NBS TECHNICAL NOTE 974

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Corrosion of Metallic Pipes Transporting Potable Water— Laboratory Testing Methods

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Corrosion of Metallic Pipes Transporting Potable Water—Laboratory Testing Methods

+ Technical Note

Jean N. Andre

Centre Scientifique du Batiment
Paris, France

James R. Clifton

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary

Dr. Sidney Harman, Under Secretary

Jordan J. Baruch, Assistant Secretary for Science and Technology

U.S. NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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CORROSION OF METALLIC PIPES TRANSPORTING POTABLE WATER - A LABORATORY TESTING METHOD

by

Jean N. Andre and James R. Clifton

A pipeline was constructed and experimental methods developed to determine the effects of several important factors on the corrosion of pipes. These factors included the composition, temperature and flow rate of the water, and type of metal. Components of the pipeline were carefully selected or designed to prevent the occurrence of extraneous corrosion.

The rates of corrosion of galvanized steel and copper pipes were measured by direct weight loss measurements and by polarization resistance methods. It appears that the polarization resistance technique is a useful tool which may be used in a variety of corrosion studies of pipe in aqueous media.

Key words: Copper pipe; corrosion; corrosion measurement; galvanized steel pipe; metal pipes; potable water; resistance polarization.

1. INTRODUCTION

In the first phase of a program being undertaken to investigate the processes associated with corrosion of pipes in buildings, the factors affecting the corrosion of pipes transporting potable water are being studied. Many factors affect both the type of corrosion and the corrosion rate of pipes [1-11]. Natural waters are complex media and their chemical composition, as characterized by pH, dissolved salts, and dissolved gases, is an important factor influencing the corrosion rate of pipes. Other important factors include the flow rate and temperature of the water and obviously the type of metal used in producing the pipe. To ascertain the relative importance of these factors an experimental test design, test methods and test apparatus have been developed. Their development is described in this report.

Included in the development of test methods was the identification and modification of existing corrosion measurement techniques and procedures which would provide the desired information. A commonly used method is based on measuring the weight change of test specimens; however, this method is normally used to obtain results integrated over a long period of time, usually months. The average corrosion rate over such a long period may not be the corrosion parameter controlling the service life of the pipe. Frequently, the corrosion rate changes significantly with time and the magnitude of the corrosion rate at the end of an experiment could be the controlling parameter. Therefore, methods for measuring instantaneous or quasi-instantaneous corrosion rate were reviewed and the resistance polarization method was selected. Its applicability for measuring the corrosion of pipes is discussed in this report.

In addition to investigating the factors affecting the corrosion of pipes, a preliminary assessment of the efficiency of silicates in reducing the corrosion rates of metallic pipes has been made. A common method of controlling corrosion in aqueous media is to use inhibitors, but in potable water the type and the quantities of inhibitors which can be used are limited because of health considerations. Silicates, phosphates, polyphosphates, zinc salts, carbonates and hydroxides are common inhibitors which are often added to potable water in Europe. Similar inhibitors are also added to some water systems in the United States. Recently, a literature review was conducted by J. N. Andre of corrosion in natural waters, which included the use of polyphosphates (or condensed phosphates) as inhibitors in potable water; the review was published by the Centre Scientifique et Technique du Batiment (CSTB) [12].

2. LABORATORY SIMULATION OF PIPE CORROSION

The experimental test design and the test apparatus developed to investigate the effects of factors associated with corrosion of pipes in buildings are discussed in this section. An important aspect of this work was the fabrication of a functional pipeline, which is shown in Figures 1 and 2. The components and operation of the pipeline are also described herein.

2.1 Properties of Metallic Pipes

One of the most important features affecting the corrosion of commonly used metals for pipes (black steel, copper, and galvanized steel) is the condition of the interior pipe surfaces, presence of scale or containment films, and smoothness of interior surfaces. Metallurgical features, such as the carbon content of steel (in the range of mild steels), appear to be of secondary importance with pipes of the same metal and their effects are generally uniform from one pipe to another [12]. Therefore, test specimens were fabricated from commercially available black steel, copper and galvanized

