Chapter 4.0 — Corrosion Control Demonstration Testing

This chapter is intended primarily for large systems and those small and medium-size systems required by the State to conduct corrosion control studies. Those small and medium-size systems that are not required by the State to conduct corrosion control studies should proceed to Chapter 5 after making their treatment recommendation.

The Rule requires corrosion control studies to be performed by large PWSs and those small and medium-size PWSs required by the State after exceeding the lead or copper AL. Further, the Rule defines certain conditions which must be met by these studies, but it does not specify the details of those studies. This chapter provides guidance for and discusses the following aspects of corrosion control studies: (1) the components necessary to accomplish the study; (2) the testing protocols to be used; (3) the procedures for evaluating data; and (4) the basis for identifying "optimal" corrosion control treatment.

The full scope of a corrosion study will vary system-by-system, and the methods and procedures used to reach a recommendation will necessarily reflect this level of site-specificity. Thus, States should consider the following criteria in the review of corrosion control studies and subsequent recommendations:

- Reasonableness of the study design and findings;
- Technical integrity of the data handling and analysis procedures; and
- Best professional judgement of the State regarding the decision-making criteria used by the PWS in determining the recommended optimal corrosion control treatment.

In the course of this chapter, examples of corrosion control studies will be presented to illustrate the approach and rationale used in the design, implementation, and interpretation of findings for corrosion control studies. A summary of those studies available in the literature is provided in Appendix B for additional resource material available to States, PWSs, and engineers involved in performing corrosion control studies.

4.1 Corrosion Study Organization

The suggested framework for a corrosion study as shown in Table 4-1 presents a logical sequence of steps, organized to satisfy the requirements and recommendations outlined. For completing steps 1-3, a logic diagram was presented in Section 3.3.1 (Figure 3-6) and these steps refer to the desk-top evaluation discussed at length in Chapter 3. The result of the desk-top evaluation for those systems performing corrosion control studies is the selection of alternative treatments to be tested. Small and medium-size PWSs which are

Table 4-1. Organization of the Major Components in Corrosion Control Studies

Step 1	**DOCUMENT HISTORICAL EVIDENCE** • Review PWS Water Quality and Distribution System Characteristics. • Review PWS Evidence of Corrosion Activity. • Identify Prior Corrosion Control Experiences and Studies Performed by PWS. • Identify Prior Corrosion Control Experiences and Studies Performed by Other PWSs with Similar Characteristics.
Step 2	**EVALUATE SOURCE WATER CONTRIBUTION** • Monitor Pb/Cu-POE. • Determine Pb/Cu Contributed Due to Corrosion. • Determine Source Water Treatment Needs.
Step 3	**IDENTIFY CONSTRAINTS** • Compatibility with Water Quality Characteristics (See Figure 3-7). • Interferences with Other Water Treatment Processes. • Compatibility of Multiple Sources of Supply. • Compatibility for Consecutive PWSs. • Reliability Features for Particular Treatment Approach, Including (1) Process Control; (2) Operational Redundancy Requirements; and (3) Chemical Supply Integrity and Availability. • Adverse Impacts on the Community: Commercial Users, Wastewater Operations, Health-Care Facilities.
Step 4	**IDENTIFY CORROSION CONTROL TREATMENT PRIORITIES** • Targeted Materials for Corrosion Control Protection. • Competing Water Quality/Treatment Objectives. • Secondary Benefits (i.e., Lowering Metal Content in POTW Sludges).
Step 5	**ELIMINATE UNSUITABLE APPROACHES BASED ON FINDINGS FROM STEPS 1-4.**
Step 6	**EVALUATE VIABLE ALTERNATIVE TREATMENT APPROACHES:** • Apply Findings from Analogous System Experiences. • Evaluate Alkalinity and pH Adjustment: Reductions in Theoretical Lead and Copper Solubility. • Evaluate Inhibitor Addition: Reductions in Theoretical Lead and Copper Solubility. • Evaluate Calcium Hardness Adjustment: Optimize Calcium Carbonate Precipitation Potential (CCPP).
Step 7	**DECISION:** **For any PWSs NOT Required to Perform Testing to Evaluate Alternative Treatments:** • Formulate Decision Criteria. • Select Analog Treatment Alternatives. • Go to Step 9. **For any PWS Required to Perform Demonstration Testing to Evaluate Alternative Treatments:** • Formulate Minimum Feasibility Criteria for Alternative Treatments. • Select the Alternative Treatments to be Included in the Testing Program. • Establish Decision Criteria to Select Optimal Corrosion Control Treatment.
Step 8	**PERFORM CORROSION CONTROL DEMONSTRATION TESTING.** • Design Testing Apparatus. • Develop Testing Protocols and Procedures. • Perform Testing Program and Collect Data. • Analyze Data Generating Corrosion Control Performance Results. • Rank Performance Results by Priority of Corrosion Control Program Goals.
Step 9	**PRELIMINARY COST ESTIMATES AND FACILITY MODIFICATIONS.** • Prepare Preliminary Facility Design. • Prepare Preliminary Cost Estimate.
Step 10	**DECISION:** Based on the Decision Criteria Established at the Outset, Formulate RECOMMENDED CORROSION CONTROL TREATMENT AND SUBMIT TO THE STATE.

not required to perform demonstration testing would select the recommended treatment based on a desk-top evaluation as shown in Figure 3-6.

A corrosion control demonstration testing program is to be formulated and implemented once alternative treatments have been selected. This includes such steps as:

- developing testing protocols, procedures and frequency for data collection and evaluation;
- analyzing the resultant data to generate performance measurements; and
- determining the performance ranking of the alternative treatment approaches on the basis of corrosion control, secondary treatment impacts, and process operations and control.

Preliminary design and cost estimates are to be prepared for the alternative treatments selected from the desk-top evaluation. While cost is not directly a factor in assigning optimal treatment, it may be decisive when alternative treatments have comparable performance. Additionally, preliminary design will be required for the State review process.

The final recommendation of optimal corrosion control treatment may be based on the results of a decision criteria matrix and the ranking of the alternative treatments. The selection process should be documented and presented to the State.

4.2 Overview of Demonstration Testing

The evaluation of corrosion control treatment through demonstration testing may be accomplished through a variety of approaches and mechanisms. While flexibility exists for the actual design of a testing program, all such endeavors should clearly define and document the following elements of the study:

- *Testing protocols*, including sampling program design which incorporates sampling frequency, locations, volume, parameters, and analytical methods; and, methods of material exposure such as flow-through or static environments under predetermined operating conditions.
- *Materials used to simulate the targeted piping environment* whether lead, copper, iron, lead soldered joints, brass, etc;
- *Measures of corrosion activity*, such as weight-loss, metal leaching, corrosion rates, and surface condition inspections;
- *Data handling and analysis techniques*, including statistical testing and guidelines for interpreting the findings;
- *Testing of secondary impacts* to determine the potential effects of alternative treatments on existing PWS operations and compliance with other drinking water standards; and
- *Quality assurance/quality control program* elements for each element of the testing program.

The premise underlying demonstration testing is that alternative treatment approaches are to be evaluated in terms of their relative reductions (or increases) in corrosion activity for specific materials of concern. Quite often, testing efforts are used to predict the behavior of various treatment components. In this respect, corrosion studies differ. EPA does not

consider the purpose of these studies to either: (1) predict the levels of lead or copper in first-draw tap samples from targeted consumers' homes; or (2) predict the actual reductions in corrosion activity within the distribution or home plumbing systems achievable through corrosion control treatment. Instead, the purpose of corrosion control testing is to **demonstrate** the relative performance of alternative treatment approaches and identify optimal treatment.

In order to determine the relative performance of alternative treatment approaches, a control condition must be clearly defined throughout the testing program. Some PWSs may find this problematic due to changing source and treated water conditions. Systems anticipating new sources of supply or new treatment process for existing sources will have to address the issue of which treated water condition to use for its experimental control. For example, a groundwater system required to perform demonstration testing currently provides water treated only with chlorination prior to its delivery. As a result of the SWTR, the well-water will be considered as under the influence of a surface water and coagulation and filtration treatment will be required. The anticipated timeframe for completing construction of the new filtration plant is mid-1995. Meanwhile, the demonstration testing program must be concluded by July 1994, prior to the new treated water being available. In this instance, the PWS should consider the water quality modifications anticipated as a result of coagulation and filtration (i.e., pH and alkalinity reductions as a result of alum addition) to determine whether the existing supply would be adequately representative of future conditions. For systems introducing new sources of supply to the distribution system, the control condition should be the existing supply and the recommended treatment should include provisions for compatible treatment of the new supply sources. The water delivered under normal operating conditions should serve as the control supply source for those PWSs that experience fluctuations in water quality either seasonally or due to the alternate use of wells.

Each PWS will be responsible for the design and execution of a testing program which meets its specific overall goals and objectives.

4.3 Testing Protocols

Testing protocols should be clearly delineated prior to initiating the demonstration testing program. Some time will need to be allocated for trouble-shooting the methods and procedures to be used. Quite often, a trial-and-error process is required to fully "de-bug" the protocols and establish a consistent monitoring, operating, and maintenance plan for the testing program. Figure 4-1 is included to assist in logically developing and successfully completing a corrosion control study. As can be seen from the diagram, several different pathways are available enroute to selecting optimum corrosion control treatment. Some studies may be designed to select more than one component, i.e., it would not be unusual for both coupons and pipe inserts to be evaluated within a single pipe loop, for example. Section numbers have been added to the diagram to assist the user in selecting which

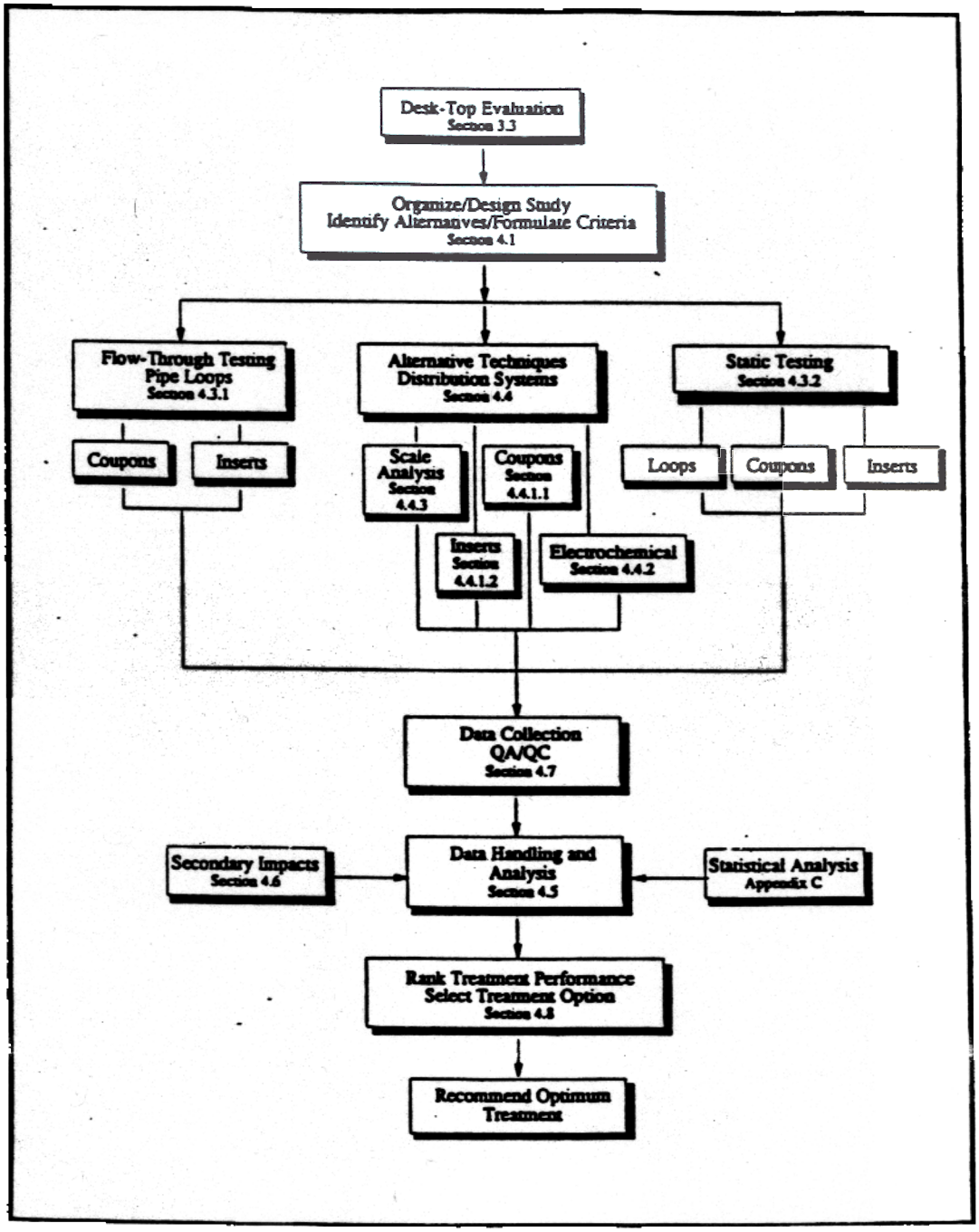

Figure 4-1. Logic Diagram for Corrosion Control Demonstration Testing

specific sections of the Guidance Manual should be utilized. It is not necessary, for instance, to read through Section 4.4.2 if electrochemical techniques are not used.

