form a complete cell, which may be termed a battery or corrosion cell or galvanic cell. Since corrosion may stem from other causes, it is important to note that the type described as galvanic may be recognized from the fact that the cell provides the forces causing corrosion, rather than external currents, etc. The cell is comprised of an anode and cathode immersed in an electrolyte. When the anode and cathode are metallically connected (as when a wire is connected across the terminals of a battery), current flows and corrosion of the anode occurs. When the anode happens to be a metallic part of a structure, piping, or cable system, severe damage may result.

2.2. Natural corrosion cells.- The environment for many electrical power structures provides conditions favoring formation of natural corrosion cells. The metal or metals of a structure serve as anode, cathode, and the necessary metallic conductor between the two. Water, either as such or as moisture in soil, provides the electrolyte required to complete the cell circuit. Such cells develop their driving force or electrical potential from differing conditions at the interfaces between metal and electrolyte of the anode and cathode. These differences fall into three categories: (a) Dissimilar metals comprising the anode and cathode, (b) in-homogeneity of a single metal, which causes one area to be anodic to another area, and (c) inhomogeneity of the electrolyte. The following are a few of many possible examples in which the essential requirements of a complete cell are satisfied in a structure.

(a) Iron will be anodic to copper ground mats or to brass bolts or other brass parts.

(b) An iron plate having some mill scale present may rust because the iron is anodic to the mill scale.

(c) An apparently homogeneous iron plate may rust because tiny areas of the surface contain impurities or grain stresses which cause them to be anodic to other areas of the surface.

(d) Weld areas of a welded pipe may rust because the weld metal is of different composition, may contain impurities, or may cause stress which make it anodic to nearby metal areas.

(e) Corrosion may be observed on the bottom of a pipeline while the top remains nearly undamaged. This may be attributable to higher oxygen concentration in the soil moisture (electrolyte) at the top of the pipe, leaving the bottom anodic. The soil being undisturbed at the bottom of the pipe provides a lower oxygen content and a lower resistance to current flow than is present in the backfill covering the top of the pipe.

(f) Exposed iron areas in contact with concrete. Encased or embedded iron may rust because the concrete creates a different and special electrolytical environment which causes the exposed iron to become anodic to the embedded iron.

2.3. Factors influencing corrosion rates.- From the above examples and the many other environmental differences which could be visualized, it might appear that almost no metalwork could survive burial in soil or immersion in water. Such is not the case because the rate at which a cell functions and corrosion occurs is controlled by several factors; these factors may virtually halt the cell action. Some of the more important factors affecting corrosion are inherent or associated with the metal itself, such as the effective potential of the metal in the solution, physical and chemical homogeneity of the metal surface, and the inherent ability of the metal to form an insoluble protective film. Environmental factors affecting corrosion rates are formation of protective coatings on metal, temperature, influence of oxygen in the electrolyte, effect of electrode potential, and others. No attempt has been made to list these factors in the order of their importance. The environmental aspect of corrosion is the more unpredictable and one that makes it impossible to describe a single, positive method of controlling a specific corrosion problem without detailed investigation.

2.4. The galvanic series.- The differing vigor with which different metals tend to dissolve in electrolytes provides the driving force for galvanic cells and gives rise to the *galvanic series.* This is a listing of metals in decreasing order of their corrosion when any two of them are the electrodes of a complete cell. That is, the metal higher on the list will be the anode and will be corroded while the lower will be the cathode and will be protected in the cell. A galvanic series tabulation developed by the International Nickel Company is shown in table 1. This series was developed by actual field and laboratory tests using electrolytes likely to be encountered under operation conditions. It takes into account that certain metals from protective oxides which cause these metals to assume more noble positions in the series than the clean metal would have. This series, then considers practical corrosion aspects as well. However, it cannot anticipate all service conditions and reversals of position which may occur. (The galvanic series should not be confused with the *electromotive series* used by chemists. The latter is referred to standard conditions which rarely occur in nature, and the order of the metals in the electromotive series does not exactly coincide with that of the galvanic series.)

Table 1 .- Galvanized series of metals and alloys *

Corroded end (anodic or least noble):

Magnesium.
Magnesium alloys.

Zinc.

Aluminum 2S.

Cadmium.

Aluminum 17ST.

Steel or iron. Cast iron.

Chromium-iron (active)

Ni-Resist.

18-8 Chromium-nickel-iron (passive).
18-8-3 Chromium-nickel-molybdenum-iron (passive).

Lead-tin solders
Lead.
Tin.

Nickel (active)
Inconel (active)
Hastelloy C (active)

Brass.
Copper.
Bronzes.
Copper-nickel alloys.
Monel.

Silver solder.

Nickel (passive).
Inconel (passive).

Chromium-iron (passive).
18-8 Chromium-nickel-iron (passive).
18-8-3 Chromium-nickel-molybdenum-iron (passive).
Hastelloy C (passive).

Silver.

Graphite. Gold. Platinum.

Protected end (cathodic or most noble)

*Metals listed together show little tendency to corrode galvanically when connected.

2.5. Use of the galvanic series.- The metals grouped together in the galvanic series cremate cells having low driving force (voltage) when connected together and little tendency for galvanic corrosion. Therefore, in general, they can be used in direct contact with each other without damaging effects. When coupled as a cell, two metals from different groupings create a source of potential, the amount of which is indicated by the separation between the metals on the listing. As shown in table 1, the most anodic or "least noble" metals are at the top of the list, and the most cathodic or "most noble" metals are at the bottom. It should be remembered that the series is a guide as to what can be expected and is not intended to replace actual experimental tests in assessing specific problems under consideration.

2.6. Characteristics of soil which affect the corrosion rates.- Three prime factors that affect the severity and acceleration of corrosion of metals in soil are moisture, salt and/or acid content, and aeration. Corrosion, as mentioned before, is an electrochemical process. It has been found that the chemical approach in analyzing soil corrosiveness is too involved to be practical. However, a correlation exists between what is called "soil corrosivity” and "soil electrical resistivity." Soil moisture in conjunction with soluble soil salts constitutes the electrolyte of the corrosion cell and is, therefore, the cell's internal circuit. Consequently, the higher the resistance of the soil electrolyte, the lower the rate at which the corrosion cell functions. The soil resistivity is especially indicative of soil corrosivity in alkaline soils and is useful as a guide in acid soils. The commonly used unit of soil and water resistivity is the ohm-centimeter, which is the resistance in ohms of a 1-centimeter cube of the material in question measured between two opposite, parallel faces. In considering soil as an electrolyte, the salt and water content determines the cell resistance. The moisture content will normally change radically with seasons. This one factor alone can give soil resistivity variation from a minimum of 2500 to a maximum of 10 000 ohm-centimeters, where extreme dryness occurs.

2.7. Soil resistivity.-In correlating the resistivity readings obtained with expected corrosion action, the following soil resistivity values can be used as a guide:

(a) Values of 1000 ohm-centimeters or lower indicate very corrosive conditions.

(b) Values from 1000 to 5000 ohm-centimeters usually indicate moderately corrosive conditions.

(c) Values from 5,000 to 10,000 ohm-centimeters indicate mildly corrosive conditions.

(d) Values above 10,000 ohm-centimeters indicate slightly corrosive conditions.

Values between the 1,000 and 10,000 ohm-centimeters should be compared to those in immediately adjacent sections of the structure. For example, if resistivity readings are running at 10,000 ohm-centimeters and there is in a short distance a drop to 2,000 ohm-centimeters, corrosion is likely to occur in the 2000-ohm-centimeter area. These areas of low resistivity are referred to as "hot spots." Also, changes in high soil resistivity can sometimes be conducive to corrosion; for example, a change from 10,000 to 100,000 ohm-centimeters.