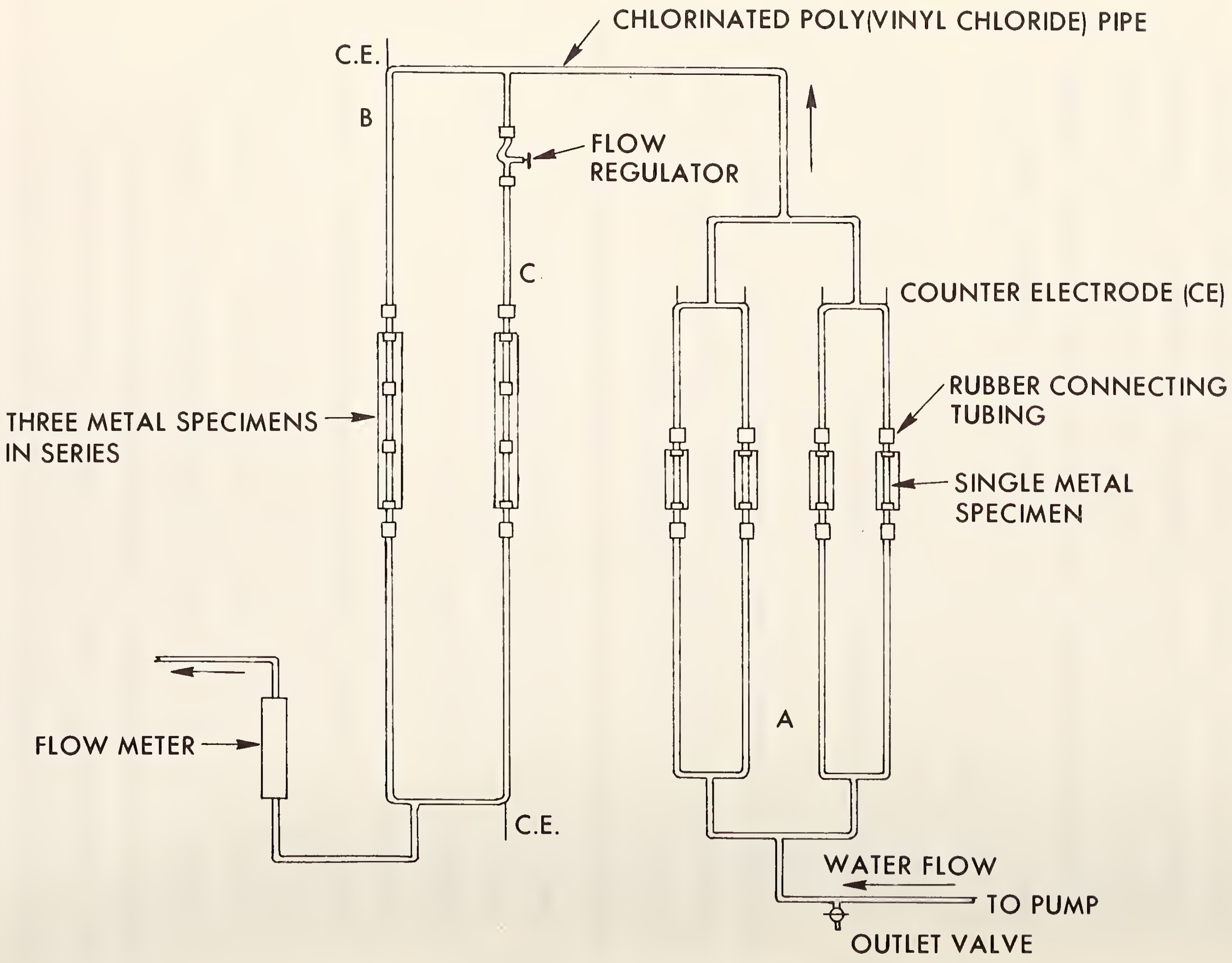

Figure 1. Schematic of Pipeline Used During Corrosion Studies.