4.3.1 Flow-Through Testing Protocols.

The use of flow-through testing methods to evaluate corrosion control performance is preferred since it more accurately simulates the home plumbing which is the major source of lead and copper. The following suggestions on flow-through testing protocols and methods should be considered by PWSs in the design and execution of their demonstration study.

4.3.1.1 General. Flow-through testing refers to continuous or cycled flowing conditions through a testing apparatus where the solution is not recirculated. Typically, flow-through testing is used to describe pipe rig operations where pipe loops or coupon/insert apparatus are attached to a central manifold which distributes the test water to one or more corrosion testing units, as shown in Figure 4-2. Detailed descriptions of standardized pipe rig construction and implementation may be found in either the AWWARF *Lead Control Strategies Manual* (1990a) or the Army Corps of Engineers Pipe Loop (CERL, 1989), including complete material and fabrication specifications.

The following recommendations regarding the design and implementation of a flow-through testing program should be considered when conducting such studies:

- Duration of testing should be between 9 and 15 months to ensure that steady-state conditions have been achieved and to capture seasonal effects; the longer the testing period, the more confidence a PWS may have in distinguishing treatment performance.
- A standardized sampling program should be established before initiating the testing period to enhance the analysis of results (See Section 3.3.3).
- Alternative locations for siting the testing apparatus should be considered: (a) laboratory or water treatment plant; (b) remote within the distribution system; or (c) distribution system *in situ* apparatus. PWSs should avoid those sites where excess vibration or humidity may be encountered as these conditions can interfere with the performance of the testing apparatus.
- Evaluation of the test material surfaces may be done at the conclusion of each test run for each material in order to assess the corrosion behavior of the treatment alternative. However, this would require the destruction of the test materials, which may be undesirable if future or on-going operation of the testing equipment is anticipated.
- When first-draw samples are being collected, the samples should be drawn slowly to minimize velocities and turbulence within the test apparatus. If air is entrained during sampling, then the sampling velocity is most likely to high.
- Water quality parameters, inhibitor residuals (if appropriate), and metals (lead and copper) should be sampled at each pipe loop (first-draw samples) and the water supply's entrance to each pipe rig.

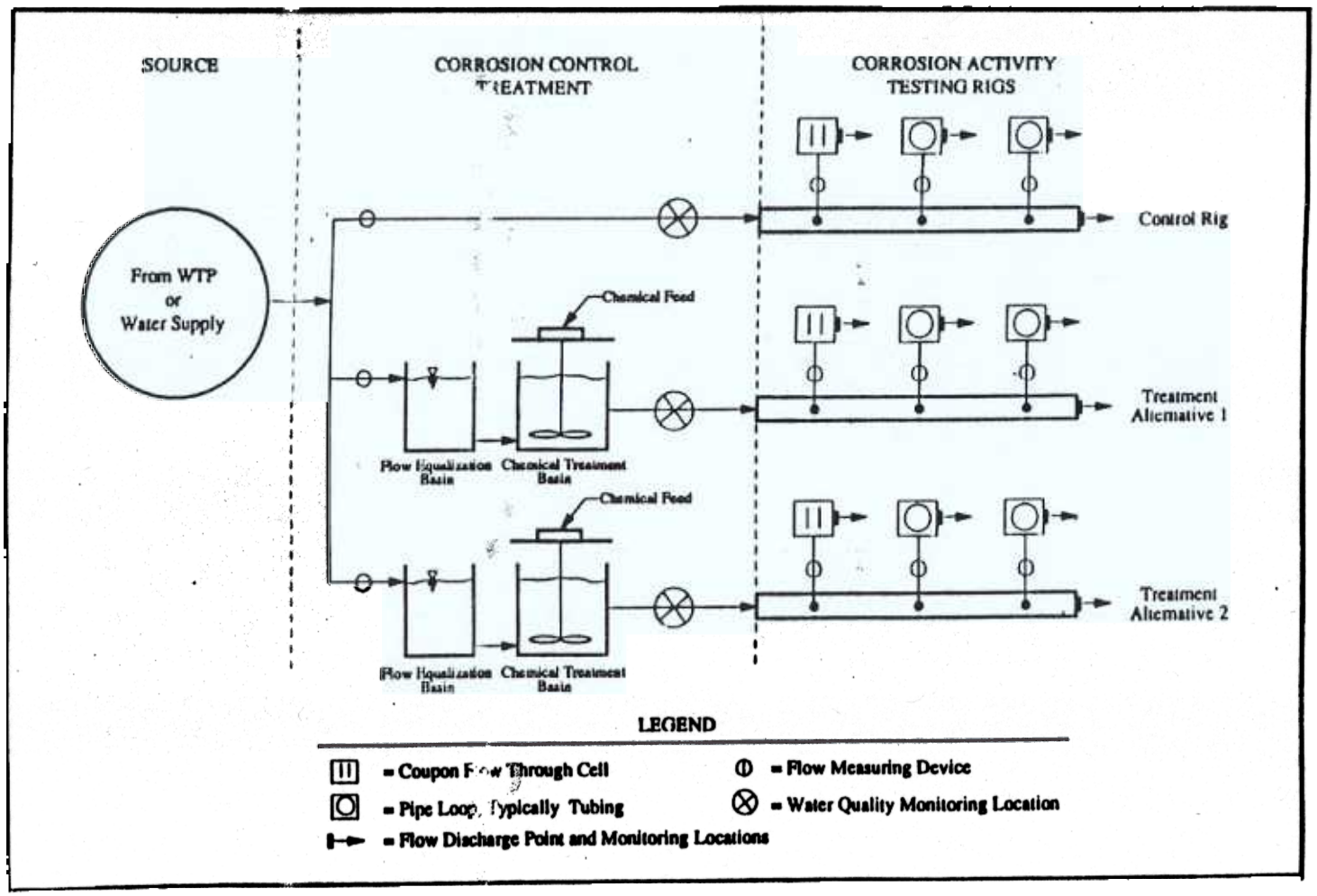

Figure 4-2. Conceptual Layout of Flow-Through Testing Schemes

- To the extent practical, the test conditions should simulate the chemical feed application points and finished water quality conditions expected during full-scale operations.

Flow-through testing methods provide the following advantages and disadvantages for determining corrosion control treatment. Several of these have been discussed by Schock (1990b):

Advantages:

- The corrosion can be measured on the pipe instead of relying solely on coupons inserted within the pipe.
- Loops can be placed at various locations within the distribution system to assist in determining differing corrosion rates as water quality changes in the system.
- Multiple loops can be set up in a single location to determine the corrosion effects of dissimilar waters.
- The method allows corrosion rates and treatment techniques to be evaluated under controlled conditions. Chemical feed rates can be refined to facilitate defining optimal corrosion control treatment.
- Using pipe loops is fairly economical.
- Pipe loop systems can include provisions for intermittent flow which should simulate "real-world" conditions more appropriately than static testing techniques.

Disadvantages:

Pipe loops need to be operated for several months before an accurate comparison between differing treatment techniques can be obtained.

- Variations in corrosion rates that occur during the testing period are not measured.
- Dynamic testing systems may require more attention than a static testing apparatus.

An important feature of this method of testing is the in-line corrosion control treatment of the water. This requires some degree of pretreatment components, such as chemical feed pumps, flow equalization basins, flowmeters, and water quality sampling stations. In some cases, the operation and control of the corrosion control treatment component of the test rig may be more complicated than operating and monitoring the pipe rig itself. Careful attention to the feasibility of creating a "continuous" supply of treated water should be addressed prior to any final testing decisions.

PWSs may be able to utilize the flow-through testing system on a long-term basis to assist in understanding the corrosion response of the distribution system. Relationships between the flow-through testing system and the metal levels found in first-draw tap samples may be developed in terms of trends in responses to treatment conditions. Calibration of the flow-through testing system to first-draw tap samples necessitates concurrent flow-through testing and first-draw sampling activity beyond the initial monitoring period. The AWWARF Pipe Loop Study (Kawczynski, 1992) [Note: Expected publication date is early 1993. Available from AWWARF, Denver, CO] presents a testing program designed to evaluate the predictive capability of pipe loop systems in simulating first-draw lead and copper levels in targeted homes. Continued

utilization of the flow-through testing systems could provide PWSs with an additional mechanism to determine the potential effects of treatment changes on the full-scale level.

4.3.1.2 Testing program elements. The design and operation of a flow-through testing program requires special consideration of several study components which are briefly discussed below to assist in directing PWSs and others performing such studies. Conducting successful testing programs is dependent on systems making the commitment to sufficiently staff the testing effort, including apparatus design, fabrication, and operation for the duration of the testing program. This resource commitment will be significant. For example, a one-year testing program could require allocation of a full-time operator responsible for fabrication, maintenance, operation, and sampling; as well as analytical support for metals and water quality parameter analyses.

4.3.1.2.1 Pipe rig operation and fabrication The required flow rate through a pipe rig depends on the number of connections it is supplying. Typically, between 0.5 and 2 gallons per minute (gpm) of flow through a single pipe loop is adequate. If a pipe rig consists of two or three loops, then at least 1.5 to 6 gpm of flow is required. Operating a rig at much higher flow rates could compromise its feasibility depending on the complexity of the pretreatment component. For example, a system feeding 20 mg/L soda ash (Na_2CO_3) for alkalinity and pH adjustment and operating a 6 gpm testing rig for 16 hours of continuous flow with 8 hours of standing time each day would require 29-gallons of stock solution (20 mg Na_2CO_3/ mL). Daily stock solution requirements much beyond 30-gallons becomes difficult to handle, especially when extremely concentrated solutions are used.

Additional attention must be given to the limitations of a slurry feed, such as lime. Analytical grade hydrated lime with a purity exceeding 98 percent is recommended for the preparation of stock solutions (the use of quick lime for testing rigs is not practical due to the large amount of impurities and the inability to properly slake the lime). To avoid plugging pump heads and tubing, solutions more concentrated than 10 mg/mL should not be used. These solutions also require continuous, rigorous mixing during their application in order to ensure a consistent suspension of the slurry solids.

Feeding a corrosion inhibitor with its typically much lower dosages and feed rates is less limiting on the design and operation of the pipe rig system. More flexibility may exist for systems testing corrosion inhibitors in terms of the number of loops, coupons, and inserts a single pipe rig can accommodate. When evaluating silicate inhibitors as a treatment alternative, consideration should be given to providing ample time and dilution for the silicates to depolymerize prior to introduction in a pipe loop system. Silicates in concentrated solutions primarily exist as polymers and break down with time to a monomeric form, which is analogous to the reversion of polyphosphates to orthophosphates. Therefore, if a silicate is injected directly into a pipe loop system, the form of silica present in the pipe loop would be different from the form of silica present in the full-scale distribution

system. A design of a pipe loop system should include some sort of holding tank to provide adequate detention time and dilution.

The pipe loops attached to the rig should be of sufficient length to permit a sample to be collected without getting water from the central pipe. Pipe loops should be sized to provide at least 15-20 percent additional sample volume to ensure that interferences from other materials in the pipe rig are avoided. Table 4-2 presents the volume of water contained in various lengths of piping by interior diameter dimension. The shaded lines correspond to the minimum length of pipe of the corresponding diameter (the last column shaded) to provide at least 15 percent additional volume in the pipe loop for a one-liter sample. Standard plumbing materials should be used for the pipe loop tubing, and all materials used for each rig should be obtained from the same lot of piping. For example, if copper piping loops are to be used in three different pipe rigs, evaluating three different treatments, then all of the copper used in each rig should be purchased at the same time from the same lot of the manufacturer. Variability in the testing results due to differences in materials can be minimized in this fashion.

For copper loops with lead soldered joints, fabrication of all of the loops should be done by the same person and at one time (do not fabricate one set of loops and then wait several weeks or months before fabricating the next set). Additionally, the solder should come from the same spool. After soldering, the piping should be flushed prior to starting the testing program to remove any loose debris.

In constructing the pipe rig, plastic materials are recommended for all parts that would be in contact with the water except the pipe loops. The use of brass materials should be avoided due to their ability to leach lead and copper into the test water, thereby cross-contaminating the samples and invalidating the test results.

During the startup of the testing program, all pipe loops and the pipe manifold should be flushed to remove any material debris attached to the interior walls of the piping. Flushing should be performed using the control water. The pipe loops should be flushed after fabrication but prior to attachment to the manifold. The complete pipe rig (manifold plus loops) may then be flushed while troubleshooting the apparatus for leaks and the performance of equipment such as flowmeters, timers, valves, and pumps.