2.8. Characteristics of water which affect the corrosion rates.- The effect of the electrolyte on the corrosion rate depends on the temperature, on the dissolved oxygen concentration, and on the nature and concentration of the dissolved salts which may or may not tend to make the water scale forming. The interrelationship of these factors with respect to corrosion is not fully understood. Therefore, we do not have firm and specific criteria for evaluating the corrosion property of water on the basis of its chemical characteristics.

2.9. Polarization.- When corrosion occurs, chemical reactions take place at the electrodes. These reactions may "plate out" the reaction products on the electrodes; for instance, hydrogen ions may be converted to uncharged hydrogen or calcium ions which ultimately may be converted to a calcium carbonate scale on the cathode. Such deposits often act to increase the electrical resistance of the internal circuit, with the result that the flow of current and the corrosion rate are reduced. Opposing chemical reactions tend to *depolarize.* For instance, oxygen in the electrolyte may react with hydrogen to form water. This reverse reaction tends to negate the beneficial effects of polarization.

2.10. Minimizing galvanic corrosion in design.- Galvanic corrosion can be minimized in design. Corrosion engineers have found the following practical rules invaluable in this respect:

(a) Select combinations of metals which will be in electrical contact from groups as close together as possible In the galvanic series.

(b) Electrically insulate from each other metals from different groups, wherever practical. If complete insulation cannot be achieved, paint or plastic coating at joints will help.

(c) If you must use dissimilar materials well apart in the series, avoid joining them by threaded connections as the threads will probably deteriorate excessively. Brazed or thermit joints are preferred, using a brazing alloy more noble than at least one of the metals to be joined.

(d) Avoid making combinations where the area of the less noble, anodic metal is relatively small compared with the area of the more noble metal.

(e) Apply coatings with judgment. Example: Do not paint the less noble metal without also painting the more noble; otherwise, greatly accelerated attack may be concentrated at imperfections in coatings on the less noble metal. Keep such coatings in good repair.

(f) Consider use of cathodic protection.

3. Stray current corrosion

3.1. Description.- Stray currents which cause corrosion may originate from direct-current distribution lines, substations, or street railway systems, etc., and flow into a pipe system or other steel structure. Alternating currents very rarely cause corrosion. The corrosion resulting from stray currents (external sources) is similar to that from galvanic cells (which generate their own current) but different remedial measures may be indicated. In the electrolyte and at the metal-electrolyte interfaces, chemical and electrical reactions occur and are the same as those in the galvanic cell; specifically, the corroding metal is again considered to be the anode from which current leaves to flow to the cathode. Soil and water characteristics affect the corrosion rate in the same manner as with galvanic-type corrosion. However, stray current strengths may be much higher than those produced by galvanic cells and, as a consequence, corrosion may be much more rapid. Another difference between galvanic-type currents and stray currents is that the latter are more likely to operate over long distances since the anode and cathode are more likely to be remotely separated from one another. Seeking the path of least resistance, the stray current from a foreign installation may travel along a pipeline causing severe corrosion where it leaves the line. Knowing when stray currents are present becomes highly important when remedial measures are undertaken since a simple sacrificial anode system is likely to be ineffectual in preventing corrosion under such circumstances.

3.2. Detection of stray currents.- Detection of stray currents which may be causing corrosion is somewhat involved and involves technical operations for which field staffs are usually not equipped. Their presence may be suspected when large direct-current installations are in the vicinity of the structure experiencing corrosion and especially when very rapid corrosion occurs. The services of a corrosion specialist should then be requested.

4. Protective coatings

4.1. Coatings and corrosion cells.- Protective coatings are widely used to prevent corrosion, and they serve this function by interposing a mechanical and often electrical barrier between the metal surface being protected and the corrosive environment. As long as the barrier remains intact, corrosion usually will not progress. Viewed from the standpoint of the corrosion cell such as a battery or corroding pipeline, an organic coating acts rather as an envelope insulating an electrode away from the electrolyte, thus ideally removing that electrode from contact and braking the electrical circuit of the cell. However, coatings may be damaged mechanically during installation, they deteriorate at varying rates with time, and high cathodic or stray currents may destroy their bond and continuity. Further, some coatings offer little or no electrical resistance. In practice, then, the corrosion cell circuit is often restored to some degree with the coating providing some measure of resistance to the flow of current.

4.2. Characteristics of specific coatings.- The type of coating and the nature of the damage or deterioration it suffers will bear strongly on the nature of the metal corrosion which may occur. Damage to coal-tar enamel, a widely used coating for buried metal, is most often of the mechanical type caused by rocks during backfilling. This damage usually produces holes in the coating at a few distinct locations, the remainder of the surface being fully protected. The enamel itself undergoes virtually no degradation over the years and offers effectively complete electrical installation of the metal. The result is that corrosion is usually concentrated at a very few points of damage which can be repaired or cathodically protected at nominal cost. Concrete or cement mortar, another widely used coating, protects by virtue of the alkaline environment it creates. This is usually effective as long as the coating is of good quality and free of wide cracks or spalls. Mortar is also a very durable coating but one which at present is considered to provide little or no electrical resistance in a corrosion cell circuit. The CA-50 coal--tar paint, asphalt, red lead and aluminum, vinyl resin, and many thin film coatings suffer much more repaid deterioration of the coating materials; and gradually, defects in the coating become generally distributed over the surface. As deterioration proceeds, the degree of electrical resistance usually provided decreases. Hot-dip zinc (galvanizing) acts as the anode of a corrosion cell and, thus, protects the base metal at points where there are small breaks in the coating. When the zinc has been entirely consumed, the base metal is exposed for corrosion.

4.3. Effect of defective coatings on corrosion. - Corrosion of metal protected by defective coatings progresses at locations of the defects; that is, where the coating is actually gone from the surface as a result of blistering, cracking, peeling, or mechanical damage. This process produces the pitting type of corrosion. Under normal corrosive conditions such as a very localized galvanic cell, the penetration of the metal at the defect may be little, if any, faster than if the coating were not present over the rest of the surface. However, if sizeable stray currents are operative or a galvanic cell is producing a significant voltage, more rapid consumption of the metal localized at the defects may be expected. In the light of these facts, it may be asked why coatings are applied. In most instances, coatings provide excellent corrosion prevention in themselves, sufficiently effective that cathodic protection is not usually needed on Reclamation structures. Coatings for bur-led structures are very durable and corrosion voltages are very rarely high enough to promote accelerated failure. Further, should detrimental corrosion occur, an insulating type of coating cuts cathodic protection costs drastically (to perhaps 10 percent of the cost of protecting bare pipe).

4.4. Compatibility of protective coatings and cathodic protection.- Coatings and cathodic protection complement each other and, where possible, should be used as a combination to achieve the best economy and protection. However, the coating must be compatible with cathodic protection. Certain materials, notably phenolic resin and aluminum pigment, deteriorate rapidly in the alkaline environment which cathodic protection creates where the structure is being protected. Coal-tar enamel and vinyl resins are relatively unaffected. Both high stray current voltages and excessive cathodic protection voltages may "blow off' coatings; that is, cause disbonding and rupture of the coatings. All coatings are susceptible, but high adhesion decreases the vulnerability to this effect. Since the cost of cathodic protection is a function of coating resistance, the better electrical insulator the coating is, the lower the cost. Coal-tar enamel and plastic tape coatings offer the greatest advantage from this standpoint. The preceding information should be considered in evaluating the condition of a coating where a corrosion problem exists. It may be found that providing protection may best be accomplished by restoring the continuity of an existing coating, and the condition of an existing coating will always be a factor in evaluating the desirability of installing cathodic protection. Reclamation's *Paint Manual* should be referred to for a discussion of the characteristics of various paints and the procedures for their application and maintenance.