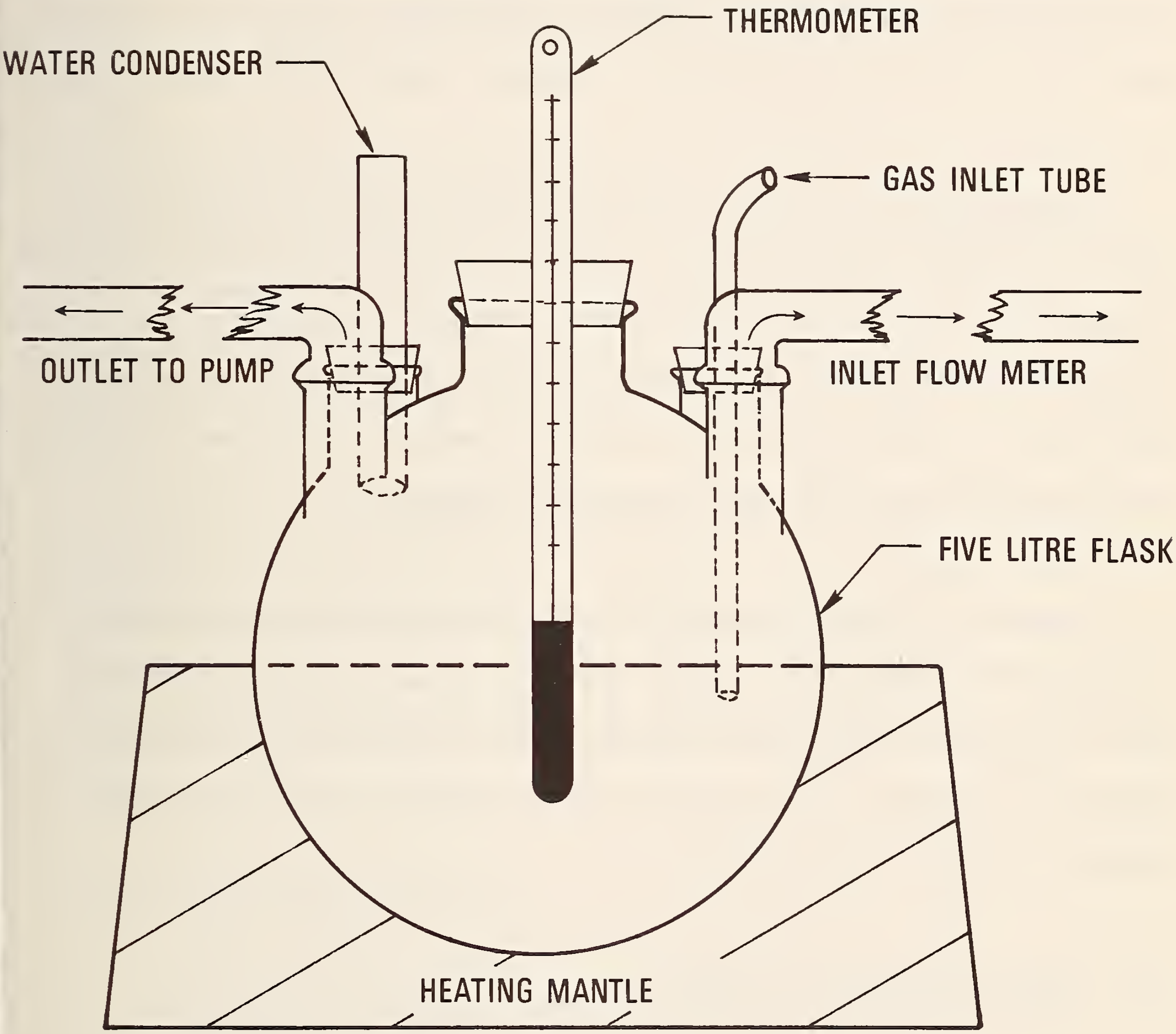

Figure 2. Schematic of Water Reservoir.

steel pipes and used without being subjected to heat treatment. The quality of the galvanized coating on galvanized steel often varies from pipe to pipe and may even vary on a specific pipe. Test specimens were made from pipes of the same origin to minimize metallurgical differences. Only small differences were found in the corrosion behavior of samples taken from the same source.

Test specimens, 10 cm in length were cut from 1.3 cm i.d pipe using a lathe. This small diameter made it possible to obtain a high water flow rate using a low capacity pump (maximum pumping rate of 21 litres/minute). Cutting with the lathe facilitated the preparation of clean and smooth cross sections which could be fitted tightly into plastic connectors. Furthermore, cutting with the lathe did not damage the galvanized coating.

Immediately prior to use, test specimens were (1) cleaned in ethanol, (2) immersed in hydrochloric acid (1 minute in concentrated acid for black steel and copper samples, about 3 seconds in a 1 Normal solution for galvanized test specimens), (3) rinsed in distilled water, then (4) dried with ethanol, and (5) finally weighed.

2.2 Chemical Composition of Water

2.2.1 Salts

The salts normally present in natural water can be divided into two main categories, (1) those responsible for the carbonate hardness of water and (2) soluble salts. The salts responsible for the carbonate hardness of water are calcium and magnesium carbonates and their bicarbonates.

These salts are only slightly soluble and if supersaturating conditions are attained the salts will precipitate and slowly form protective scales on the walls of the pipes [4, 7].

The commonly encountered soluble salts having the greatest effect on corrosion are the alkali chlorides, sulfates, nitrates, and sodium carbonate and bicarbonate. One process by which these salts can increase corrosion rates is by increasing the conductivity of water. Sulfate and chloride ions have especially great influences on the corrosion rate and type of corrosion.

The effects of other impurities in water such as organic matter, which is often present in surface water, or naturally occurring silicates (sometimes referred to as the cristalloidic form) are difficult to reproduce. These impurities are generally considered to have beneficial effects [13] in controlling corrosion and no attempt was made to incorporate them in our study.

2.2.2 Dissolved $CO_{2(g)}$ and $O_{2(g)}$

The two gases which usually have the most significant affect on the corrosion of water-transportating pipes are $O_{2(g)}$ and $CO_{2(g)}$. The amount of dissolved $CO_{2(g)}$ controls the pH of the water as indicated by the simplified equation:

$$CO_{2(g)} + H_2O_{(liq)} \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^{2-} \qquad (1)$$

The CO_2 content also affects the extent of scaling by carbonates.

The amount of oxygen dissolved is very important because the electrode reaction:

$$1/2\ O_{2(g)} + H_2O_{(liq)} + 2e \rightleftarrows 2OH^-_{(aq)} \quad (2)$$

is generally the main cathodic reaction involved in the corrosion process. This reaction is, in most cases, diffusion controlled, which means that its rate is dependent on the oxygen concentration gradient next to the pipe walls. If the oxygen at the wall surface is consumed at a rate rapid enough to substantially drop the oxygen concentration, then the diffusion rate of oxygen will control the cathodic reaction. At a specific temperature, the main factors affecting the diffusion rate of oxygen are the oxygen concentration in the bulk solution, and the thickness of the diffusion layer between the bulk solution and the water-metal interface.