Some PWSs may want to incorporate pre-conditioning of the pipe loops into the testing program. Pre-conditioning consists of using control water for all pipe rigs until all pipe loops achieve steady-state corrosion activity. The alternative test waters would then be introduced into the pipe loops for their respective pipe rig system. The relative performance of the control and alternative test conditions would be assessed in the same manner as those testing programs which did not pre-condition the test loops with control water. It is not known whether this step would provide PWSs with any greater accuracy in the evaluation of corrosion control performance, or whether it would reduce or increase the required testing duration.

Table 4-2. Pipe Volume by Tubing Length and Diameter

Pipe Volume Table (Volumes Listed in Liters)						
Pipe Length (Feet)	Pipe Diameter (Inches)					
	3/8	1/2	5/8	3/4	1	1-1/4
1	0.02	0.04	0.06	0.09	0.15	0.24
2	0.04	0.08	0.12	0.17	0.31	0.48
3	0.07	0.12	0.18	0.26	0.46	0.72
4	0.09	0.15	0.24	0.35	0.62	0.97
5	0.11	0.19	0.30	0.43	0.77	1.21
6	0.13	0.23	0.36	0.52	0.93	1.45
7	0.15	0.27	0.42	0.61	1.08	1.69
8	0.17	0.31	0.48	0.69	1.24	1.93
9	0.20	0.35	0.54	0.78	1.39	2.17
10	0.22	0.39	0.60	0.87	1.54	2.41
11	0.24	0.42	0.66	0.96	1.70	2.65
12	0.26	0.46	0.72	1.04	1.85	2.90
13	0.28	0.50	0.78	1.13	2.01	3.14
14	0.30	0.54	0.84	1.22	2.16	3.38
15	0.33	0.58	0.90	1.30	2.32	3.62
16	0.35	0.62	0.97	1.39	2.47	3.86
17	0.37	0.66	1.03	1.48	2.63	4.10
18	0.39	0.69	1.09	1.56	2.78	4.34
19	0.41	0.73	1.15	1.65	2.93	4.58
20	0.43	0.77	1.21	1.74	3.09	4.83
25	0.54	0.97	1.51	2.17	3.86	6.03
30	0.65	1.16	1.81	2.61	4.63	7.24
35	0.76	1.35	2.11	3.04	5.40	8.44
40	0.87	1.54	2.41	3.47	6.18	9.65
45	0.98	1.74	2.71	3.91	6.95	10.86
50	1.09	1.93	3.02	4.34	7.72	12.06
55	1.19	2.12	3.32	4.78	8.49	13.27
60	1.30	2.32	3.62	5.21	9.27	14.48

Notes: 1. Volumes can be added together for pipe lengths not listed.
2. Liters can be converted to gallons by dividing by 3.785.

In order to collect first-draw sample, the pipe rigs must be operated in a cyclical fashion with water running off and on, permitting a standing time of six-eight hours for the sampling program. The on/off cycles used by a PWS should be consistent throughout the testing program's duration and for each pipe rig under evaluation. Timers may be installed to control the operating cycle of the testing program, or manual operations may be used.

The water entering the pipe rigs should be treated per the operation of the PWS facility. The presence of a disinfectant residual, however, entering the pipe rig may not ensure the absence of biological growth within the testing system. Participants in the AWWARF Pipe Loop Study (Kawczynski, 1992) noted significant growth of heterotrophic plate count (HPC) bacteria at the sample taps in the pipe rigs. To reduce the biological growth, the taps were removed, soaked in a concentrated chlorine solution, and then rinsed prior to being re-attached. Even though the pipe loops and/or manifold may become seeded with bacteria, they should not be superchlorinated or receive excessive dosages of disinfectant as this could affect the steady-state corrosion behavior of the pipe loops.

4.3.1.2.2 **Test monitoring programs.** The sampling program for testing rigs should include: (1) the metals being investigated; (2) water quality parameters defining the treatment process; (3) chemical feed rates and stock solution strengths; (4) water flow rate through each testing apparatus; and (5) sample identification criteria such as test run, date, analyst, time of sampling, sample handling steps, and location of sample. The frequency of monitoring for specific parameters and the method of sample collection should be defined prior to the initiation of the testing program. Lead and copper samples from the pipe loops should be first-draw sample representing a standing time between six and eight hours. For example, first-draw samples may be collected every two weeks over a 12-month period for metals and water quality parameters representative of tap samples. Daily water quality parameter sampling and recording of the appropriate chemical feed and flow rate measurements may be performed when operating the pipe rig, even though tap samples are not collected, in order to document the water quality conditions to which the test loops are exposed during the study.

4.3.2 Static Testing Protocols.

Static tests may offer an alternative to flow-through pipe loops to ascertain the performance of various treatments with different piping materials (Frey and Segal, 1991). Static testing generally refers to "no flow-through" conditions, or batch testing (for example, jar testing to evaluate coagulant dosages represents a batch testing protocol). The most common form of static testing is immersion testing where a pipe material, typically a flat coupon, is immersed into a test solution for a specified period of time. Corrosion can then be described by weight-loss, metal leaching, or electrochemical measurement techniques. Other static testing methods include: (1) using a pipe segment of the desired material, filling it with test water and measuring the metal pick-up at the conclusion of a specified holding time; and

(2) recirculation testing where a reservoir of test water is circulated through pipe segments or pipe inserts over a period of time (Note that while water is flowing through the piping segments, it is the same "batch" of water which is being recirculated during the holding time; in this sense, it represents a static test.). These methods have not been widely used, and appropriate test design would be a function of the overall goals and objectives of the testing program.

Static testing procedures do not directly simulate distribution systems. Furthermore, substantial time-savings over flow-through testing methods are not realized with this approach. Single short-term exposure of the metal specimens does not adequately give results about long-term corrosion. Data must be collected for at least nine months before equilibrium conditions are approached and metal leaching has stabilized. Several other critical limitations of static testing are:

- Static testing conditions do not represent the conditions to which piping systems are subject during normal operations. Containers are typically not pressurized and experimental procedures allow the intermittent exposure of containers and coupons/inserts to atmospheric drying. Household plumbing environments experience on-and-off cycles of flow and the distribution system piping network experiences continuous flow-through conditions.
- Exposing coupons and containers to atmospheric conditions, disturbing films on coupons/specimens and containers during replenishing of the containers, evaporation, and other bench-scale limitations will affect the system water chemistry. Subsequent film formation and metal leaching may not accurately reflect the relative effectiveness of various treatment techniques.
- The variation of test results may confound a PWS's ability to differentiate treatment performance among the alternatives tested. Replicate testing and measurements are important components to the test design in order to provide adequate precision and accuracy.
- Comparability of the test results with full-scale performance is uncertain based on existing information. PWSs may want to place coupons or pipe inserts within the service area and at the POE during the testing program. This would provide a basis of comparison between the static tests (control conditions only) and the full-scale system.

In spite of these disadvantages, some utilities may find static testing useful to screen various potential treatments prior to flow-through testing or full-scale implementation. Static tests may be used to evaluate a greater number of treatment alternatives for a PWS. Time permitting, this procedure could allow a PWS to narrow the treatment approaches to a more limited number for additional flow-through testing, if required. Since flow-through testing programs tend to be more complex and costly, satisfying the demonstration testing needs of a PWS or else eliminating inappropriate treatment alternatives prior to performing flow-through testing would be advantageous. To the extent that static testing may

provide such capabilities, it should be included in the demonstration testing.

As discussed in the previous section on flow-through testing protocols, the testing of silicates as a treatment alternative poses special difficulties. The initial silicate mixture will likely contain polymeric forms which will change over time. This reversion may be partially mitigated by pre-mixing the silicate in a separate container and letting the diluted mixture age for a day or two prior to using.

4.4 Alternative Measurement Techniques

The amount of corrosion may be determined by measuring a number of physical parameters, including weight-loss, metal leaching, corrosion rates, or inspection of surface films and corrosion byproducts. A summary of each of these methods is presented below.

4.4.1 Weight-Loss Measurement Techniques.

Gravimetric analysis, or weight-loss, is the traditional method of measuring corrosion in the drinking water industry. Many PWSs have placed rectangular coupons or pipe inserts into distribution system mains and service lines to assess corrosion within their system. Figures 4-3 and 4-4 illustrate a typical coupon and pipe insert installation, respectively.

4.4.1.1 Coupons. Rectangular coupons can be obtained directly from the manufacturer prepared for installation. Once installed, they are typically exposed for a period of no less than 30-days, and more commonly, for a period of 90 to 180 days. The coupons are then removed, cleaned, and reweighed using specific procedures. In many cases, the coupons can be shipped back to the manufacturer for final preparation and weighing.

Coupon geometry and materials have been standardized by ASTM. Flat coupons typically are made from sheet metal; however, cast iron and cast bronze coupons can be prepared from castings. Coupon sizes should be 13 by 102 by 0.8 millimeters (0.5 by 4.0 by 0.032 inches) for all sheet metals, and 13 by 102 by 4 mm for cast metals. Other sizes may be used provided the total surface area is approximately 258 cm^2 (or 4 in^2). A 7-mm hole is punched through the coupon such that its center is approximately 8-mm from one end of the coupon. The coupons are then smoothed and stamped with an identification number between the edge and the mounting hole in order to track the results.

Table 4-3 lists the ASTM material specifications for coupons by the metal alloy and its reference number (ASTM 1990, G-1). ASTM has standard protocols for coupon preparation for weight-loss experiments with water (ASTM 1990, D-2688). These protocols can be obtained directly from ASTM or at most technical libraries. ASTM references are used throughout the industry regarding the application and handling of mild steel, copper, and galvanized coupons. Tables 4-4 and 4-5 summarize the cleaning procedures for the coupons after they have been exposed to the test environment for the required period of time.