5. Cathodic protection

5.1. General.- Cathodic protection is the use of an impressed or galvanic current to reduce or prevent corrosion of a metal in an electrolyte by making the metal to be protected by the cathode of a corrosion cell. The source of the protective current is immaterial, and it may be derived from zinc or magnesium anodes or external sources of power, i.e., a rectifier. Whenever corrosion takes place at the surface of steel in contact with an electrolyte, it can be controlled by cathodic protection. It is not always the most economical method since other more corrosion-resistant materials may be applied. However, after careful study of all the factors, cathodic control of corrosion by itself or in conjunction with protective coatings will often prove to be the most efficient means of protecting buried or submerged metals. Cathodic protection is not considered a practical means for protecting the interior surfaces of smaller diameter pipelines. In this bulletin, methods of using cathodic protection by sacrificial anodes for protection of the exterior of buried pipeline installations will be described. Other applications of cathodic protection will be briefly covered, and some reference to adaptability of the systems to other structures will be made. It must be remembered that for each structure, protection is a specific problem and has to be handled as such in cathodic protection installations.

6. Sacrificial anode systems

6.1. Theory.- Sacrificial anodes, metallically connected to a corroding structure and suitably immersed in the electrolyte (water or moist soil), create a simple galvanic cell in which the structure is the cathode or protected surface. By this device, detrimental corrosion is replaced by localized and controlled corrosion of an expendable anode which can readily be examined and replaced as necessary.

Figure 1 shows a typical problem and its solution. in figure 1A, an iron pipe with a break in the mill scale is in moist soil or water. Since the pipe metal is anodic to the mill scale and all elements of a corrosion cell are present, current flows and corrosion (formation of ferrous ion, Fe + +) progress at the break in the mill scale (fig. 1B); and if left for a sufficient period of time, a pit is likely to develop, possibility resulting in eventual perforation and failure of the pipe. However, as shown in figure 1C, installation of a magnesium anode has created a new corrosion cell in which the corrosion (formation of magnesium ion, Mg + +) is now taking place at the anode. The iron of the pipe (as well as the mill-scale coating) has become the cathode of the new cell and is said to be cathodically protected. This type of cathodic protection is easily recognizable as the sacrificial anode type since the cell generates all of the current for protection, there being no external sources involved.

6.2. Anode metals.- Reference to table1 shows that magnesium heads the list as the most anodic metal and is widely separated from iron in the galvanic series. Magnesium coupled to iron provides sufficient galvanic potential to provide positive protection. An important feature of a sacrificial anode system is that it is inherently a safe system because the normal potentials generated are insufficient to damage coatings present on the surface to be protected. Because of the low potentials generated, sacrificial systems can be used only in low-resistance soils, i.e., with a resistivity less than 3000 ohm-centimeters.

6.3. Assumptions of protective current require-merits and bare metal areas.- To obtain a starting point, certain general assumptions have been found helpful.

a. For bare metal in the ground, a current of 11 to 22 mA/m^2 (1 to 2 mA/ft$^{2)}$ of bare metal surface has been found adequate, except under extreme or unusual conditions. This value must then be modified to suit the particular conditions.

b For coated pipe, the current required is difficult to estimate without field tests. The primary reason is the unknown condition of the protective coat which can vary from nearly 0 to 98 percent coverage. For a fairly new protective coat properly applied, assume 2 percent bare and 22 mA/m^2 (2 mA/ft^2) for use

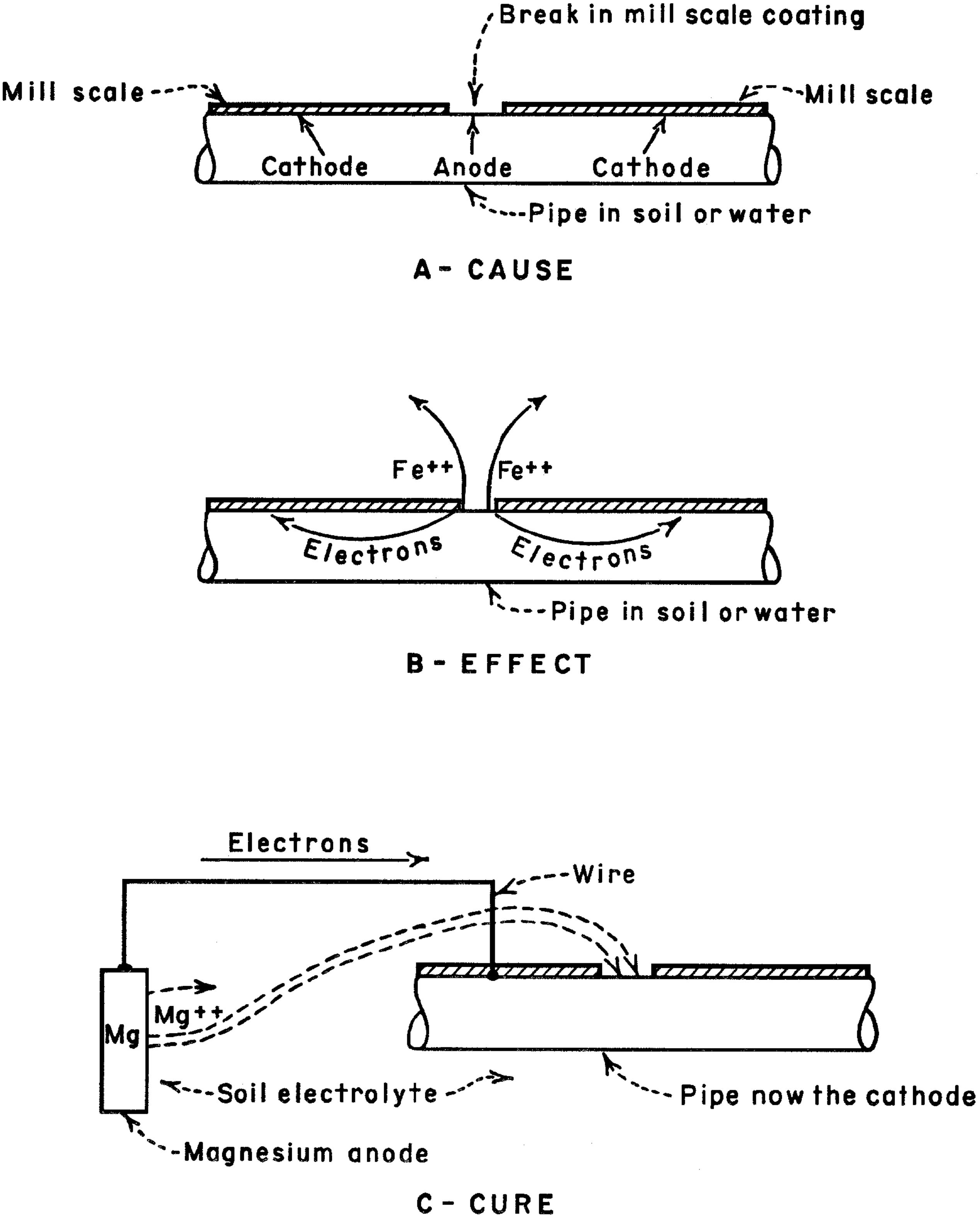

Figure 1. - Corrosion of buried iron pipe.

in tentative calculations. Field test may show that this figure should be modified.

c. Bare pipelines can usually be protected by 11 to 22 mA/m^2 (1 to 2 mA/ft^2). This is seldom justifiable economically for extensive or long lines, however, and the necessary protection is usually afforded by the application of cathodic protection to localized areas called "hot spots."

d. Bare steel tanks are treated the same as bare pipelines, inside steel surfaces in contact with fresh water at zero or low velocities require from 22 to 65 mA/m^2 (2 to 6 mA/ft^2), depending on the nature of the water. The low value is used for water which is scale forming. That is, the water will form a calcareous coating on the surface of the metal.

e. Protecting steel surfaces in contact with water in motion presents another problem. Water in motion produces a scouring effect which prevents the formation of the above-mentioned coating and even the formation of a hydrogen film. Therefore, surfaces ex. posed to water in motion require a higher current density. The amount required is hard to predict. In this case, an experimental determination of the current requirement should be made.