2.2.3 Test Water

To evaluate the effects of dissolved salts and gases on the corrosion of pipes, experimental waters were made by adding the desired salts and gases to distilled water. The pH's of the solutions were lowered by bubbling $CO_{2(g)}$ through them or increased by flushing dissolved $CO_{2(g)}$ from the solutions with $N_{2(g)}$. For example, the pH was lowered with $CO_{2(g)}$ to permit the complete solution of $CaCO_3$ and $MgCO_3$. The gas content in the test water was controlled during studies by continuously bubbling a mixture of $O_{2(g)}$ and $CO_{2(g)}$ through the water (Fig. 2).

The corrosion process itself progressively changes the composition of the water. Oxygen and eventually $CO_{2(g)}$ are depleted if they are not replaced and the concentrations of metallic ions coming from the corrosion of the pipes are increased if they are not precipitated as oxides, hydroxides, or carbonates. The scaling process in a water of positive Langelier index[1] will progressively reduce the concentration of calcium and magnesium carbonates. In a large operational system the water is continuously being changed which is difficult to do in a laboratory controlled experiment because of the need to adjust the composition of the test water. The effect of the corrosion process on water composition may be minimized by using a very high ratio of corroding surface to volume of test water.[2] However, a more realistic approach would be obtained by using a ratio similar to the one encountered in the field. A value of 140 cm^2/litre is given [13] as being a sufficient value for the ratio of $\frac{\text{corroding surface}}{\text{volume of water}}$, if the test water is replaced every five hours. In the present experiments, a ratio of 65 cm^2/litre was used and the test water was replaced approximately every 24 hours. In non-scaling water, as used in our first experiments, this replacement rate appeared to be sufficient. In conditions where scaling is to be expected, the replacement time should be determined by monitoring changes in the composition of the water. It is felt that concentration changes of less than 20 percent would have little effect on the corrosion rate.

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[1] Langelier index is the difference between the actual pH of the water and the pH this water would have once brought in equilibrium with calcium carbonate [4].

[2] Corroding surface indicates the internal surface area of the pipe system in contact with the water.

2.3 Flow Rate of Water

The Reynolds number, $RV = \frac{\rho DV}{\mu}$ (where ρ is the fluid density, V is the average fluid velocity, D is the pipe diameter, and μ is the fluid viscosity), has been developed based on fluid dynamic considerations [14] and is regarded as being a more significant parameter than the average fluid velocity when considering corrosion. In the present study, the internal diameter of the pipe is the same for every test specimen, 1.3 cm, and ρ and μ are known for water as a function of temperature. Therefore, measuring the average water velocity with a flowmeter is sufficient to determine the Reynolds number at a given temperature. The transition between turbulent and laminar flow which occurs around RV = 2000 [14] corresponds, for a diameter of 1.3 cm, to a velocity of approximately 7 cm/s at 60°C.

The corrosion rate is affected by the thickness of the boundary layer[3/] because the chemical species involved in the corrosion processes must pass through this layer. An increase in velocity of the water decreases the thickness of this boundary layer and accelerates mass transfer processes [15, 16, 17]. The smoothness of the pipe walls also affects the thickness of the boundary layer.

A moderately high water velocity is generally a favorable condition for preventing localized corrosion because the strong stirring action helps to prevent the formation of concentration cells. At higher velocities

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[3/] Thin zone of flowing water in the immediate vicinity of the surface of the pipe [14].

corrosion-erosion (impingement attack) may occur. In addition, high water velocities can influence the deposited film characteristics by causing the removal of loose or slightly adherent deposits.

In this work, the effects of a range of velocities, low velocity (less than .07 m/s), medium velocity (.4-.6 m/s), and high velocity (around 2 m/s), were investigated. After passing through the pump, (see Fig. 1) the water was separated into four equal portions during passage through segment A of the pipe network (medium flow), then the water was recombined and passed through segment B (high flow), except for a small amount which passed through segment C (low flow). The flow through segment C was regulated by a needle value. The needle value was calibrated by collecting and measuring the water flowing through segment C during a specific time interval. The bulk flow was measured by the flowmeter F. The low flow was probably laminar and the medium and high flows were considered to be turbulent.

Two experiments have been carried out to determine the effects of the flow rate of water on corrosion. The first experiment lasted one month and consisted of exposing copper pipes at 60°C to a test water with a pH between 8.3 to 8.5 (measured at ambient temperature). No attempt was made to measure the pH at 60°C and the water was aerated with room air. The test water initially contained 80 ppm of $CaCO_3$, 225 pm of $NaHCO_3$, 60 ppm of NaCl, and 20 ppm of $MgSO_4 \cdot 7H_2O$. Under these conditions, the corrosion rate was little affected by changes in the water velocity. For an exposed surface of 43.3 cm^2, the average weight loss was 12 mg for low flow (ca .07 m/s), in medium flow (0.37 m/s) the weight loss was 16 mg, and in high flow (1.5 m/s), the weight loss was 10 mg. In the second experiment, galvanized steel was tested at 60°C for 60 days. The test water was similar to that used in the previous experiment except that the pH was lowered to 6 (measured at ambient temperature) by bubbling $CO_{2(g)}$ through the solution. Under these conditions, the corrosion rate was significantly dependent on the water velocity. The average weight losses were 1.4 g at high velocity (2.7 m/s), 0.46 g at medium velocity (0.46 m/s), and 2 g at low velocity (ca. .07 m/s) for samples with exposed surfaces of approximately 40 cm^2. Visual inspection of the galvanized test specimens indicated that localized corrosion took place at low velocity. These results clearly indicate that the flow rate of the transported water can significantly affect the corrosion rate of certain types of metallic pipes.