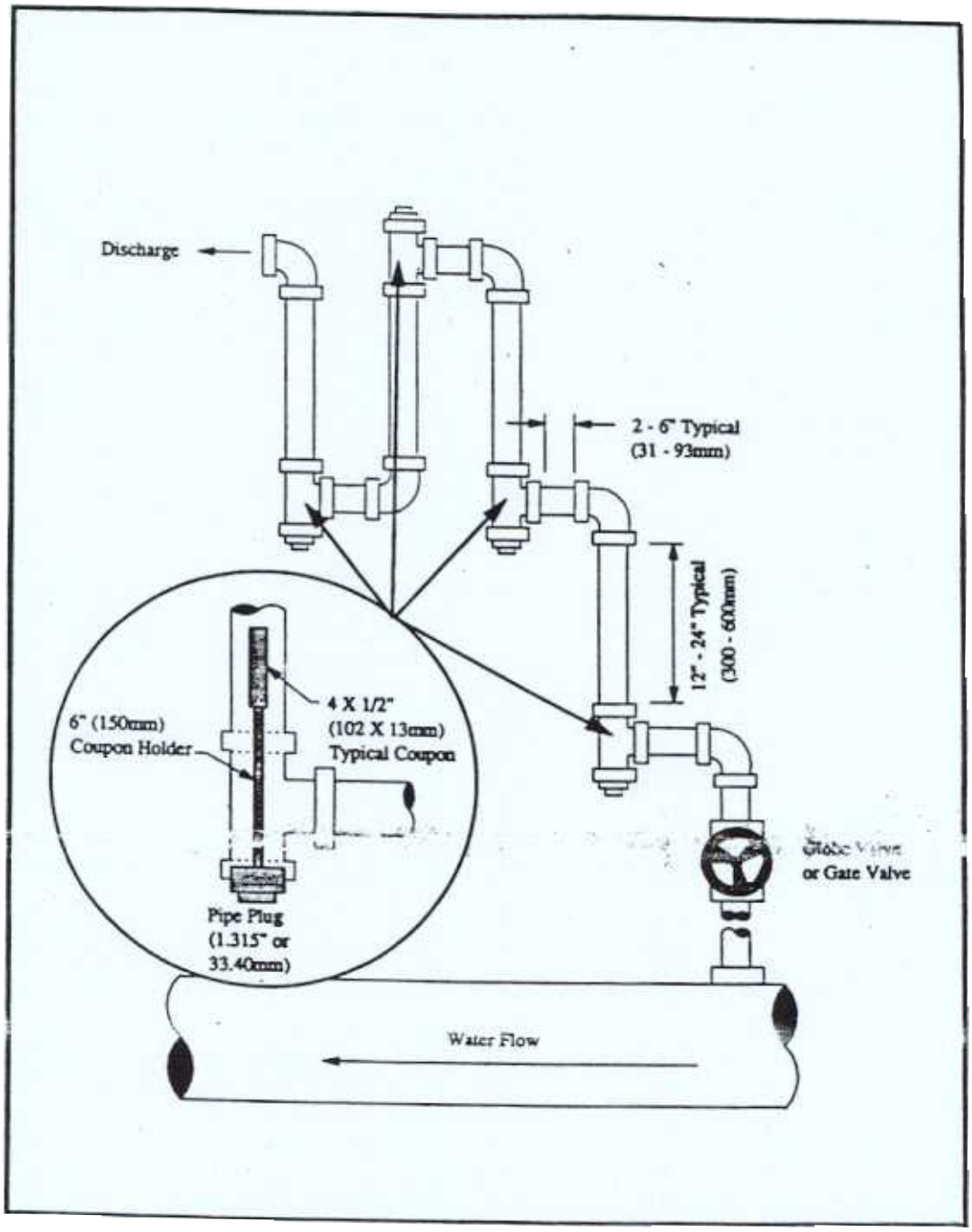

Figure 4-3. Typical Coupon Testing Installation

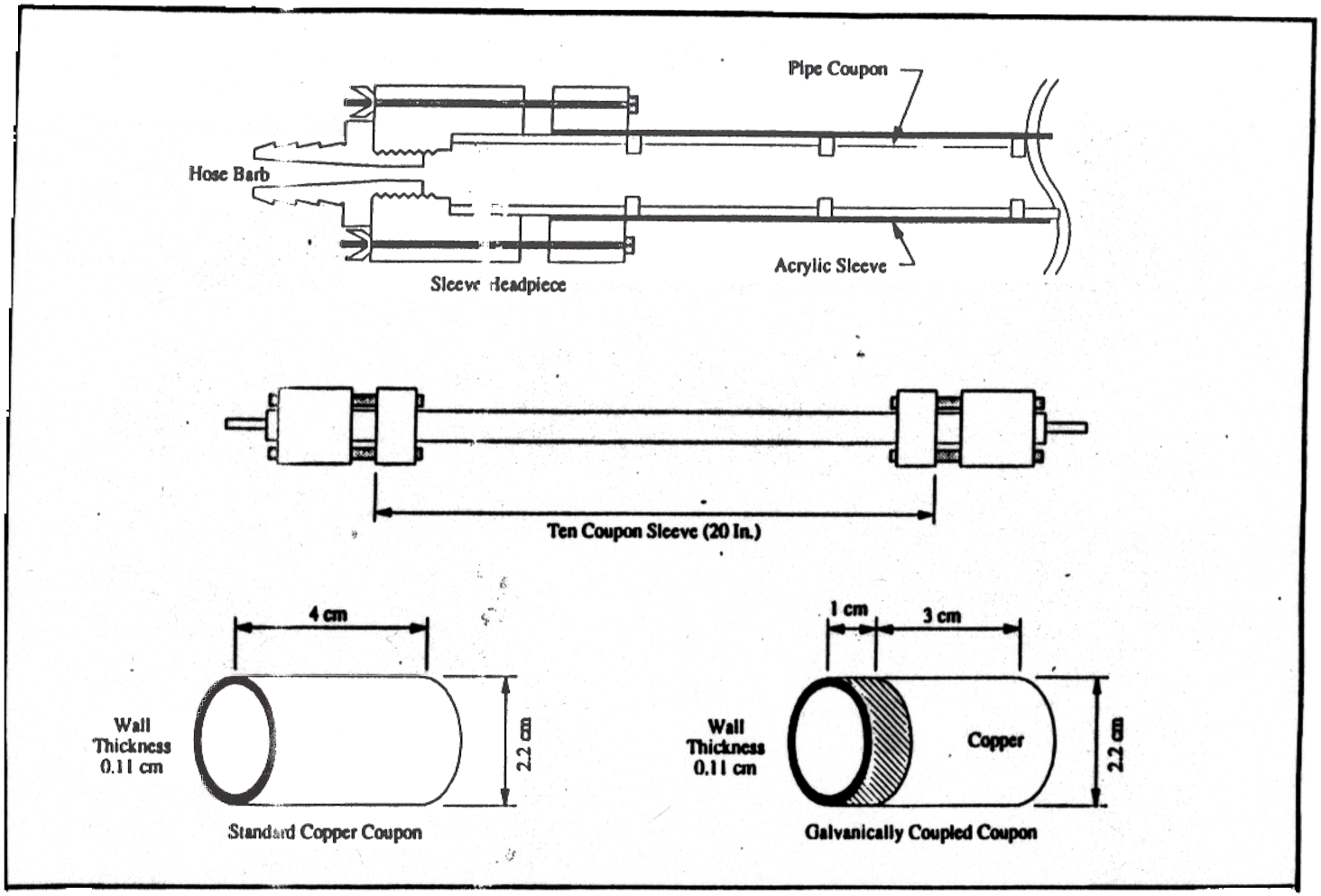

Figure 4-4. Typical Pipe Coupon Insert Installation
From Wysock et al. 1991

Table 4-3. Densities for a Variety of Metals and Alloys

UNS Number	Stainless Steels	Density (g/cm^3)
520100	Type 201	7.94
520200	Type 202	7.94
530200	Type 302	7.94
530400	Type 304	7.94
530403	Type 304L	7.94
530900	Type 309	7.98
531000	Type 310	7.98
531100	Type 311	7.98
531600	Type 316	7.98
531603	Type 316L	7.98
531700	Type 317	7.98
532100	Type 321	7.94
532900	Type 329	7.98
N08330	Type 330	7.98
534700	Type 347	8.03
541000	Type 410	7.70
543000	Type 430	7.72
544600	Type 446	7.65
550200	Type 502	7.82
Copper and Copper Alloys - Brass & Bronze		
C38600	Copper	8.94
C23000	Red brass 230	8.75
C26000	Cartridge brass 260	8.52
C44300, 44400, 44500	Admiralty 443, 444, 445	8.52
Aluminum Alloys		
C68700	Aluminum brass 687	8.33
C22000	Commericial bronze 220	8.20
C60800	Aluminum bronze, 5% 608	8.16
*	Aluminum bronze, 8% 612	7.78
*	Composition M	8.45
*	Composition G	8.77
Lead		
L53305-53405	Antimonial	10.80
L5XXXX	Chemical	11.33

Note X1.1 All UNS numbers that include the letter X indicate a series of numbers under one category.
Note X1.2 An asterisk indicates that a UNS number not available.

Table 4-4. Chemical Cleaning Procedures for Removal of Corrosion Products

Designation	Material	Solution	Time	Temperature	Remarks
C.2.1	Copper and Copper Alloys	500 mL hydrochloric acid (HCl, sp gr 1.19) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Deaeration of solution with purified nitrogen will minimize base metal removal.
C.2.2		4.9 g sodium cyanide (NaCN) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Removes copper sulfide corrosion products that may not be removed by hydrochloric acid treatment (C.2.1).
C.2.3		100 mL sulfuric acid (H_2SO_4, sp gr 1.84) Reagent water to make 1000mL	1 to 3 min	20 to 25° C	Remove bulky corrosion products before treatment to minimize copper redeposition on specimen surface.
C.2.4		120 mL sulfuric acid (H_2SO_4, sp gr 1.84) Reagent water to make 1000 mL	5 to 10 s	20 to 25° C	Removes redeposited copper resulting from sulfuric acid treatment.
C.2.5		54 mL sulfuric acid (H_2SO_4, sp gr 1.84) Reagent water to make 1000 mL	30 to 60 min	40 to 50° C	Deaerate solution with nitrogen. Brushing of test specimens to remove corrosion products followed by re-immersion for 3 to 4 s is recommended.
C.3.1	Iron and Steel	1000 mL hydrochloric acid (HCl, sp gr 1.19) 20 g antimony trioxide (Sb_2O_3) 50 g stannous chloride ($SnCL_2$)	1 to 5 min	20 to 25° C	Solution should be vigorously stirred or specimen should be brushed. Longer times may be required in certain instances.
C.3.2		50 g sodium hydroxide (NaOH) 200 g granulated zinc or zinc chips Reagent water to make 1000 mL	30 to 40 min	80 to 90°C	Caution should be exercised in the use of any zinc dust since spontaneous ignition upon exposure to air can occur.
C.3.3		200 g sodium hydroxide (NaOH) 20 g granulated zinc or zinc chips Reagent water to make 1000 mL	30 to 40 min	80 to 90°C	Caution should be exercised in the use of any zinc dust since spontaneous ignition upon exposure to air can occur.

Table 4-4. Chemical Cleaning Procedures for Removal of Corrosion Products (continued)

Designation	Material	Solution	Time	Temperature	Remarks
C.3.4	Iron and Steel (continued)	200 g diammonium citrate ($(NH_4)_2HC_3H_4O_7$) Reagent water to make 1000 mL	20 min	75 to 90° C	Depending upon the composition of the corrosion product, attack of base metal may occur.
C.3.5		500 mL hydrochloric acid (HCl, sp gr 1.19) 3.5 g hexamethylene tetramine Reagent water to make 1000 mL	10 min	20 to 25° C	Longer times may be required in certain instances.
C.3.6		Molten caustic soda (NaOH) with 1.5-2.0 % sodium hydride (NaH)	1 to 20 min	370° C	For details refer to Technical Information Bulleton SP29-370. "DuPont Sodium Hydride Descaling Process Operating Instructions."
C.4.1	Lead and Lead Alloys	10 mL acetic acid (CH_3COOH) Reagent water to make 1000 mL	5 min	Boiling	---
C.4.2		50 g ammonium acetate (CH_3COONH_4) Reagent water to make 1000 mL	10 min	60 to 70° C	---
C.4.3		50 g ammonium acetate (CH_3COONH_4) Reagent water to make 1000 mL	5 min	60 to 70° C	---

Table 4-5. Electrolytic Cleaning Procedures for Removal of Corrosion Products

Designation	Material	Solution	Time	Temperature	Remarks
E.1.1	Iron, Cast Iron, Steel	75 g sodium hydroxide (NaOH) 25 g sodium sulfate (Na_2SO_4) 75 g sodium carbonate (Na_2CO_3) Reagent water to make 1000 mL	20 to 40 min	20 to 25° C	Cathodic treatment with 100 to 200 A/m² current density. Use carbon, platinum or stainless steel anode.
E.1.2		28 mL sulfuric acid (H_2SO_4, sp gr 1.84) 0.5 g inhibitor (diorthotolyl thiourea or quinoline ethyliodide or bethanaphthol quinoline) Reagent water to make 1000 mL	3 min	75° C	Cathodic treatment with 2000 A/m² current density. Use carbon, platinum or lead anode.
E.2.1	Lead and Lead Alloys	28 mL sulfuric acid (H_2SO_4, sp gr 1.84) 0.5 g inhibitor (diorthotolyl thiourea or quinoline ethyliodide or betanaphtol quinoline) Reagent water to make 1000 mL	3 min	75° C	Cathodic treatment with 2000 A/m² current density. Use carbon, platinum or lead anode.
E.3.1	Copper and Copper Alloys	7.5 g potassium chloride (KCl) Reagent water to make 1000 mL	1 to 3 min	20 to 25° C	Cathodic treatment with 100 A/m² current density. Use carbon or platinum anode.

In general, ASTM recommendations are that coupons should be similar in composition to the piping within the system being evaluated. Materials commonly found within water distribution systems include cast iron, ductile iron, galvanized iron, copper, lead, lead/tin solder, mild steel, brass, bronze, asbestos-cement, and plastic. Some of these materials, such as brass and bronze, may be present in household plumbing fixtures and may contain metal impurities such as lead and zinc.

Several advantages and disadvantages of coupon testing are summarized below (Schock, 1990b):

Advantages:

- Provides information on the amount of material undergoing corrosion for a specific set of conditions.
- Coupons can be placed within actual distribution systems.
- The method is relatively inexpensive.

Disadvantages:

- Coupons are generally in the system for 90 to 120 days before data are obtained.
- Variations in corrosion rates within the testing period are not identified.
- Standard coupons may not be representative of the actual material within the system undergoing corrosion.
- The coupon is located within the pipe section. Thus, it may not accurately indicate the corrosion occurring at the pipe wall because the weight-loss may be due to abrasion not corrosion.
- It is difficult to remove corrosion products during analysis without disturbing some of the attached metal.

4.4.1.2 Pipe inserts. The first use of piping inserts in lieu of rectangular coupons was developed by T.E. Larson at the laboratories of the Illinois State Water Survey (1975), corresponding to ASTM standard 2688-82 method C. Pipe inserts consist of a short piece of 1-inch diameter tubing of the desired material, inserted into a PVC sleeve and plumbed into a convenient delivery line or laboratory testing equipment.

A modified approach using pipe inserts was presented by Reiber et al. (1988) which permitted multiple inserts within a single assembly and allowed replicate results to be gathered. Additionally, the methods used by Reiber et al. (1988) use only mechanical means of insert preparation and cleaning after exposure which eliminates chemical treatment and acid rinses.

4.4.1.3 Calculation of corrosion rates. The difference between the initial and final weights of the coupon or pipe inserts reflects the corrosion activity within the system. This measurement is in mils per year of material-loss or gain.