6.4. Examples for designing a system.- Several factors enter the determination as to how many sacrificial anodes may be required for a given structure and corrosion problem and the manner of distributing them with respect to the location where corrosion is occurring. The anode requirements for a small installation will normally involve the steps taken in the two following examples. For cathodic protection of larger structures involving use of six or more anodes or an impressed current rectifier) system, additional steps must be taken to assure
proper functioning of the system, i.e., proper distribution of the anodes, prevention of damage to other buried metal work, design of an economic system, and proper operation and maintenance.

Problem 1: Determine the galvanic anode requirements for a cathodic protection system of 45.7 m (150 ft) of 0.1-m- (4-in.-) coated pipe buried in the ground.

Required data

A. Knowledge of the condition of pipe protective coating (see paragraph 6.3. as basis for assumptions).

B. Soil resistivity in ohm-centimeters (do not use sacrificial anodes in soil whose resistivity exceeds about 3,000 ohm-centimeters.

C. Assume a current demand (see paragraph 6.3.).

D. Protective current required is equal to area of bare metal to be protected times the required current.

E. Number of anodes required must be computed.

Data and assumptions for the problem

A. Pipe surface 5 percent bare.

B. Soil resistivity determined as 1,000 ohm-centimeters.

C. Assume 11 mA/m^2 (1 mA/ft^2) of bare steel.

Solution

A. Protective current required is the total area of bare steel in square meters (square feet) times the required current per square meter (square foot).

Amperes = length of pipe (m) x pipe circumference (m):

$$\times \frac{\text{percent bare metal}}{100}$$

$$\times \frac{\text{ma / square meter}}{1{,}000}$$

For the example of 45.7 m of pipe in 1,000-ohm-centimeter soil:

Amperes = 45.7 x 0.3597 x 5/100 x 11/1,000
= 0.009 ampere

Amperes = length of pipe (ft) x pipe circumference (ft)

$$\times \frac{\text{percent bare metal}}{100}$$

$$\times \frac{\text{ma / square meter}}{1{,}000}$$

For the example of 150 ff of pipe in 1,000-ohm-centimeter soil:

Amperes = 150 x 1.18 x 5/100 × 1/1000
= 0.009 ampere

B. Number of anodes equal to total current required times the installation life divided by the ampere-hour rate of the magnesium anodes.

Number of anodes =

current required (amperes x installation life (hr
ampere-hour rating per anode

The ampere-hour rating varies with different conditions but 0.45 kg (1 lb) of magnesium can be rated at about 500 ampere-hours. Thus, a 3.6-kg (8-lb) magnesium anode would be expected to deliver about 4,000 ampere-hours.

Number of 3.6-kg (8 Ib) anodes required =

$$0.009 \text{ amperes} \times \frac{365 \text{ days}}{\text{year}} \times \frac{24 \text{ hrs}}{\text{day}} \times 10 \text{ yrs}$$

400 ampere-hr per 3.63-kg (8-lb) anode

In this case, a single 3.6-kg (8-lb) magnesium anode would be used with an indicated useful life of 50 years.

Problem 2: Determine the sacrificial anode requirement to protect four bare steel transmission tower footings in 3000 ohm-centimeter soil. Given exposed area of each footing as 9.3 m^2 (100 ft^2).

Required Data

A. Soil resistivity

B. Current demand.

C. Number of anodes required.

Solution

A. Total area to be protected 37.2 m^2 (400 ft^2).

B. Soil survey shows 3000-ohm-centimeter soil.

C. Assume 11-mA/m^2 (1-mA/ft^2) current density requirement.

D. Protective current required = area to be protected x current density required

= 37.2 m^2 x 11 mA/m^2 = 0.4 ampere =

400 ft^2 x 1 mA/ft^2 = 0.4 ampere

E. From the previous problem, 0.45 kg (1 lb) of magnesium will give about 500 ampere-hours or a 7.7-kg (17 lb) anode will yield about 8500 ampere-hours. Desired life of the anode installation is 10 years.

Number of 77. kg (17 Ib) anodes required =

$$\frac{0.4 \text{ amperes} \times \frac{365 \text{ days}}{\text{year}} \times \frac{24 \text{ hrs}}{\text{day}} \times 10 \text{ yrs}}{8500 \text{ ampere} - \text{hrperanode}} = 4.1$$

However, in 3000-ohm-centimeter soil, a 7.7.-kg (17- lb) anode will only deliver about 0.028 A (fig. 2); thus,

$$\frac{0.4 \text{ amperes}}{0.028 \text{ amperes / anode}} = 14.3$$

Therefore, 15 anodes would be required to completely protect the structure. Installation life, however, would be raised to over 30 years, determined as follows:

$$\frac{\text{8,500 ampere-hr per 7.7-kg (17-lb) anode}}{\text{0.028 amperes x 365 days/year x 24 hr/day}} = 34.6$$