In obtaining information on the effect of a range of water velocities on the corrosion rate, constant water velocities were used, that is each velocity was kept constant. In real systems, however, there are alternate periods of low, medium and high water velocities. While it is possible to reproduce those conditions in the laboratory the interpretation of the results would be more difficult.

2.4 Water Temperature

Temperature is an important variable which affects the kinetics of chemical reactions. The reaction rates of many activation controlled processes are roughly doubled for every 10°C increase. While diffusion controlled processes are less affected by temperature, they are slightly accelerated because diffusion rates are temperature dependent. The temperature may also effect the thermodynamic equilibrium controlling the phase stability of oxides and hydroxides, and the solubilities of salts and gases in water. Considering the materials used in water supply systems and the range of temperatures encountered (10 to 70°C) an increase in temperature will usually increase the corrosion rate.

In our apparatus, water is heated in a 5 litre round bottom glass flask by a jacket heater with controlled power (Fig. 2). The temperature of the laboratory is relatively constant and consequently heat losses are fairly uniform, therefore 60°C is easily obtained within ± 2°C. Significant changes in temperature only occur when a portion of the test water is replaced. At this time, the temperature would decrease by as much as 15°C, however in less than one hour the temperature increased back to its original value. The temperature difference between the inlet water and the outlet water in the flask was found to be less than 0.5°C. The temperature in the branch with the low flow (segment C, Fig. 1) appears to be slightly lower than that in the main part of the pipeline. In further experiments this problem will be eliminated by wrapping the low flow branch with a thermal insulation material.

2.5 Water Pressure

The main influence of externally applied pressure on corrosion rates in water appears to be to increase the solubility of O_2 and CO_2 gases. Similar results can be obtained by bubbling through the water gaseous mixtures of O_2 and CO_2 with, if desired, high partial pressures of either gas.

The experimental pipe system was not pressurized, it was connected to the atmosphere of the room through a water-cooled condenser to avoid excessive evaporation of the test water.

2.6 Prevention of Extraneous Corrosion

Components of the pipeline were carefully selected or designed to prevent the occurrence of corrosion extraneous to the scope of this work, such as deposition, crevice, and galvanic corrosion.

Copper ions in concentrations less than 1 ppm can cause the deposition corrosion of metallic pipes such as black steel and galvanized steel [7]. Such small concentrations can be readily generated by the corrosion of copper or copper alloy parts, especially in a recirculating system. As a consequence, an apparatus for testing black steel and galvanized pipes has to be free of components containing copper or copper alloys. Separate pipelines were setup to test copper pipes, black steel, and galvanized pipes individually and there are no copper components in the pipeline used for the study of black steel and galvanized pipe. For example, the pump has an epoxy body and epoxy impeller, the flow meter has a stainless steel body and glass flow tube, and the needle valve consists of a glass housing and poly(tetrafluorethylene) adjustable needle.

A method was developed to connect test specimens to the water loop in such a way that neither differential aeration nor unusual turbulence occurred at the junctions. This connection system shown in Figure 3 has prevented the occurrence of any corrosion localized (crevice corrosion) at the edges of the specimens. The plastic used for the connector was initially poly(tetrafluorethylene) but at 60°C this material creeped so much that leaks developed at the metal-plastic joints and therefore is being replaced with chlorinated poly(vinyl chloride) which has performed satisfactorily to date.

Galvanic corrosion is prevented by constructing the pipe network (Figure 1) from 1.3 cm i.d. chlorinated poly(vinyl chloride) pipe. All other components, such as the pump, needle valve, test specimen holders, were connected to the pipeline with chemically and thermally resistant synthetic tubing. Three pipe specimens tested in series in branches B and C (Figure 1) were separated from each other with chlorinated poly(vinyl chloride) spacers (Figure 4).

3. CORROSION RATE MEASUREMENTS

Classical corrosion studies on metallic pipes usually involved visual observation of the samples, weight loss measurements and, if pitting took place, measurements of the depth and density of pits. These techniques are not entirely satisfactory because visual observation gives only qualitative information on the extent and rate of corrosion.