For most applications, the following equation is sufficiently accurate to estimate the corrosion rate based on coupon testing results:

$$P = [H(W_1 - W_2)/W_1D] \times 1.825 \times 10^5$$

where, P = corrosion rate, mils per year; H = original thickness of the coupon, inches; W_1 = original weight of the coupon, milligrams; W_2 = final weight of the coupon, milligrams; and D = exposure time,

days. In those cases where more precise control is exerted over all variables defining the test conditions, the corrosion rate for a rectangular coupon may be calculated as follows:

$$P = 1/[1/H + 1/X + 1/Y]] \times [(W_1 - W_2)/W_1 D] \times 1.825 \times 10^4$$

where P = corrosion rate, mils per year; H = original thickness of the coupon, inches; X = original length of the coupon, inches; Y = original width of the coupon, inches; W_1 = original weight of the coupon, milligrams; W_2 = final weight of the coupon, milligrams; and D = exposure time, days.

Rates of corrosion using pipe inserts may be calculated as either milligrams per square decimeter per day (mdd) or as mils per year of loss/gain. The method for calculating corrosion rates in mdd is as follows:

For Steel and Galvanized Specimens:
mdd = 1180 W/T,

For Copper specimens:
mdd = 1230 W/T,

where W = actual weight loss of the insert, milligrams; and T = installation time, days. To convert mdd to mpy, use the following equation:

mpy = (1.437 mdd/d)

where d = density of the coupon material, grams/cubic centimeter.

4.4.2 *Corrosion Rates.*

Electrochemical methods of determining corrosion rates may also be applied to drinking water systems. The difference in electrostatic potential between a test and reference electrode under applied current densities can be related to the rate of corrosion reactions. Linear polarization techniques have produced good correlation with weight-loss measurement techniques (Reiber and Benjamin, 1990).

Figure 4-5 illustrates the polarization cell utilized by Reiber and Benjamin (1990). The test electrodes are actual pipe inserts, and can be of materials of interest to the PWS. The cell and its instrumentation can be easily reproduced by PWSs. The investigators felt that their cell design simulated pipe flow conditions which allowed turbulence and scour effects on the corrosion control to be investigated.

4.4.3 *Surface Inspection.*

Visual inspection of piping or coupon surfaces should be performed when possible in all testing programs. The type of corrosion action should be noted, i.e., pitting, uniform corrosion, scale characteristics (continuous, patchy, non-existent), and coloration. Additionally, the scale, if present, may be scraped from the surface of the pipe material and chemically analyzed to determine the key components contained in the scale. This process does not identify the specific chemical compounds composing the scale, but it does indicate the elements which are part of the chemical matrix.

Beyond visual inspection and chemical analyses of scale material, X-ray diffraction techniques may be employed to further identify the scale composition and crystallization characteristics. However, these methods are extremely expensive, and only a few laboratories are capable of performing such tests.

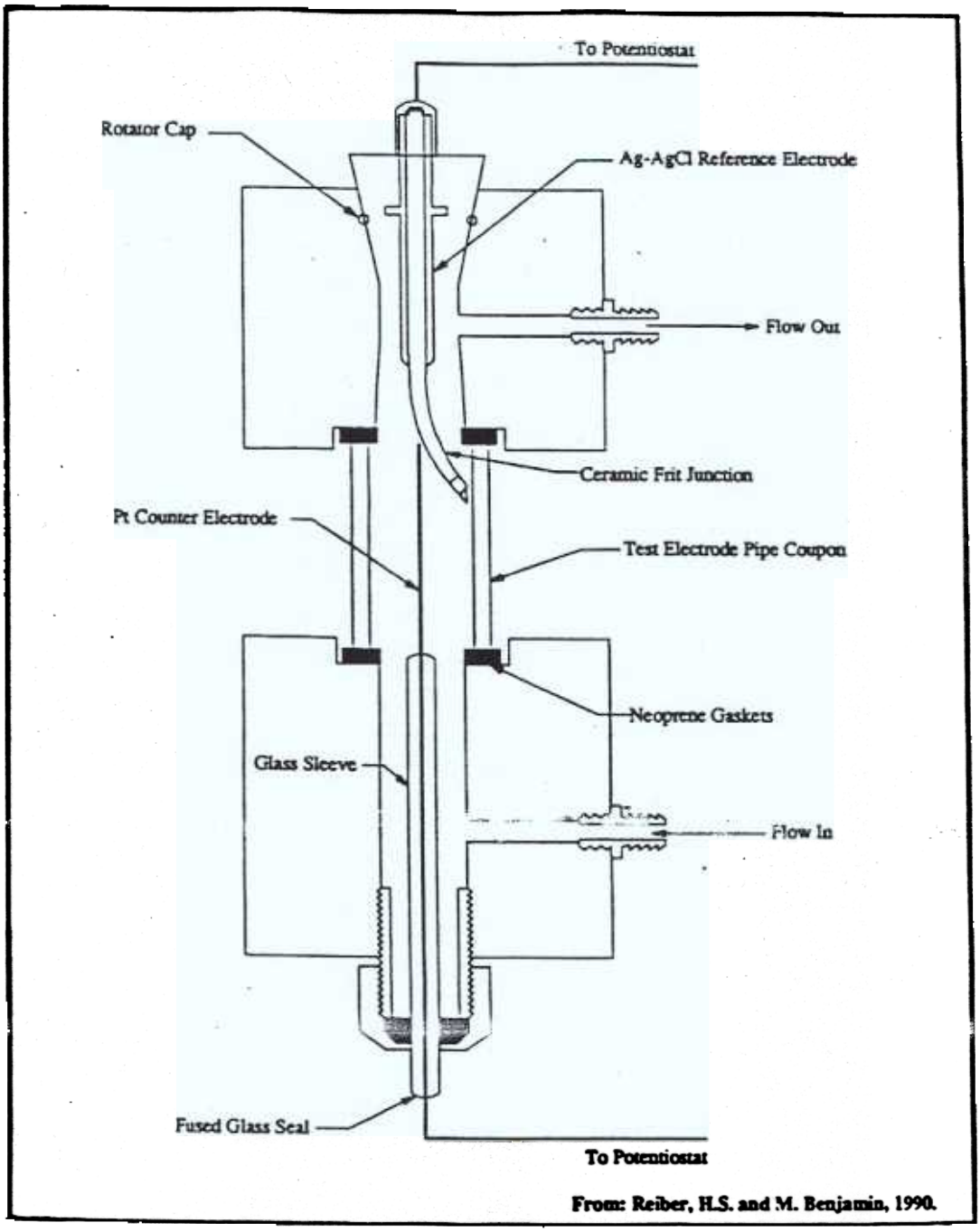

Figure 4-5. Cross-Section of Polarization Flow Cell

4.5 Data Handling and Analysis

Data needs are an important consideration in the design of the testing program. Analytical procedures should be clearly defined as part of the testing program development to: (1) describe the behavior of the testing data; and (2) generate performance rankings for the alternative treatments. The most useful approach to statistically evaluating corrosion control data involves the application of non-parametric statistics.

Underlying all statistical measures are certain, fundamental assumptions regarding the "true" behavior of the data. Those statistical tests which are most commonly applied (such as the Student-t Test, chi-square distribution, difference of means, analysis of variance) are based on populations of data that are normally distributed. A normally-distributed population will form a bell-shaped curve which is symmetrical about the mean, or average, of the data. Although standard statistical tests developed for a normal population are often used for sets of water quality data, most water quality data do not follow a normally-distributed curve. The reader is referred to Appendix C and statistical reference books for further discussions of this topic.

Corrosion control testing data tend to be non-normal, and therefore, conventional statistical measures may not accurately describe the behavior of the data, or reliably generate results which could be used to rank alternative treatments without modification. The example presented in Section 4.9.1 demonstrates the use of traditional statistical tests using the skewness coefficient and Student's t test to compare the performance of alternative treatments.

Alternatively, non-parametric analyses accommodate non-normal conditions, and can be applied to develop relative performance measures for numerous treatments. The non-parametric tests of importance are: (1) the Wilcoxon test or U-test which can compare the results of two conditions to determine whether they behave similarly (i.e., no difference in corrosion performance can be ascertained) or whether they behave differently (i.e., one treatment method produces better corrosion protection); and (2) the Kruskal-Wallis test, or H-test, which is the more general case and can evaluate more than two test conditions. Additional information on the application of non-parametric statistics in evaluating demonstration testing data is provided in Appendix C.

The information to be collected for each testing run include descriptions of: (1) the test conditions (run number, treatment dosages of applied chemicals, water quality parameters, and date); (2) sampling event (control versus test apparatus, location of sampling point, time, and type of material); and (3) the analytical results (water quality parameters such as pH, temperature, alkalinity, hardness, inhibitor residual, disinfectant residual, lead, copper, iron, etc. and/or coupon weight conditions).

The use of spreadsheets or database management skills with personal computers will be satisfactory for the analysis of data from most corrosion studies. Computer software, including statistical analysis programs, is generally locally available.

4.6 Testing of Secondary Impacts

Testing of secondary impacts is vital to the overall study design for optimal treatment. A primary area of concern for secondary impacts is how the alternative corrosion control treatment may be successfully installed and operated so as to meet future State-mandated operating conditions that define compliance with the Lead and Copper Rule. When pH, alkalinity or calcium adjustment are components of a treatment alternative, the stability of these parameters between the point of adjustment, the POE, and throughout the distribution system should be ascertained. Additionally, the likelihood of inhibitors and key water quality parameters to remain within acceptable limits in the distribution system should be investigated.

Compliance with existing and future drinking water standards must be achieved after the installation of corrosion control treatment. Testing to evaluate these conditions should be included in the design of the corrosion control study. Of particular concern may be changes in: (1) the impact on compliance with the disinfection performance requirements of the SWTR and the up-coming Ground Water Disinfection Rule (GWDR); (2) the levels and types of disinfection byproducts (DBPs) that may occur; (3) the occurrence of positive total coliform events or inducement of confluent growth in total analyses due to increases in heterotrophic plate count bacteria; or (4) disinfectant residual concentrations.

The impact of alternative treatment on compliance capability of current and future regulatory requirements should be fully explored. Disinfection performance may be determined by applying the CT values and calculation procedures presented in the *SWTR Guidance Manual* (USEPA, 1989) and briefly discussed in Section 3.3.3 of this manual. The regulation of disinfection byproducts will affect all PWSs regardless of the population served. Evaluating the effect of corrosion control treatment alternatives on the formation of total trihalomethanes (TTHMs) and other DBPs can be accomplished during the testing program by generating either rate of formation curves for the key DBPs or simulated distribution system levels of DBPs. PWSs may reference the AWWA *Standard Methods, 17th Edition* (AWWA, 1989) for an analytical method to determine the simulated distribution system total trihalomethane concentration (SDSTTHM).

4.7 Quality Assurance/ Quality Control Programs

The interpretation of data is founded upon the assurances that proper quality assurance and quality control (QA/QC) procedures were followed during the testing program. A well-designed QA/QC program permits the investigator to more accurately describe the variability introduced into the data by the response of testing materials to the corrosion control treatment processes being evaluated alone. Elements to be included in a QA/QC program include:

- Sufficient sampling frequency for water quality parameters during the period of time when water is flowing to adequately describe the test conditions to which the materials where subject

between first-draw samples. For example, if standing samples are collected each week, then at least daily sampling for water quality parameters should be performed for the treated water supplied to the pipe rig.

- Split samples for metal analyses, especially when metal test kits are being used. EPA recommends that at least five percent of the samples collected be split samples.
- Sample blanks and spikes should be prepared by someone other than the chemical analyst to verify routine measurements. A sample blank and spike should be performed during each testing period for metals.
- Proper calibration of all analytical instruments should be performed at the beginning of each testing period. Chemical feed and flow rate meters should be fully calibrated prior to the initiation of testing and periodically checked during the testing program.
- Sample handling procedures should follow those required in the Rule for metals and water quality parameters. Special care should be given to the cleaning procedures utilized for metals sample containers to minimize cross-contamination between samples.

Each testing program will need to address its specific QA/QC requirements, and should delineate these elements at the beginning in order to prevent the collection of data which cannot be adequately verified.

4.8 Selecting the Recommended Treatment Option

The factors affecting the selection of a treatment technique include:

- **Performance** of alternative treatments evaluated during demonstration testing for mitigating corrosion based on the prioritization of (a) the targeted materials; (b) the measurement technique used to describe corrosion activity (metal solubility, weight-loss, corrosion rate, etc); and (c) confidence in the testing program results (QA/QC and statistical analysis validity).
- **Feasibility** of implementing the alternative corrosion control treatment.
- **Reliability** features of the alternative treatment approaches based on treated water quality and full-scale operational characteristics.
- **Costs** associated with installation and operation, where alternative treatments have comparable performance.

A decision matrix including each of the above factors may be developed and applied as the basis for selecting the 'optimal' corrosion control treatment. Weighting factors which assign relative priorities should be related to site-specific criteria. In most cases, however, the performance of the alternative treatments in reducing lead and/or copper should receive the greatest priority.