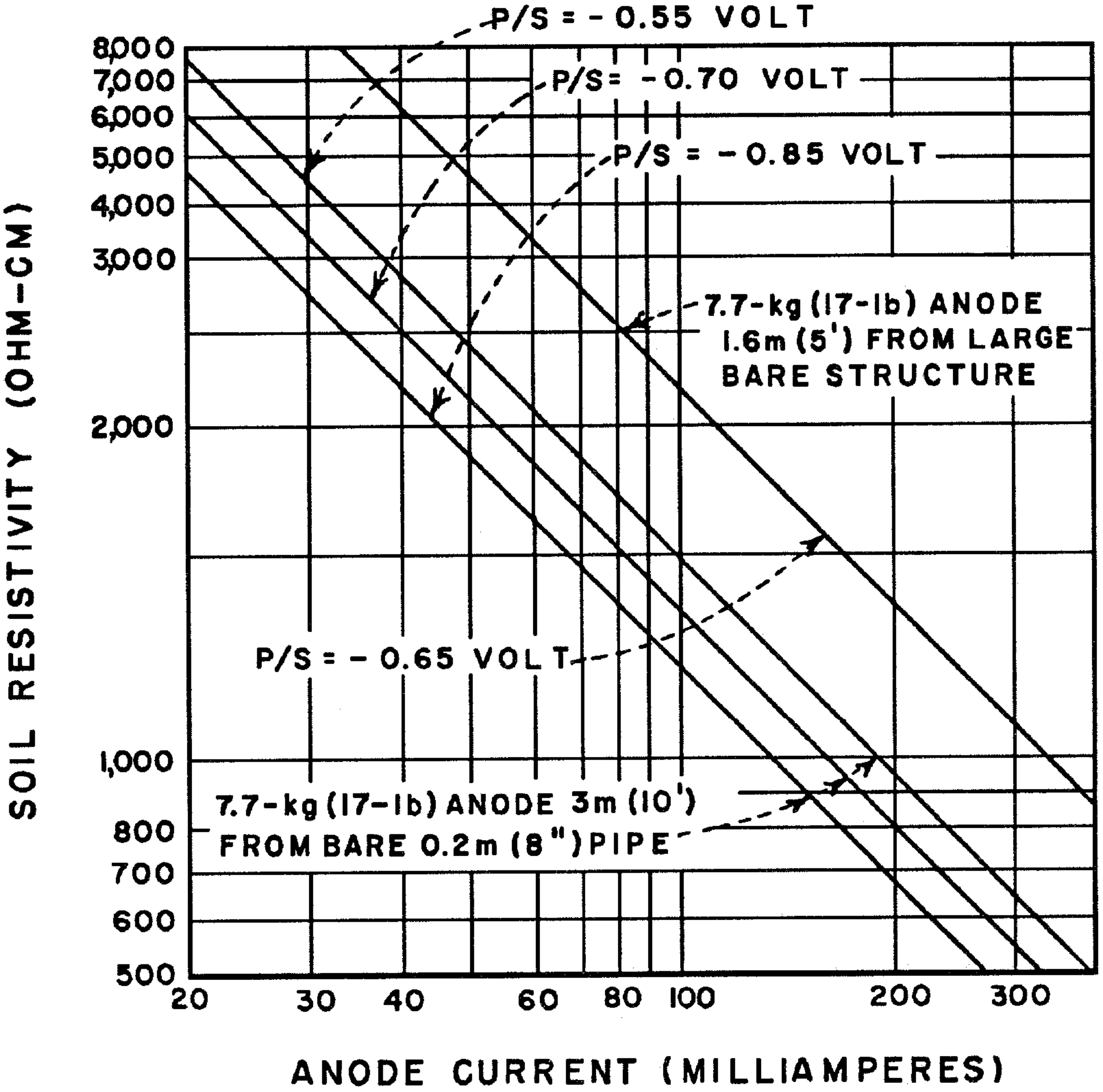

Figure 2. - Typical performance curve for magnesium anodes*

* Office of Chief of Civil Engineers, "Corrosion Prevention", Part M Maintenance and Operation of Public Works and Public Utilities, December 7, 1956.

This problem shows that sacrificial anodes should not, in general, be used in soils or water whose resistivity exceeds about 3000 ohm-centimeters as the number of anodes required to supply sufficient current for protection may be quite large and the cost of installing the system may be excessive.

If the computations call for a major installation of anodes (more than five), the problem should be referred to the Operation and Maintenance Engineering Branch, Denver Office, D-5850, for coordination with the Division of Design for evaluation. Any request for evaluation of such problems sent to the Denver Office should be accompanied by a completed copy of the pertinent *Design Data Questionnaire* found at the end of this manual. Soil or water samples sent to the Denver Office (to be tested for corrosivity to metals) should also be accompanied by a completed questionnaire.

6.5 Anode spacing.- After determining the number of anodes required in an installation, the success or failure of the system is dependent primarily upon the proper location and installation of the galvanic anodes. Locating galvanic anodes along a comparatively short bare pipe line in homogenous soil is quite simple as the required number of anodes can be equally spaced along the pipeline and connected to the line with insulated wires. The same thing is true of a long-coated pipeline under identical conditions. However, the problem is not usually that simple as the proper spacing along a continuous structure depends upon the varying physical condition of the structure surface and the surrounding soil. For example, an evenly-coated pipeline located in soil that changes form mildly corrosive (5,000 to 10,000 ohm-centimeters) to very corrosive (1,000 ohm-centimeters or less), the spacing of the anodes along the line would vary. Closer spacing or anodes along the pipeline would be required for the part of the pipe in the very corrosive soil to afford the same protection being received by the pipeline section in the mildly corrosive soil with greater distances between the anodes. The same closer spacing of anodes is required if the soil conditions are found to be constant, but it is known that the condition of the protective coating varies. A closer grouping of the anodes is required where the protective coating is inferior. In the case of a bare pipe of considerable length, it is usually not economical by protect the entire pipeline. However, a bare pipeline located in the above-mentioned soil condition can usually be protected economically by protecting with sacrificial anodes the pipe sections in the very corrosive soils. This type of protection is referred to as “hot spot” protection and is economically justifiable in that the useful life of the entire pipeline has been extended by the cathodic protection of the severely corroding areas. Sacrificial anodes should be placed around the structure symmetrically to provide good current distribution and to increase anode efficiency. Some structures, however, are very irregular and care must be taken to distribute the anodes to provide adequate protection to as much of the metal work as possible. Installation of the anodes should be made at a distance of 3.1 m (10 to 30 ft) from the structure.

6.6 Anode installation.- Anodes should be buried a minimum of 0.6 m (2 ft) into a low-resistivity material. This may necessitate deep holes to reach moist soil. Clays are common, low-resistivity materials. In order to assure minimum electrical resistance between the anode and ground, a chemical backfill is used. Anodes are sometimes supplied prepacked, with the chemical backfill in a cloth bag around the magnesium. If prepacked anodes, which are preferred, are used, no additional chemical backfill is required. If bare anodes are used, chemical backfill should be tamped around the bare anodes as shown in figure 3. The anode and backfill shall be placed in a water-filled hole and tamped. The anode leads should be buried a minimum of 0.5 m (18 in) and the free end should be attached to the structure by thermosetting resin, welding, or brazing, if resin is used, care must be taken to ensure a metal-to-metal contact. This connection should be protected by a suitable protective coating. Another lead should be connected to the structure in a similar manner and the other end brought to the surface to terminate in a test structure as shown in figure 4. This lead should have at least 0.3 m (1 ft) of slack to facilitate testing This lead may be used by a corrosion engineer to determine (by a pipe-to-soil potential test) whether the cathodic protection system is working properly and whether the anodes have been consumed. The anode-to-structure lead should be constructed of No. 10 or 8 AWG type TW copper wire. Splice connections should be made using a split, bolt-type electrical connector of the proper size. The connection should be wrapped with three layer of plastic electrician's tape, followed by three layers of self-vulcanizing, rubber insulating tape and the joint encased in a suitable electrical waterproofing compound. In low resistivity soils, a resistor is often required in the anode lead to reduce the current supplied to the structure to the amount necessary to maintain the proper protection.

7. IMPRESSED CURRENT (RECTIFIER) SYSTEMS

7.1. DESCRIPTION.- The corrosion situation depicted in figures 1A and 1B may also be solved by cathodic protection using an impressed current or rectifier system. Such a