Weight loss measurements and the measurement of pits are destructive in that the actual state of the sample is changed during cleaning of the sample; also only the amount of corrosion is determined, whereas the rate of corrosion may be more important. As the measured weight values are often scattered, a number of identical samples should be tested to check the reliability of the results (for example, 3 samples were tested in the

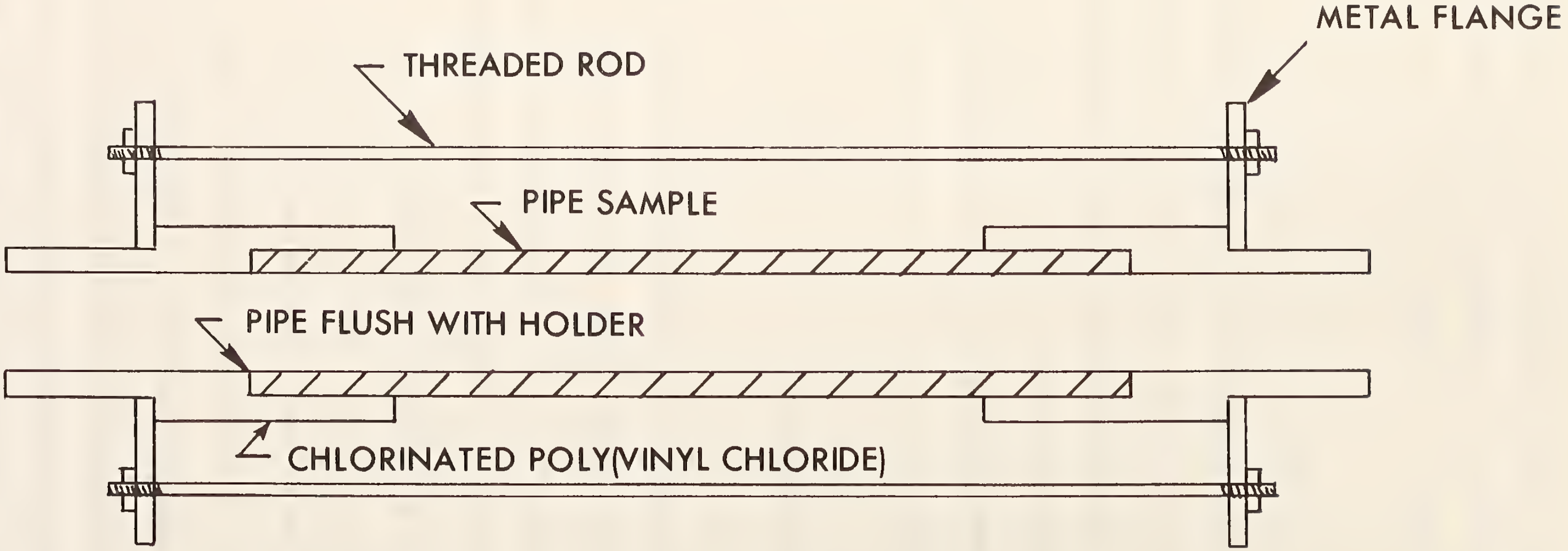


Figure 3. Connection System Developed to Prevent Crevice Corrosion

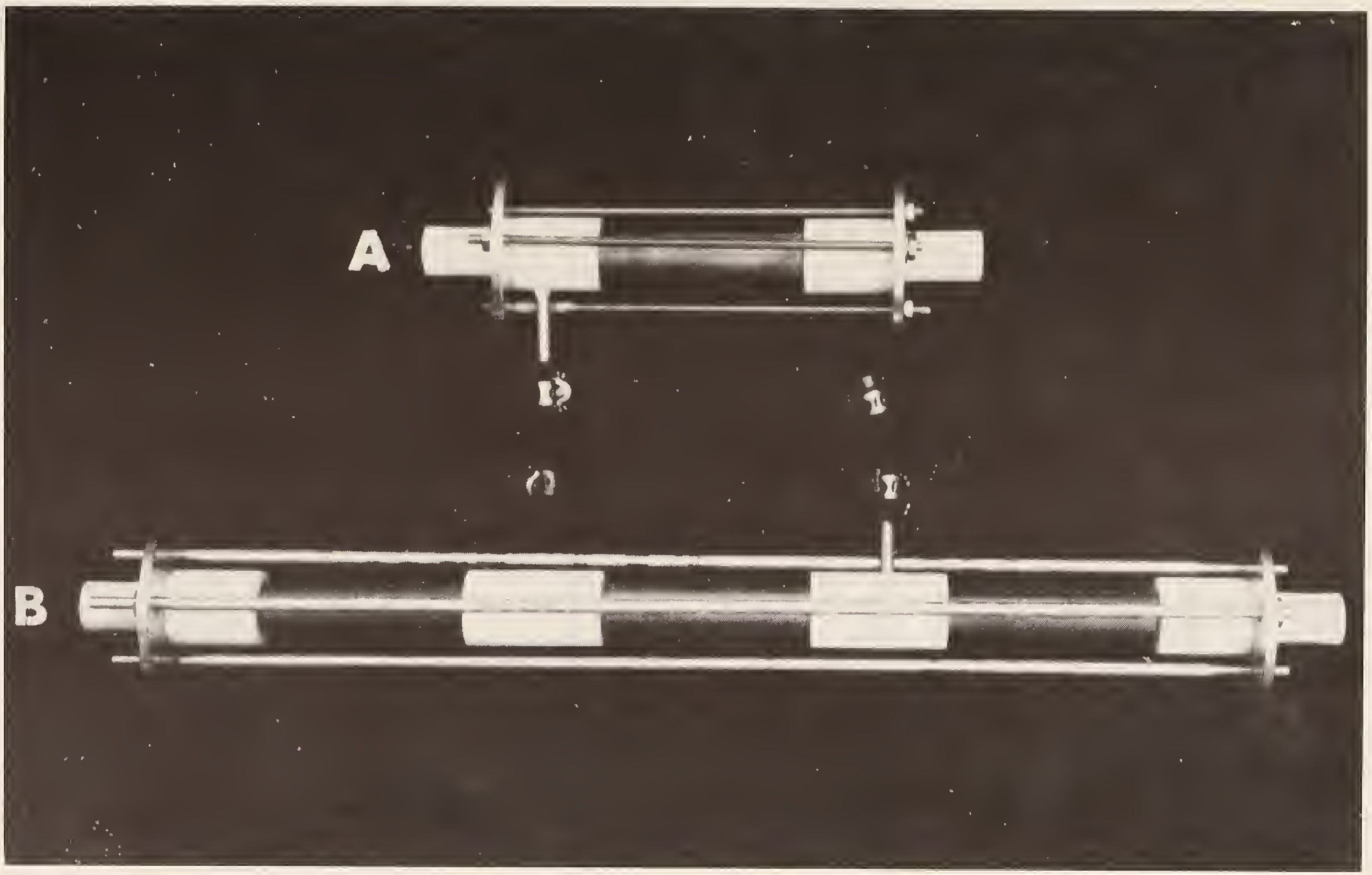


Figure 4. Pipe Specimen Holder Assemblies. A. Single Pipe Specimen. B. Three Pipe Specimens in Series Separated by Chlorinated Poly(Vinyl Chloride) Spacers.

present study). Considering the destructive character of the measurements and the necessity of using several samples for each measurement, the desirability of employing methods for the nondestructive, instantaneous measurements of the corrosion rate is understandable.

Several electrochemical techniques have been developed for nondestructive corrosion rate measurements. Of these methods, polarization resistance measurements [18, 19] appear to be most appropriate for