4.8.1 Example of Treatment Selection.

A large PWS performed a desk-top evaluation of their system and identified two alternative treatments for further study by

corrosion testing. Flow-through testing was performed using pipe rigs with: (1) iron tubing and copper tubing with lead solder, and (2) copper, lead, and iron coupon flow-through cells. Figures 4-6A and 4-6B present results of corrosion testing in terms of reductions in metal concentrations for standing samples and average weight-loss for treatment alternatives A and B as compared to the existing treatment.

The first-step in developing the final treatment selection decision matrix is defining the performance ranking of each treatment evaluated. The score for the best treatment option used in this analysis is 7, for second 4, and for the worst option 0. Given the priorities of the PWS, the weighting factors used for each metal were 0.45, 0.40 and 0.15 for lead, copper, and iron, respectively. Due to the increased importance in controlling lead and copper solubility, the weighting factors for measurement technique were 0.7 and 0.3 for metal concentration and weight-loss results, respectively, for lead and copper. For iron, however, the measurement weighting factor was 0.3 and 0.7 for metal concentration and weight-loss results, respectively, due to more concerns about maintenance and repair of iron piping.

Table 4-6 presents the corrosion control performance matrix with the appropriate weighting factors. The resultant score indicates that treatment A provided the best corrosion control protection, while treatment B provided the second best and the existing treatment provided the worst performance. These results are used in the final treatment selection matrix.

Table 4-7 presents the final treatment selection matrix for the PWS. A desk-top evaluation of treatments A and B prior to testing revealed that these treatment options were equally feasible. As a result, feasibility of treatments A and B is not a part of the decision matrix. By far, the most important factor for identifying optimal treatment in this case is treatment performance, shown by setting its weighting factor at 0.75. The reliability and cost weighting factors were set at 0.15 and 0.10, respectively. The reliability of the treatment options is considered more important than the costs since compliance will eventually be determined by the ability of the PWS to consistently produce finished water which meets its treatment objectives. The costs of treatment should be assigned a low weighting factor (here 0.1) to reflect the fact that costs are not directly relevant to selecting the optimal treatment, exept in helping to decide between alternative treatments with comparable performance. Based on the results of the final treatment selection decision matrix, Treatment A would be recommended as optimal corrosion control treatment.

4.9 Examples of Corrosion Studies

4.9.1 Flow-Through Testing.

Utility A exceeded the action level for lead during its first 6-month period of diagnostic monitoring and initiated a corrosion control study. The Utility treats water from a surface supply to provide a treated water with the following general characteristics:

pH	= 7.8	Total hardness	= 85 mg/L as $CaCO_3$
SO_4	= 40 mg/L	Ca hardness	= 52 mg/L as $CaCO_3$
Cl	= 5 mg/L	Total alkalinity	= 60 mg/L as $CaCO_3$
Na	= 10 mg/L	Total solids	= 275 mg/L

As illustrated on Figure 3-7, several avenues for treatment exist. After conducting a desk top study and visiting with some other utilities using similar water sources, Utility A decided to utilize pipe loops to further define optimal corrosion control treatment.

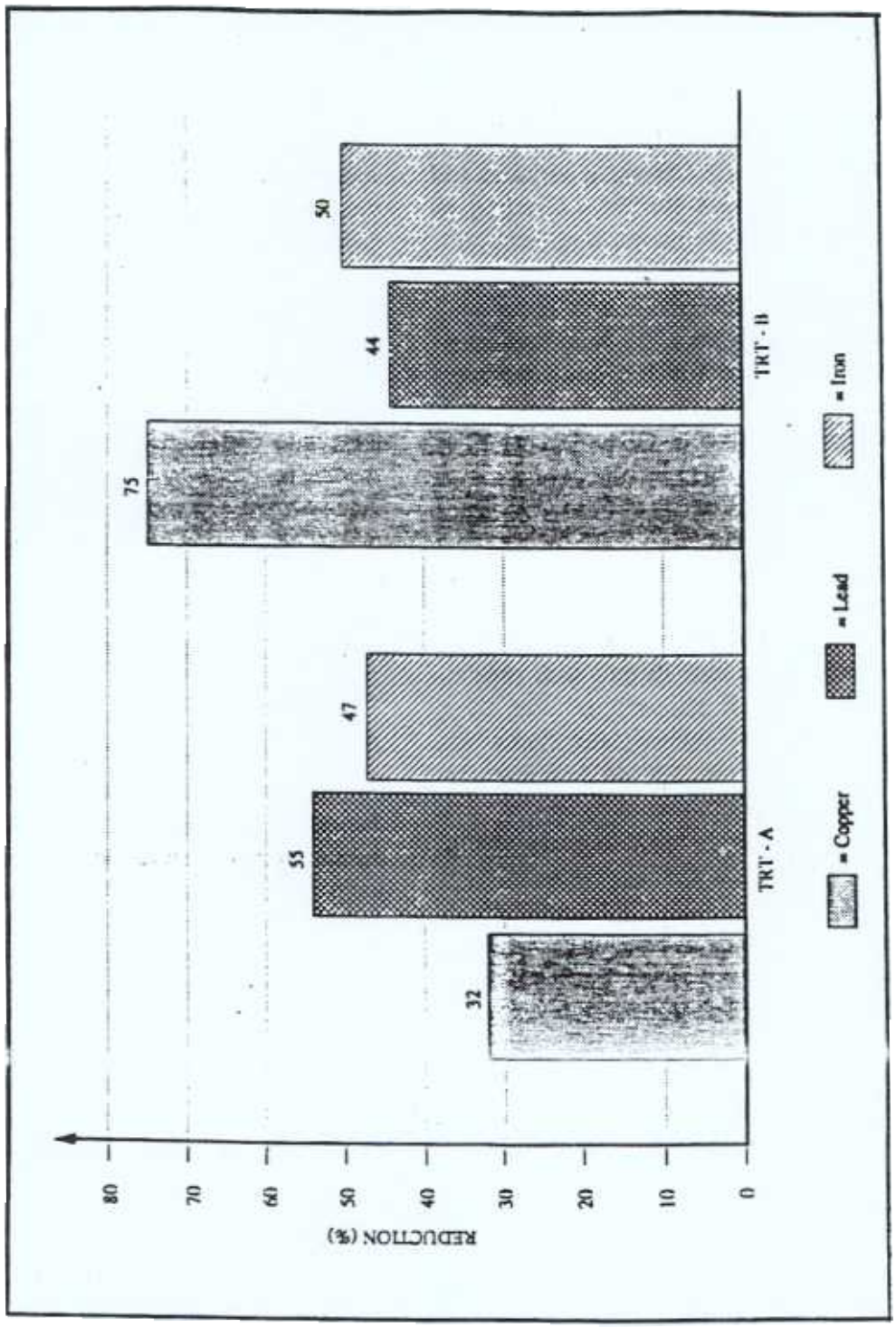

Figure 4-6A. Reduction in Metal Concentrations by Treatment Alternatives

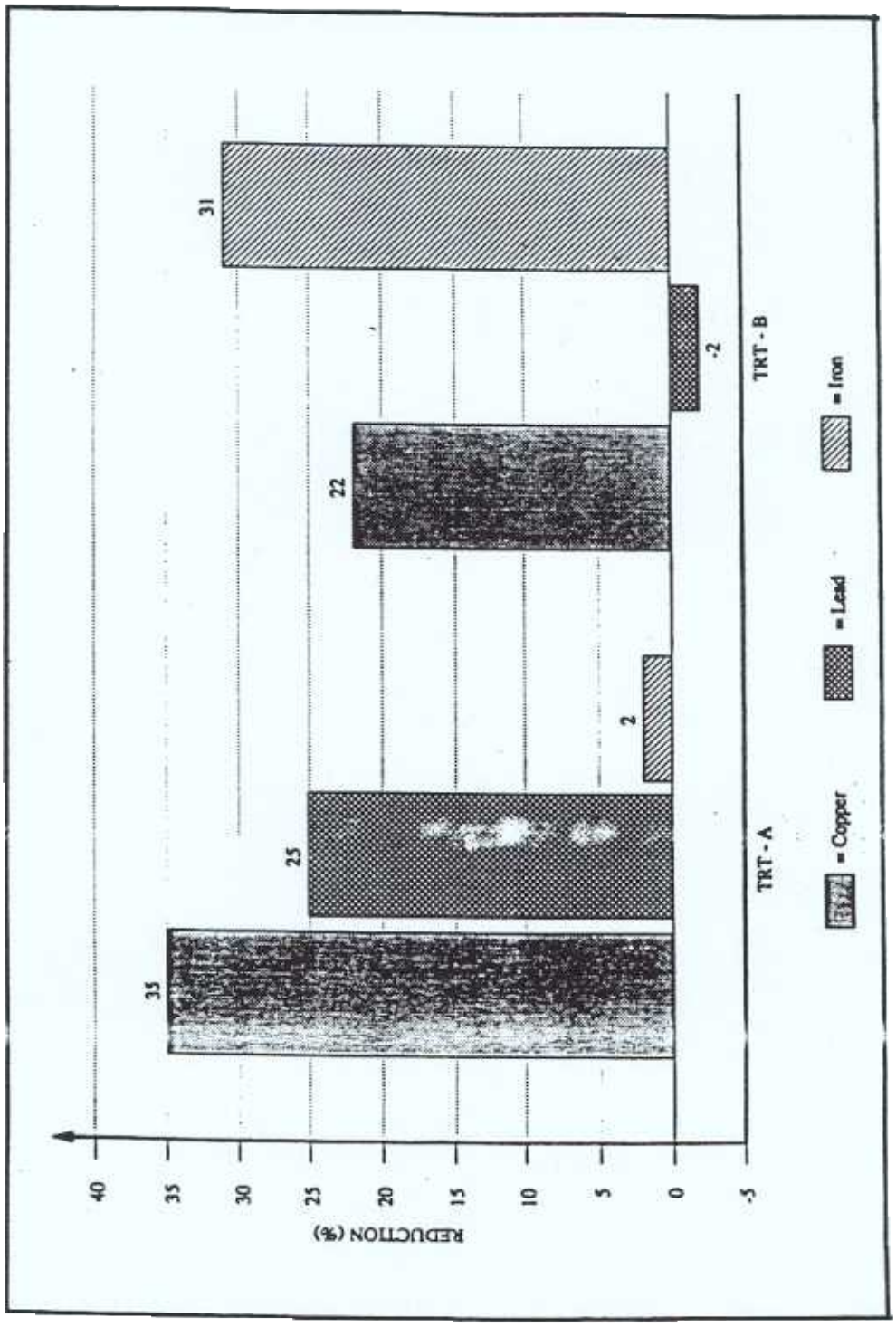

Figure 4-6B. Reduction in Coupon Weight-Loss by Treatment Alternatives

Table 4-6. Corrosion Control Treatment Performance Ranking Matrix

Treatment Alternative	Performance Criteria					
	Metal Solubility			Weight-Loss		
	Copper	Lead	Iron	Copper	Lead	Iron
Weighting Factors	0.40	0.45	0.15	0.40	0.45	0.15
Treatment A	4	7	5.5	7	7	4
Treatment B	7	4	5.5	4	0	7
Existing	0	0	0	0	4	0
Interim Performance Scores						
Treatment A	1.6	3.2	0.8	2.8	3.2	0.6
Treatment B	2.8	1.8	0.8	1.6	0.0	1.1
Existing	0.0	0.0	0.0	0.0	1.8	0.0
Measurement Technique Weighting Factors	0.7	0.7	0.3	0.3	0.3	0.7
Measurement Scores						
Treatment A	1.1	2.2	0.2	0.8	0.9	0.4
Treatment B	2.0	1.3	0.2	0.5	0.0	0.7
Existing	0.0	0.0	0.0	0.0	0.5	0.0
Total Score						
Treatment A	5.8					
Treatment B	4.7					
Existing	0.5					

Table 4-7. Final Corrosion Control Treatment Selection Matrix

Treatment Alternative	Corrosion Control Performance	Treatment Reliability	Estimated Costs	Total
Weighting Factors	0.75	0.15	0.1	1
Treatment A	7	7	0	6.3
Treatment B	4	0	4	3.4
Existing	0	4	7	1.3

Three identical pipe loops were constructed of copper pipe with lead/tin soldered connections. Loop 1 represented a control loop without treatment, Loop 2 used finished water treated with lime addition, and Loop 3 used finished plant water with the addition of a phosphate inhibitor. The target pH for Loop 2 was 8.3 and the alkalinity and final hardness were allowed to fluctuate to satisfy the final pH goal. Loop 3 water was treated by the addition of a proprietary phosphate inhibitor at a dose calculated to yield 1 mg/L as PO_4.

The three loops were run for a period of 35 weeks until they appeared to stabilize and testing was terminated. Water flowed through the loops for 16 hours followed by an 8 hour standing period. Standing water samples were collected for lead analysis once per week for the 35-week period. Data from the tests are given in Table 4-8.

Unless conditioned for an extended period, new piping materials are likely to yield higher metals concentrations than actual household plumbing systems. Yet, it is extremely difficult to construct pipe loops with materials removed from household plumbing systems without disturbing films and scales present on piping interiors. Results from testing programs, therefore, are used to select treatment techniques; and final action levels after installation of full scale treatment can only be estimated. In the testing program being discussed here, finished water from the treatment facility flowed continuously through all three loops for four weeks in order to partially acclimate the pipe rig before the initiation of the weekly sampling program.