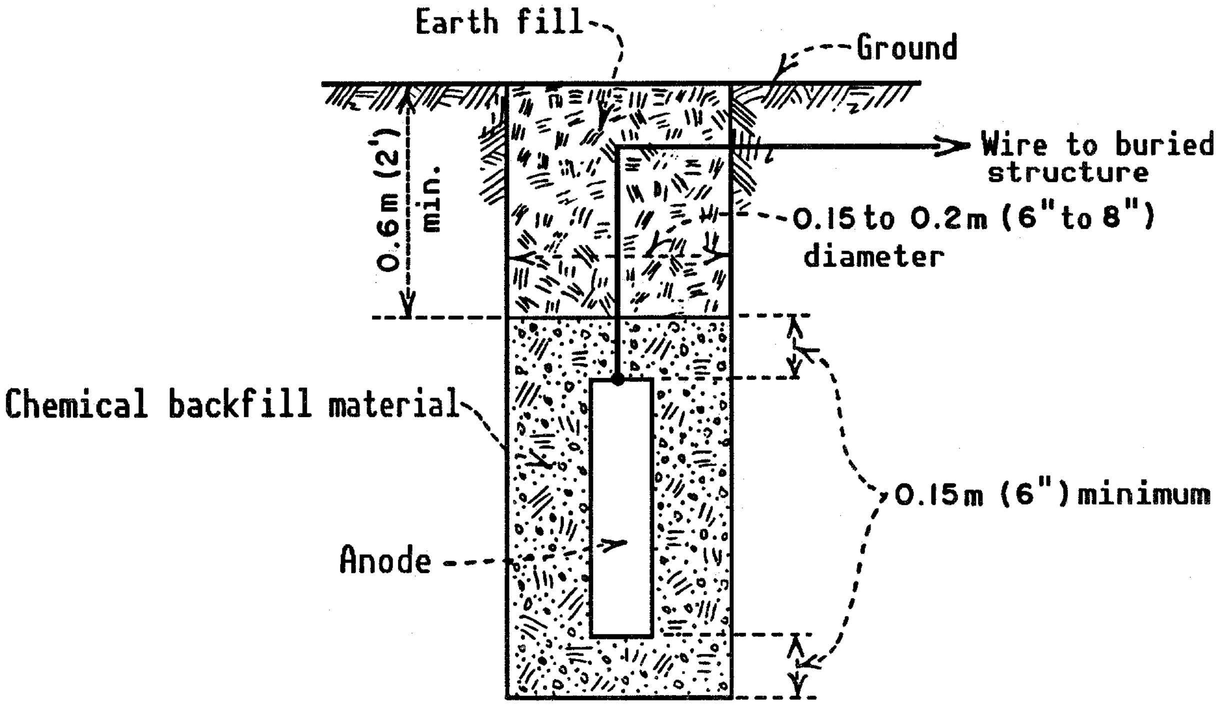

Figure 3. - Installation of galvanic anode.

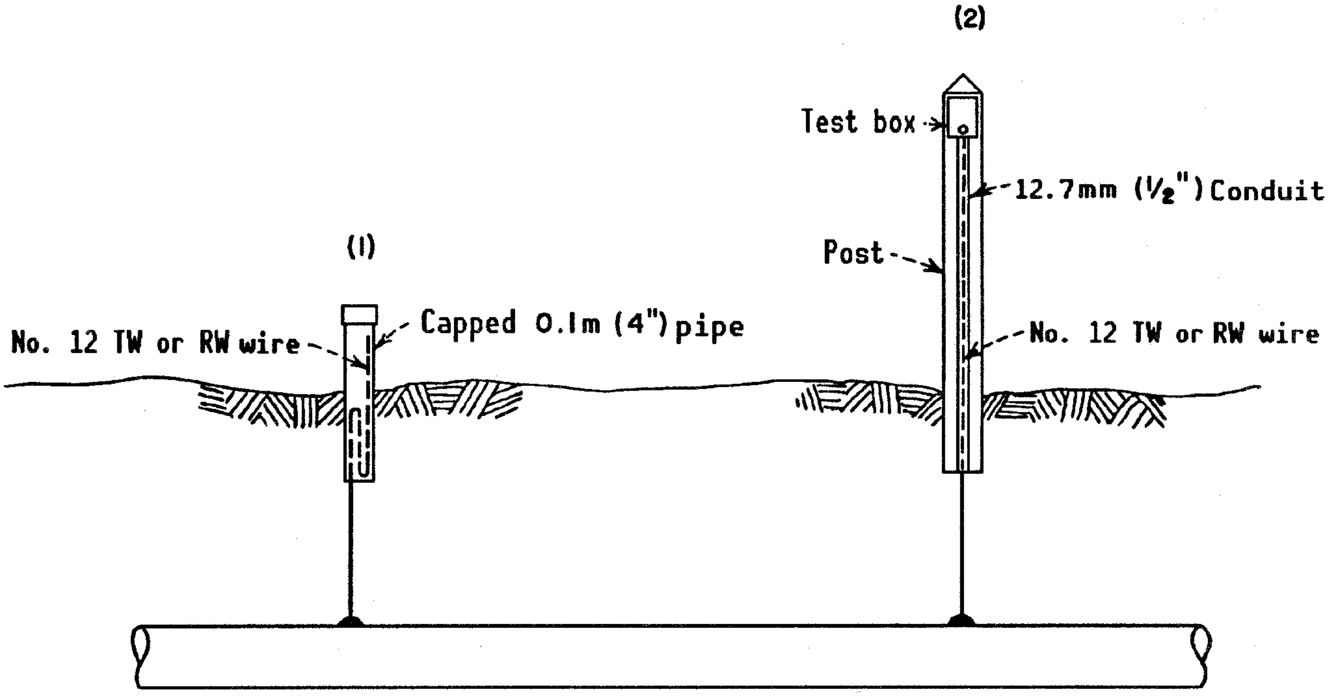

Figure 4. - Two types of test lead installations.

system is physically comparable to the sacrificial anode system in that an anode is installed in the electrolyte (soil or water) and is metallically connected to the corroding structure which is made the cathode. However, rather than rely for protection on the current which results from the anode-cathode couple, an artificial source of current is introduced into the circuit as shown in figure 5. This has several consequences. First, the galvanic potential of the anode is no longer relevant, and almost any electrode material may be used. Scrap iron, abandoned structures, driven steel anodes, etc., among sacrificial materials will suffice; or nonsacrificial materials, such as high silicon iron, graphite, or platinum, may be selected as anodes. Second, a more powerful and flexible system can be designed because the artificial current source makes available higher voltages and currents which can be manipulated to advantage. For instance, anodes can be located considerable distances from a pipeline and sufficient current supplied to protect the lines for as much as an 80.5-km (50-mi) length. Also, high enough voltages can be obtained to supply necessary currents for protection in high-resistance soils where sacrificial anodes are ineffective. Third, the power potential in a rectifier system carries with it the danger that at excessive current densities, coatings on the structure may be damaged or destroyed or that accidental reversal of the polarity of the impressed current source may cause highly-accelerated corrosion of the structure instead of protecting it.

7.2. General installations procedure.- Impressed current systems are appropriate for protection of larger structures and are more effective in handling the more complicated corrosion problems than are sacrificial anodes. The correct installation of such systems ordinarily requires a preliminary field survey of the structure and surrounding terrain to obtain soil resistivities and other information and data. A temporary anode ground bed may be installed and a temporary source of direct current such as a welding machine used to supply current to determine current and other system requirements necessary to assure correct distribution. After the permanent system has been designed and installed, follow up measurements should be made to assure that adequate protection has been supplied where required and that no excessive voltages occur. The design and installation of an impressed current system calls for specialized knowledge and considerable experience in this field. The operation and maintenance of a rectifier system is more complex than for a sacrificial anode system, and field personnel will usually require instruction to obtain the best results.

8. Isolation and sectionalization

8.1. Purposes.- Two purposes can be served by the use of insulated joints in cathodic protection, that of isolation and that of sectionalization. Isolation is the application of insulated joints to prevent a galvanic cell from being formed with a portion of the structure being the sacrificial metal or to insulate a structure being protected from others that would add an excessive drain on a cathodic protection system. Sectionalization is the dividing of a group of structures into smaller units for cathodic protection because of different current requirements or merely to simplify a system. Although both purposes are mentioned here, the most common application in powerplant work would be that of isolation.