measuring the corrosion of metallic pipe. It has been shown that under proper conditions the corrosion current, Ic, of a metal specimen in a solution is proportional to the applied voltage, ΔV, usually 10 millivolts. The formula is:

$$Ic = \frac{K}{RP} = \frac{K \Delta I}{\Delta V} \qquad (3)$$

where RP (polarization resistance) is the ratio $\Delta V / \Delta I$ and K is a constant whose value depends on the specific metal.

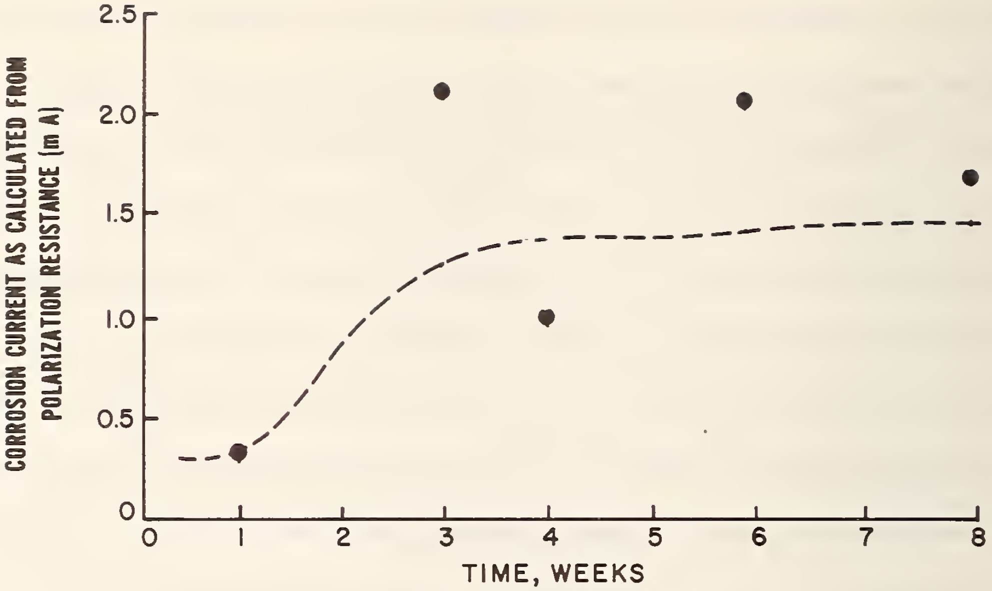
A value of 35 volts was used for K when calculating I_c for zinc, iron and copper. This value was obtained by assuming a Tafel slope of 60 mv/decade, two electron oxidation processes, and that the cathodic reaction is diffusion controlled [4]. As the polarization resistance method involves only small changes of electrical potential from the open circuit corrosion potential, the actual corrosion state of the sample should not be seriously altered by the measurement. Therefore, measurements can be taken on samples in situ as many times as desired. The polarization resistance method is sensitive to small changes in the corrosion condition of metals and when coupled with weight loss measurements to check its validity, it is a very useful tool.