Parametric statistics were selected to compare the two treatments with the control. The data were found to be skewed and were transformed into the log normal mode for analysis. This type of transformation is frequently made when analyzing water quality data and the procedure is

Table 4-8. Lead Concentrations from Pipe Loop Testing

Week	Loop 1 Pb, mg/L	Loop 2 Pb, mg/L	Loop 3 Pb, mg/L
1	0.062	0.130	0.078
2	0.078	0.100	0.102
3	0.125	0.080	0.115
4	0.110	0.095	0.109
5	0.175	0.110	0.126
6	0.205	0.135	0.102
7	0.190	0.108	0.098
8	0.162	0.092	0.075
9	0.078	0.079	0.082
10	0.112	0.085	0.070
11	0.095	0.090	0.068
12	0.132	0.076	0.065
13	0.126	0.079	0.081
14	0.103	0.108	0.073
15	0.115	0.087	0.065
16	0.138	0.072	0.068
17	0.092	0.068	0.072
18	0.100	0.052	0.038
19	0.118	0.097	0.055
20	0.107	0.075	0.062
21	0.068	0.048	0.050
22	0.082	0.072	0.068
23	0.097	0.103	0.076
24	0.112	0.096	0.072
25	0.085	0.072	0.075
26	0.078	0.080	0.080
27	0.060	0.052	0.062
28	0.092	0.058	0.054
29	0.075	0.045	0.058
30	0.087	0.053	0.045
31	0.063	0.060	0.052
32	0.072	0.055	0.068
33	0.068	0.052	0.030
34	0.080	0.048	0.051
35	0.091	0.057	0.042

explained more fully in Appendix C for this example. The Student's t statistic was used to compare paired data among the three loops and the results from these analyses are reproduced in Table 4-9 from Appendix C.

Using the entire data set for 35 weeks, the data in Table 4-9 seem to indicate that either treatment would be beneficial for reducing lead concentrations. However, after reviewing the data, it was noted that the data had fewer fluctuations during the later weeks. These results are reasonable as the pipes become more acclimated and the system stabilizes as the testing program proceeds. Using a data set from week 25 on, the data were examined once again. This analysis showed that each treatment was significantly different when compared to the control, but there was no apparent statistical difference between treatments. Thus, Utility A will examine other factors such as initial cost, operating costs, and operating philosophy before deciding which treatment to implement for full-scale treatment.

4.9.2 Static Testing.

The City of Starboard, a large PWS, has a surface water supply with low pH, alkalinity and hardness levels as shown in Table 4-10. Based on the desk-top evaluation, the optimal corrosion control treatment recommended for further evaluation was pH/alkalinity adjustment. The use of inhibitors was eliminated on the basis of the desk-top evaluation. The water quality goals selected on the basis of lead and copper passivation were: pH 7.6 - 7.8; total alkalinity = 40 - 45 mg/L $CaCO_3$; and total hardness ≥ 30 mg/L $CaCO_3$.

Three treatment alternatives were selected for demonstration testing using static tests: (1) lime and carbon dioxide; (2) soda ash and carbon dioxide; and (3) lime and sodium bicarbonate. The average chemical feed rates and water quality characteristics for testing are presented in Table 4-11.

The demonstration tests used to evaluate corrosion control performance consisted of immersion tests with flat

Table 4-9. Calculated Student's t Values

Comparison	t
Loop 1 and Loop 2	5.46***
Loop 1 and Loop 3	6.98***
Loop 2 and Loop 3	2.87**

Notes: All test data transformed to logarithmic values
** Highly significant difference at the 0.01 level
*** Extremely significant difference at the 0.001 level

Table 4-10. Average Raw, Treated, and Finished Water Quality for the Static Demonstration Tests by the City of Starboard

Water Quality Parameter	Raw Water	Treated Water	Finished Water
pH	7.2	6.7	7.4
Alkalinity, mg/L $CaCO_3$	24	10	16
Calcium Hardness, mg/L $CaCO_3$	18	16	20
Chlorine Residual, mg/L	N/A	0.4	1.2

Table 4-11. Average Chemical Feed Rates and Water Quality Characteristics by Treatment Alternative for the Static Demonstration Testing Program by the City of Starboard

Treatment Alternative	Water Quality Characteristics, mg/L			Chemical Feed Rates, mg/L			
	THd	Talk	pH	CaO	Na_2CO_3	$NaHCO_3$	CO_2
CaO/CO_2	42	32	8.0	17.4	0	0	15.3
Na_2CO_3/CO_2	22	27	8.0	0	16.8	0	7.8
$NaHCO_3/CaO$	22	29	8.0	1.4	0	31.5	0

metal coupons of iron, lead, and copper. Figure 4-7 illustrates the experimental set up for the immersion tests. The testing program was conducted by suspending four metal coupons in each of three test jars and the one control jar for each metal included in the investigation. The solutions were maintained for one-week testing periods, then sampled, drained, and replaced with fresh solutions. Water quality parameters were measured daily in each jar to ensure their relative consistency throughout the testing period. The pH was adjusted with carbon dioxide or sodium hydroxide, as needed. Alkalinity and hardness contents remained very stable during the week holding period, and did not require adjustment.

The testing schedule, as presented in Figure 4-8, included: iron coupon testing for 4.5 months; lead coupons for 7 months; and copper coupons for 13 months in order to achieve stable conditions by the end of the testing period. Metal leaching data were collected by sampling the test and control solutions prior to draining the jars at the conclusion of each week. The control and test jars were all treated the same in terms of the monitoring frequency. This ensured the integrity of the relative metal leaching data between control and test conditions.

Table 4-12 presents the raw data generated during the testing program in terms of water quality parameter monitoring and metal leaching. A sample log sheet for the testing program is presented in Figure 4-9 to illustrate the data recording and documentation requirements.

Figures 4-10A and 4-10B present the metal leaching results for copper and lead in terms of the reduction in total metal between the test and control jars. A high degree of variability is evident from the copper results, while more consistent data was found for lead. The lime and carbon dioxide treatment provided the greatest reduction in copper levels consistently throughout the testing period. The difference in the performance between the other two treatments for copper control is minimal, and, throughout the majority of the testing period, both indicated increased copper corrosion over the existing conditions (i.e., negative reductions as presented in Figure 4-10A).

Each of the three alternative treatments provided positive reductions in lead corrosion as shown in Figure 4-10B. Large variability was observed in the performance of soda ash plus carbon dioxide while lime plus carbon dioxide and sodium bicarbonate plus carbon dioxide provided very consistent results. The lime and carbon dioxide treatment, however, resulted in lower lead levels with respect to the control throughout the entire evaluation period.

Based on these results, the lime and carbon dioxide treatment was selected as optimal treatment since it provided the greatest and most consistent reduction in corrosion for lead and copper.

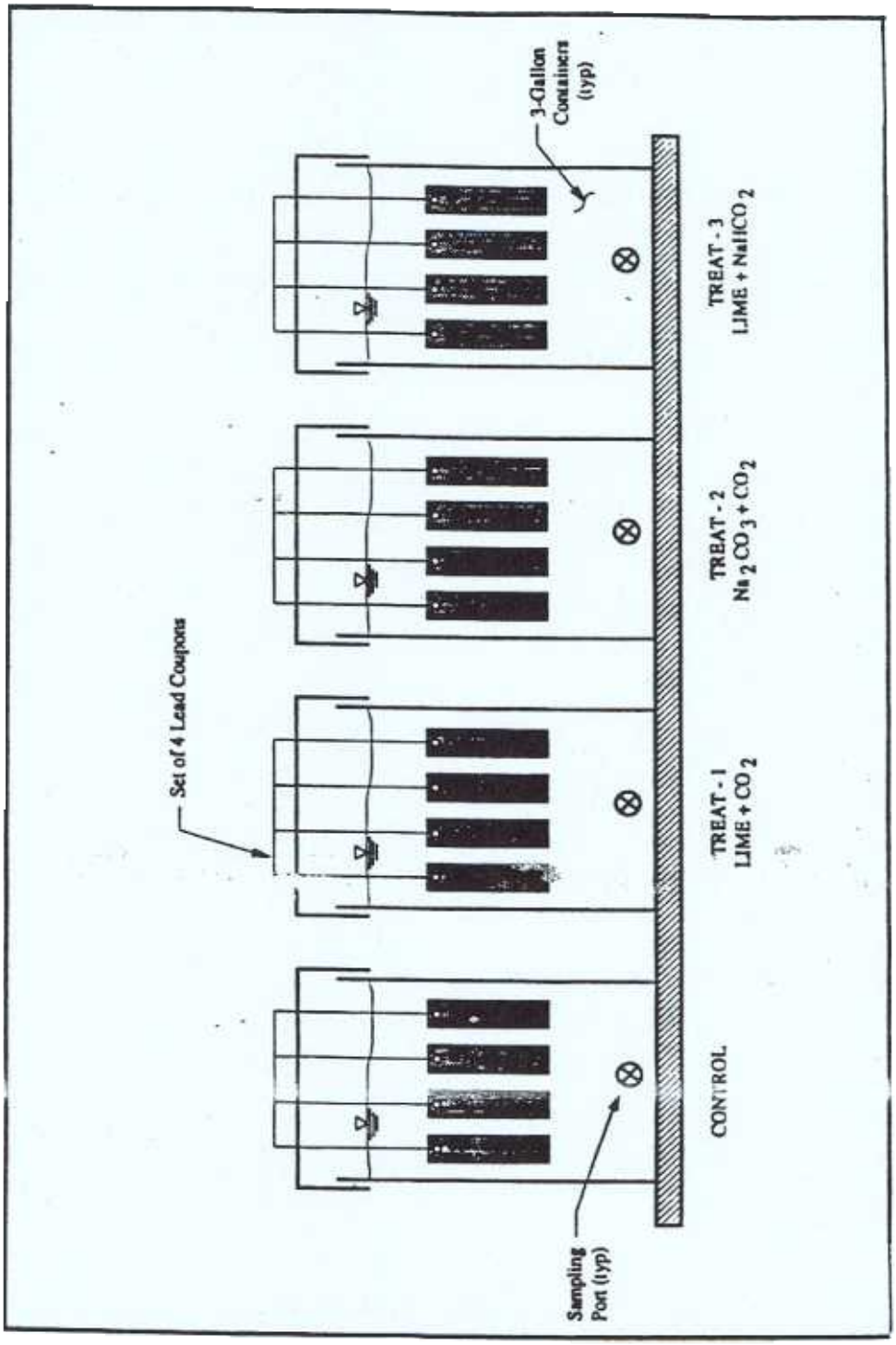

Figure 4-7. Immersion Testing Set-Up

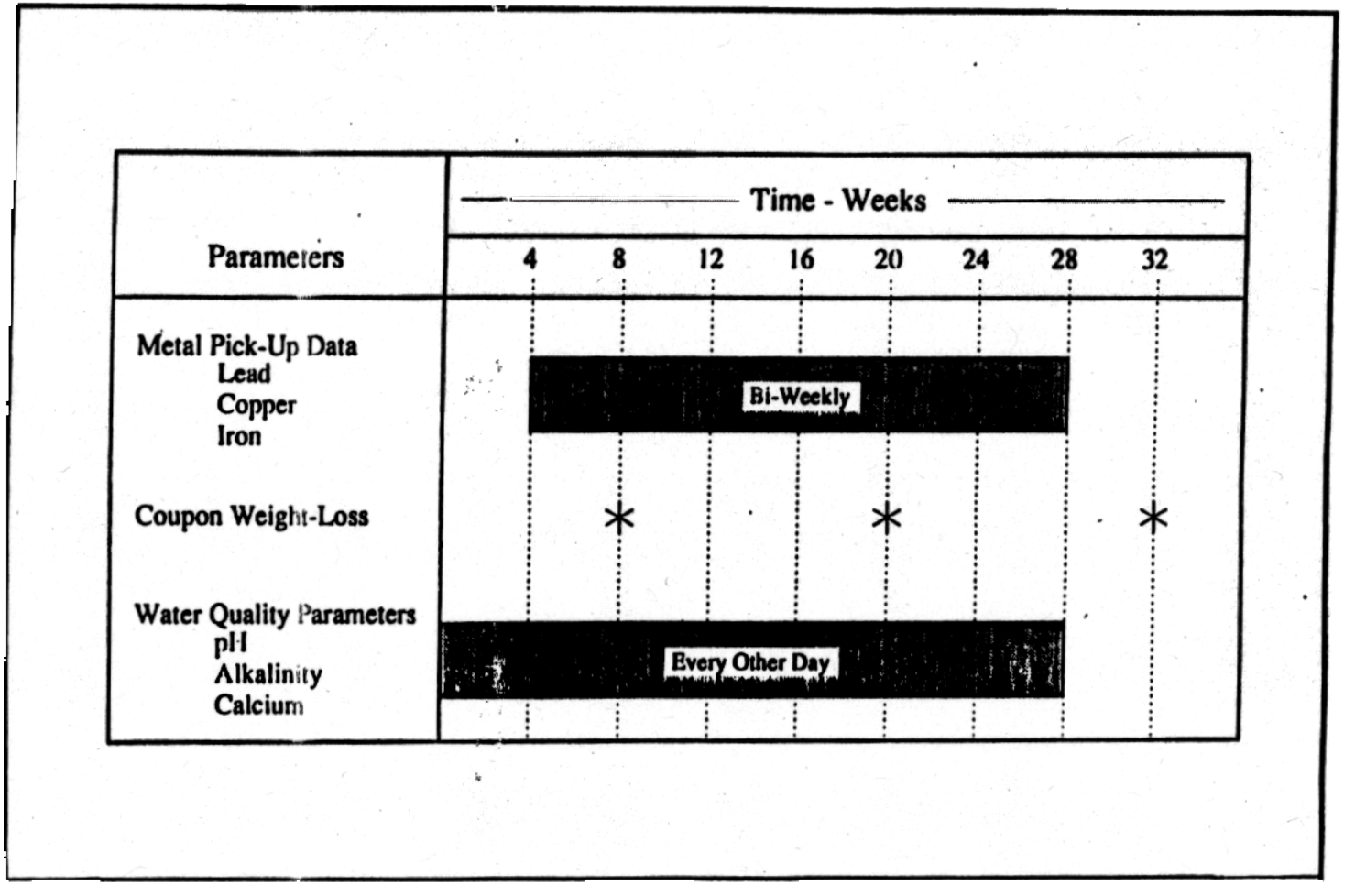

Figure 4-8. Testing Program for City of Starboard Static Demonstration Tests

Table 4-12. Testing Program Raw Data for Water Quality Parameters[3] and Metal Leaching[4] Measurements for the Static Demonstration Tests by the City of Starboard