8.2. Examples using insulating joints.- A typical example of an isolation application is shown in figure 6. Figures 6A and 6B show an installation subject to severe corrosion, depending, of course, on the soil characteristics. In figure 6A, the direct connecting of the dissimilar metals provides an ideal path for the flow of current from the iron to the copper through the ground (electrolyte). The iron in this case is anodic, or the sacrificial metal. The same conditions are provided in figure 6B as the copper ground mat is connected directly to the steel pipe, and both are in a common electrolyte, the ground. The flow of current in this case is from the steel pipe to the copper ground mat. The steel pipe is anodic, or the sacrificial metal. The condition depicted in figures 6C and 6D is identical to that shown in figures 6A and 6B With the exception that the wire connection in figure 6D has been isolated from the copper ground mat by the installation of an insulated joint. Under this condition, the only corrosion action is local, caused by inhomogeneity in the metal or contacting solution. Therefore, in figure 6C, the condition will still permit the flow

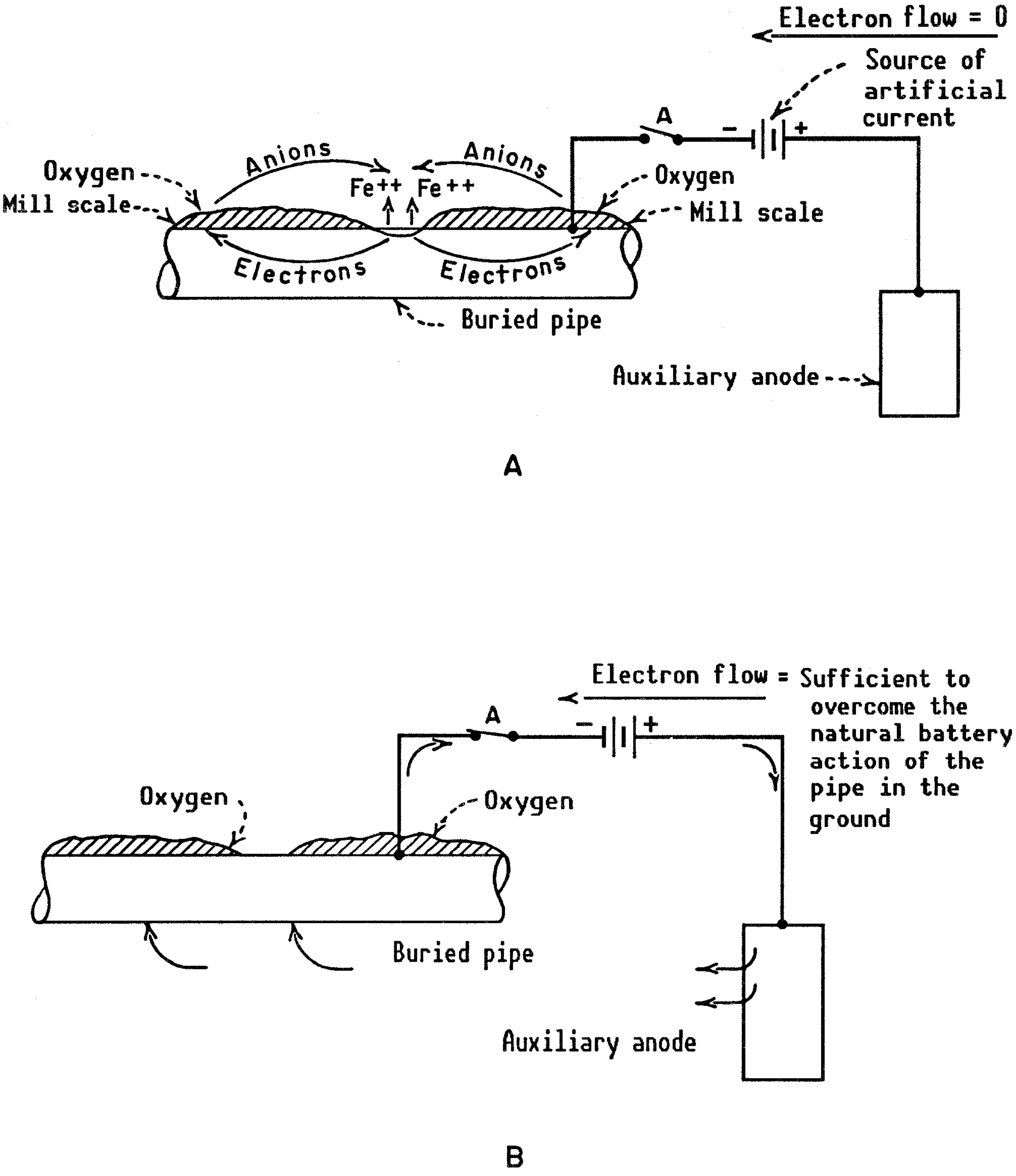

Figure 5.- Protection of buried pipe by impressed current rectifier method.

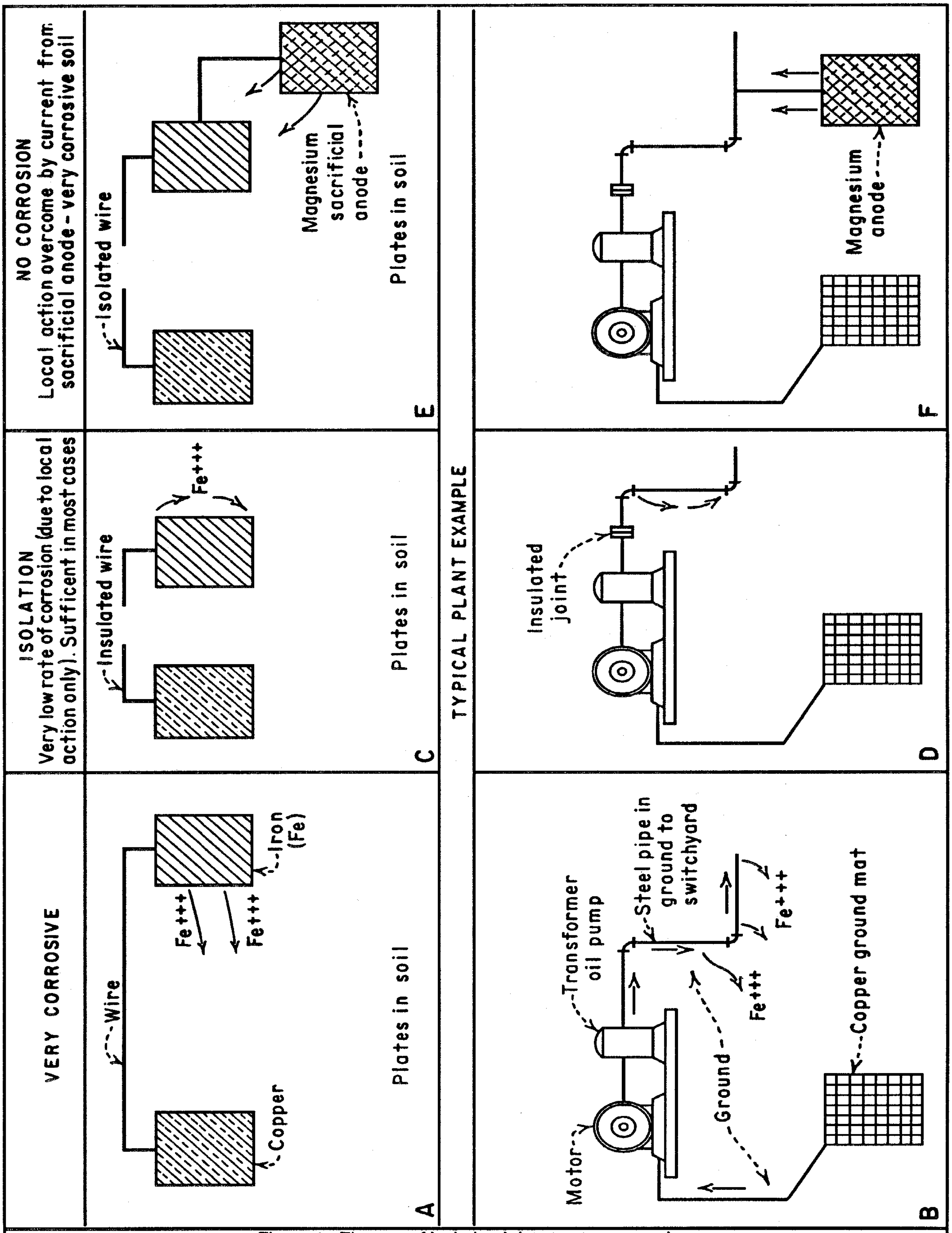

Figure 6.- The use of isolating joints to stop corrosion

of current from an anodic section of the steel plate to a cathodic section of the steel plate to a cathodic section of the same plate. The same is true in figure 6D. One section of the pipe can be anodic with respect to another section of the pipe and, therefore, deteriorate at that point. The examples in figures 6E and 6F are identical to the examples in figures 6C and 6D except that a sacrificial anode of magnesium has been added. Since the magnesium anode is the least noble of the three metals in the ground (electrolyte), it becomes the sacrificial metal and deteriorates from the corrosive action in lieu of the iron plate and steel pipe.