Test Week	Alternative Treatment	Inita. Conditions, mg/L					Final Conditions, mg/L				
		pH[1]	Alk[2]	Ca[2]	Cu	Pb	pH[1]	Alk[2]	Ca[2]	Cu	Pb
2	Lime + CO_2	6.48	5	9	ND	ND	7.88	32	44	0.248	0.124
4	Lime + CO_2	6.52	6	8	ND	ND	7.98	33	42	0.254	0.135
6	Lime + CO_2	6.22	5	9	ND	ND	8.25	35	43	0.361	0.122
8	Lime + CO_2	6.38	5	7	ND	ND	8.12	37	44	0.182	0.146
10	Lime + CO_2	6.51	4	12	ND	ND	8.05	30	50	0.268	0.138
12	Lime + CO_2	6.47	4	10	ND	ND	8.16	28	48	0.177	0.166
14	Lime + CO_2	6.44	6	15	ND	ND	8.23	34	48	0.198	0.153
16	Lime + CO_2	6.52	5	9	ND	ND	7.92	27	42	0.241	0.142
18	Lime + CO_2	6.66	4	8	ND	ND	7.78	29	37	0.220	0.121
20	Lime + CO_2	6.56		9	ND	ND	8.16	30	40	0.154	0.118
22	Lime + CO_2	6.31	5	9	ND	ND	8.08	34	42	0.146	0.092
24	Lime + CO_2	6.43	6	7	ND	ND	8.01	32	44	0.132	0.062
26	Lime + CO_2	6.54	4	6	ND	ND	8.11	30	38	0.148	0.056
28	Lime + CO_2	6.63	5	8	ND	ND	8.04	35	39	0.162	0.078
30	Lime + CO_2	6.48	5	8	ND	ND	7.94	29	40	0.127	0.063

1 The measurement units are standard pH units.
2 Alkalinity and Calcium measurements are in mg/L $CaCO_3$.
3 Water Quality Parameter results are the average of measurements taken every other day within the two week test period.
Metal results are the average of three aliquots taken at each sampling event.

Figure 4-9. Immersion Testing Data Recording and Documentation Sheets

Date:	
Time:	
Analyst:	
Test Week:	
Test Day:	

Water Quality Parameters

Treatment	Water Quality Parameters							
	pH		T		Alk		Ca	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Control								
Trt Alt 1								
Trt Alt 2								
Trt Alt 3								

Metal Leaching Analysis

Immersion Testing

Treatment	Metal Content in mg/L					
	Lead		Copper		Iron	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Control						
Trt Alt 1						
Trt Alt 2						
Trt Alt 3						

QA/QC Testing Results:

Treatment	Lead		Copper		Iron	
	Blank	Spike	Blank	Spike	Blank	Spike
Control						
Trt Alt 1						
Trt Alt 2						
Trt Alt 3						

Weight-Loss Measurments, mpy

Treatment	Lead		Copper		Iron	
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Control						
Trt Alt 1						
Trt Alt 2						
Trt Alt 3						

Figure 4-9. Immersion Testing Data Recording and Documentation Sheets (continued)

Date:	
Time:	
Analyst:	
Test Week:	
Test Day:	

NOTES:

Visual Inspection of Coupons:

Testing/Analytical Procedures:

QA/QC Program:

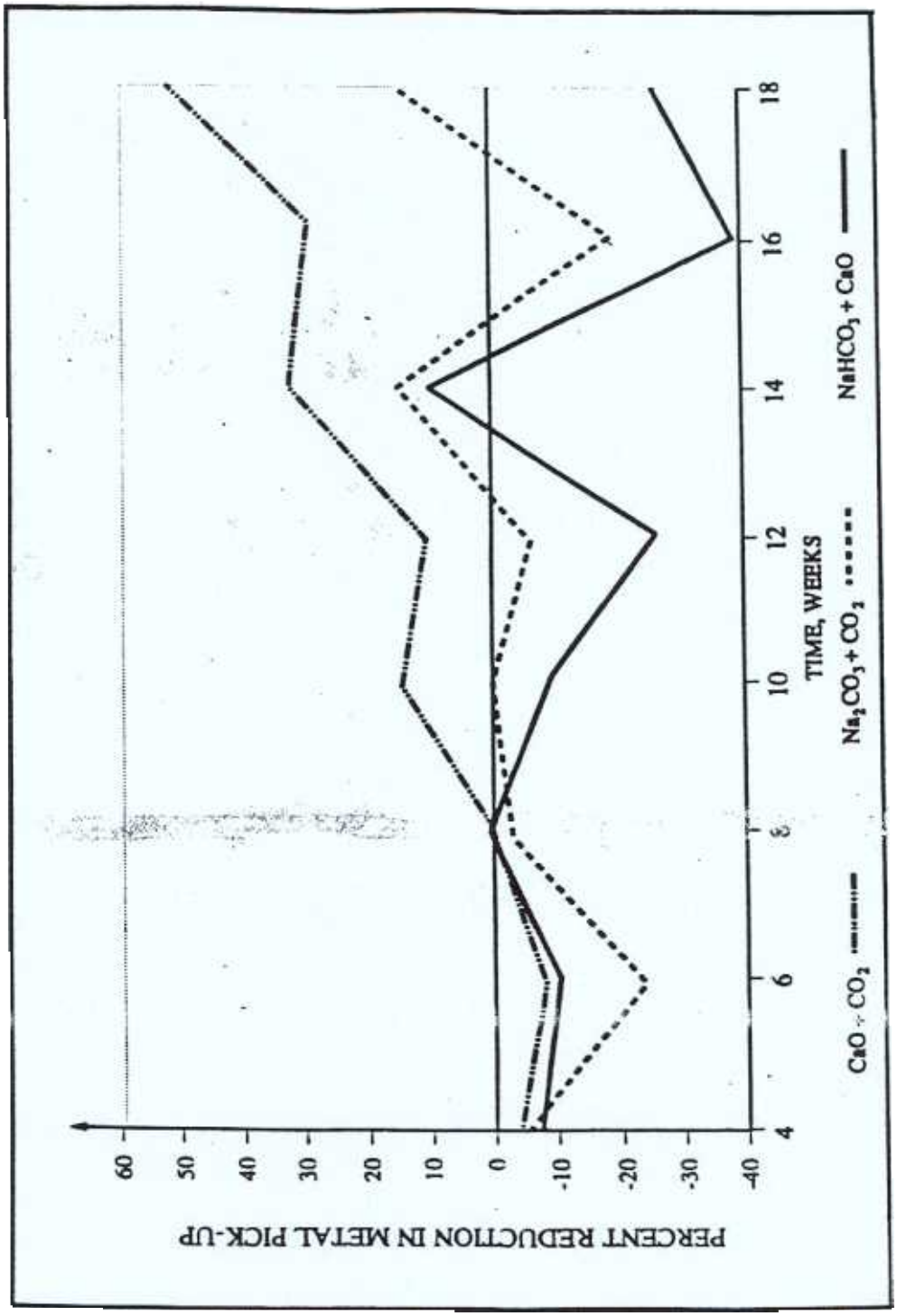

FIGURE 4-10A. Reductions in Copper Corrosion for Treatment Alternatives

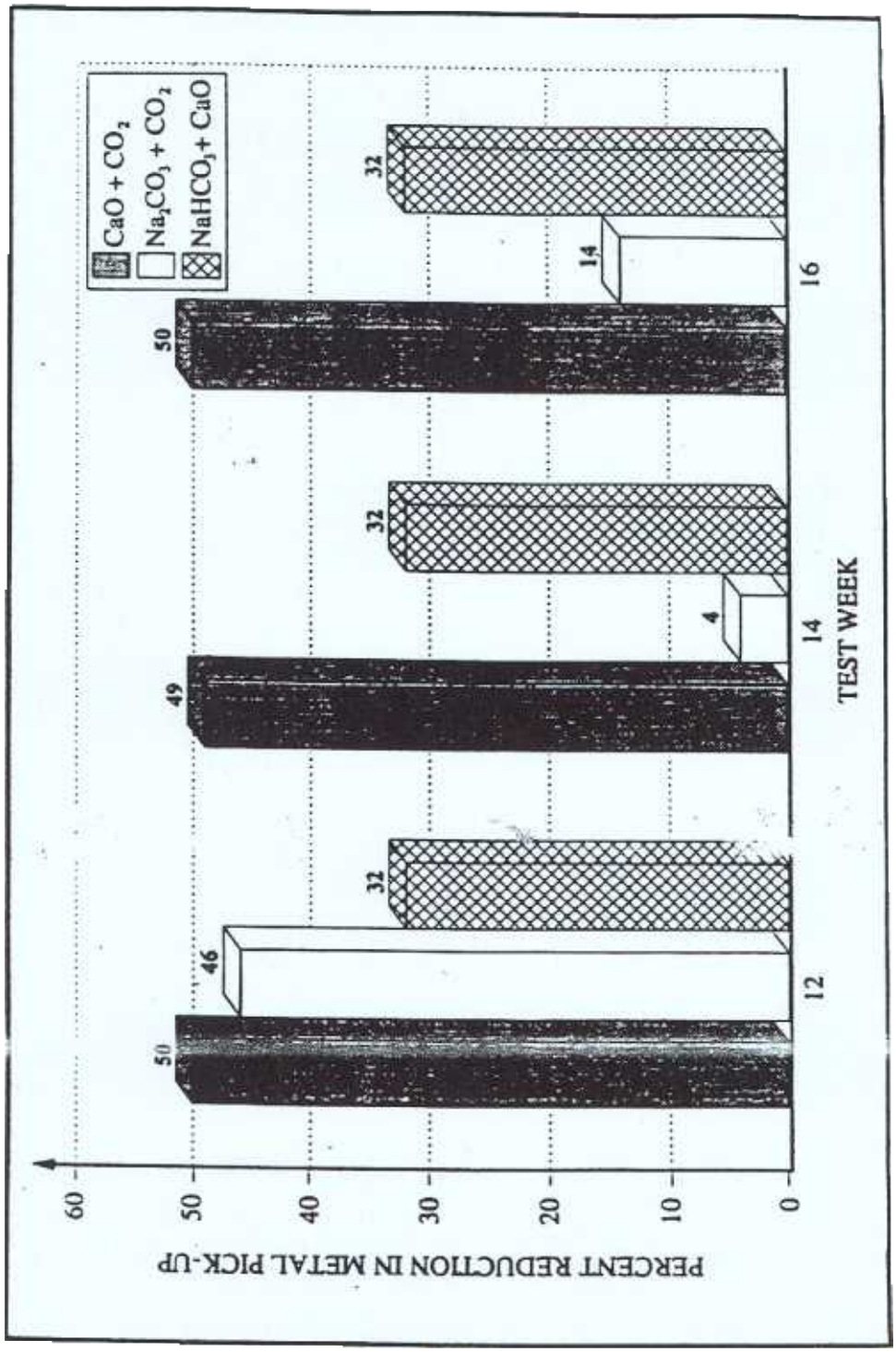

Figure 4-10B. Reductions in Lead Corrosion for Treatment Alternatives

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