9. Evaluation and solution of a field corrosion problem

9.1. Initial examination.- When the existence of significant corrosion of a structure is revealed, a method of controlling it must be selected, and the procedure outlined in paragraphs under this heading should be lollowed by O&M personnel. A preliminary investigation should first be made to ascertain the extent and severity of the damage. Enough of the corroding surface should be exposed to permit adequate examination at various locations. Special note should be taken of the type and condition of any protective coatings on the surface. The character of the corrosion is of considerable importance; that is, whether corrosion is of the pitting type which may rapidly perforate a pipeline or general surface corrosion which may consume considerable metal before failure or structural weakening would occur. With the results of the inspection in hand, consideration can be given to application of protective coatings, cathodic protection, or other remedies as means of controlling the corrosion.

9.2. Sources of information.- Protective coatings are discussed in this bulletin especially in conjunction with cathodic protection, but the Paint Manual provides a more comprehensive treatment of coatings in general. The two types of cathodic protection installations, the sacrificial anode and impressed current or rectifier systems, must be investigated to enable selection of the best method which depends on the complexity of the structure and on whether the corrosion is galvanic or stray current. Design of systems for long, large, or complex structures and for prevention of stray current corrosion requires specialized knowledge, experience, and techniques. Likewise, economic considerations enter the picture with the more costly installations. Thus, specialist advice or a field survey may be necessary.

9.3. Protection methods for various situations. - The summary below lists a number of common field exposures where corrosion problems may be encountered. One or more protection methods may be appropriate when further corrosion must be prevented. These methods are numbered below and listed as possible solutions.

Protection methods

1. Application of protective coating.

2. Install cathodic protection by sacrificial anodes.

3. install cathodic protection by impressed currents.

Corroding item	Possible solutions*
Metal surfaces exposed to the atmosphere.	1
Metal surfaces intermittently exposed to water and atmosphere.	1 1 and 2 or 3.
Gates, piping, or other metal work in water, including interior of water tanks.	1 1 and 2 or 3.
Interior of water pipes.	1
Heat exchangers.	1 2 1 and 2.
Exterior of pipe tanks, or conduit buried in earth,	1 (touch up defects in good existing coating).
Guy rods and anchors in earth.	2

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*The above listing is not an attempt to list the possible solutions in order of their preference, and the normal design practice is to provide the initial corrosion protection by selection of material and through painting. However, if damaging corrosive conditions still exist, additional corrosion prevention can usually be obtained by the addition of a sacrificial anode or an impressed current system.

9.4. Action to be taken.- If the results of the preliminary inspection, taken in the light of the discussion which follows, indicate that a sacrificial anode protection system consisting of less than six anodes will afford the necessary protection, O&M personnel may wish to proceed with the installation. If, on the other hand, it appears that a larger sacrificial anode system, an impressed current system, or other measures may be required, the problem should be presented to the Operation and Maintenance Engineering Branch, Denver Office, Attention D-5850, for coordination with the Division of Design. In so doing, it is important to supply the information listed in the appropriate questionnaire (appendix) so that the initial letter will furnish the data required for analysis of the problem.

10. Appendix

Design Data Questionnaire for Corrosivity Determination of Soils or for Cathodic Protection Design

Statement of problem (use another sheet of paper if additional space is required): ______

______

______

______

______

Describe soil environment as applicable to the structure:

(a) Moisture content of sample when taken

wet	moist	dry
☐	☐	☐

(b) General statement as to anticipated seasonal change in moisture content ______

______

(c) Depth at which soil sample taken in meters

______

(d) Estimated depth range of water table in meters ______

(e) Sequence and thickness of geologic beds through which structure passes (sand, silt, shale, etc.) ______

(f) Soil drainage

excellent	fair	poor
☐	☐	☐

(g) Topological structure such as hill, gully, swamp (attach copies of construction profiles, if available) ______

(h) Soil resistivity in ohm-centimeters ______

(i) Previous experience or data as to corrosivity of the water and soil concerned ______

Describe the corroding structure as applicable:

(a) Estimated area of exposed metal work in square meters ______

(b) Describe metals involved (steel, brass)

______

(c) Describe structure (common name, dimensions) ______

______

(d) Portion of metal work covered by protective coating and type and condition of coating

______

(e) Describe deposits present on the corroding structure (color, texture, hardness, etc.)

______

(f) Failure records - Has the structure had any history of corrosion failure? Explain: ______

______

______

Describe corrosive conditions in the area:

(a) Other structures in electrical contact with the structure ______

(b) Direct-current sources present in the area (streetcar tracks, electric fences, foreign cathodic protection installations) ______

______

If cathodic protection seems to be indicated, furnish information on the following, if applicable:

(a) Voltage of alternating-current and direct-current power sources which are available at the site

(b) Power cost considerations (cost, additional costs to furnish year- around power, etc.)

(c) Available right-of-way at the site

(d) Location drawing of buried or submerged metal work in the immediate area of the structure

(e) Drawing of the structure details and structure location

Answers added to this sheet may be estimated except for the soil resistivity which should be measured. If the equipment for measurement is not available, samples should be forwarded to the Facilities Engineering Branch, Denver Office, Attn D-5210, for coordination with the Denver Office laboratories. A copy of this sheet with answers to applicable questions should be submitted with a soil sample for either a corrosivity determination or cathodic protection design request.

Design Data Questionnaire for Corrosivity Determination of Waters or for Cathodic Protection Design

Statement of problem: ____________________

____

____

____

Describe the environment as applicable to the structure:

(a) Site of the sample (taken from the pipeline, reservoir, river, etc.) ____________________

(b) Water velocity at the structure ____________

(c) Site of the corrosion (downstream from pipeline valve, unpainted portion of radial gate, interior of water tank, etc.) ____________

(d) Water treatment (chlorination) ____________

(e) Previous experience as to corrosivity of the water ____________________

(f) Scale-forming water Yes ☐ No ☐

(g) Does the structure have a wet and dry zone (i.e., waterline) Yes ☐ No ☐

(h) Is the structure in use for the entire year Yes ☐ No ☐

(i) During the off-season, what conditions are present (structure drained, structure not in contact with water except during power generation, etc.) ____________________

____

(j) Is condensation on the metal surface present during the off periods ____________________

Describe the corroding structure as applicable:

(a) Estimated area of exposed metal work in square meters ____________________

(b) Describe metal involved (steel, brass, etc.)

____

(c) Describe the structure (common name, dimensions, etc.) ____________________

(d) Portion of the metal work covered by protective coating and condition of the coating ____________________

(e) Describe the deposits present on the corroding structure (color, hard, dense, etc.) ____________________

(f) Failure record - Has the structure had any history of corrosion failure? Explain: ____________

____

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