Open circuit corrosion potentials and polarization resistance measurements were taken after 1, 2, 3, 4, 6 and 8 weeks of testing. At the end of the test period, the test specimens were visually inspected, weighed, then cleaned and reweighed, and finally the cleaned surfaces were inspected for evidence of pitting. The early polarization resistance studies indicated the necessity of taking additional measurements at 1, 3, and 10 days because it was found that corrosion rate changes rapidly during the first two weeks of the test. Actual measured curves are shown in Figure 5 illustrating different corrosion rate behaviors. These curves indicate the importance of commencing the taking of corrosion measurements at early test periods and also that the duration of the testing is very important. Our first results, and those of other laboratories [6], indicate that a minimum time is required before the corrosion rate is stable. It appears that a reasonable period for short-term experiments would be at least 2 months. Under some conditions, a sufficiently stable rate may be realized in less than 2 months, but such processes as the formation of a protective scale are usually slow and may not form within a short test period.

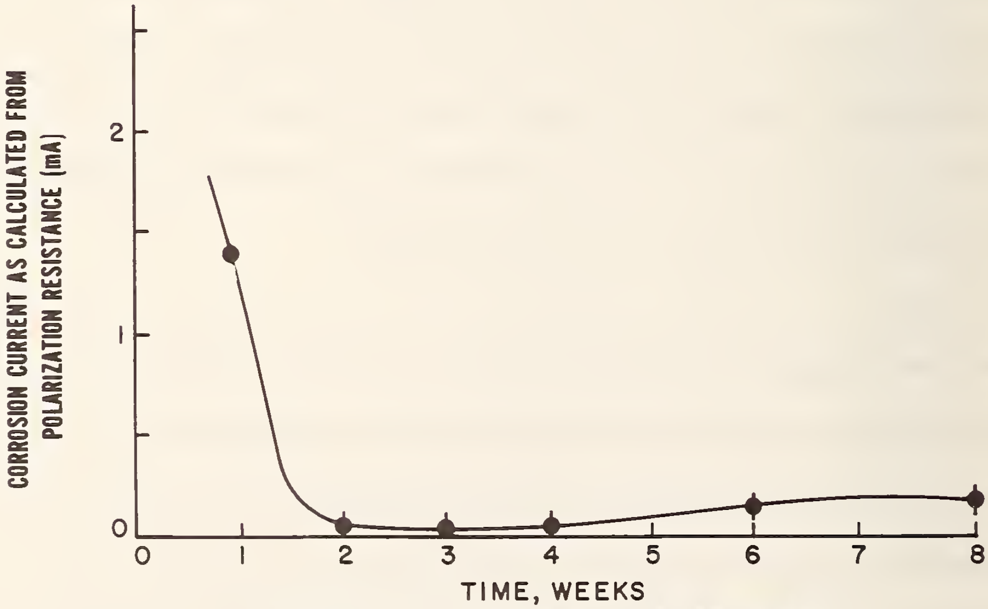
When investigating a specific problem, long-term testing is usually feasible, but in a systematic testing program a reasonably short period must be selected based on some understanding of the corrosion processes taking place.

3.1 Weight Loss Measurements

Test specimens were cleaned and then weighed before being placed in the pipe network. After the experiment was completed the samples were



GALVANIZED STEEL IN SYNTHETIC WATER 60°C
LOW FLOW CONDITION (few cm/s)



GALVANIZED STEEL IN SYNTHETIC WATER+SILICATES 60°C
HIGH FLOW CONDITION (2.5 m/s)

Figure 5. Different Corrosion Rate Behaviors Based on Actual Measurement. The Corrosion Rate Shown by Curve A was Initially Low then Rapidly Increased and did not Completely Stabilize even after 2 Months of Testing. The Initial High Corrosion Rate Shown by Curve B Rapidly Decreased then Gradually Increased.

cleaned again. The cleaning agent for copper was either concentrated hydrochloric acid or hydrofluoric acid. A preliminary test indicated that these cleaning agents did not produce any significant corrosion of copper (1 mg) when the immersion time was approximately 15 minutes. The cleaning of galvanized steel was accomplished with a saturated aqueous solution of ammonium acetate and a soft brush. A galvanized specimen lost up to 20 mg when subjected to the cleaning process for 15 minutes. Therefore, this cleaning method should be used only when, at least, medium corrosion rates are anticipated. It was suitable for our first experiment with galvanized steel, in which the measured weight losses were between 0.5 g and 2.5 g. Black steel test specimens were cleaned with Clarke solution (2 parts of Sb_2O_3, 5 parts of $SnCl_2$, and 100 parts of concentrated HCl, by weight). All the samples were dried with ethanol and weighed to within 0.5 mg.

3.2 Electrochemical Measurements

The circuit used for polarization resistance measurements is shown in the schematic of Figure 6. A saturated calomel electrode was used as the reference electrode and a stainless steel rod was the counter electrode. The geometry of the system used for making preliminary polarization resistance measurements with copper specimens is shown in Figure 7. Different results were obtained if made with counter electrode 1, counter electrode 2, or with sample 2 as the counter electrode (Figure 7A). There was more than a tenfold difference between the weight loss calculated from polarization resistance measurements and the actual measured weight losses. An investigation indicates that IR drop was influencing the polarization measurements.

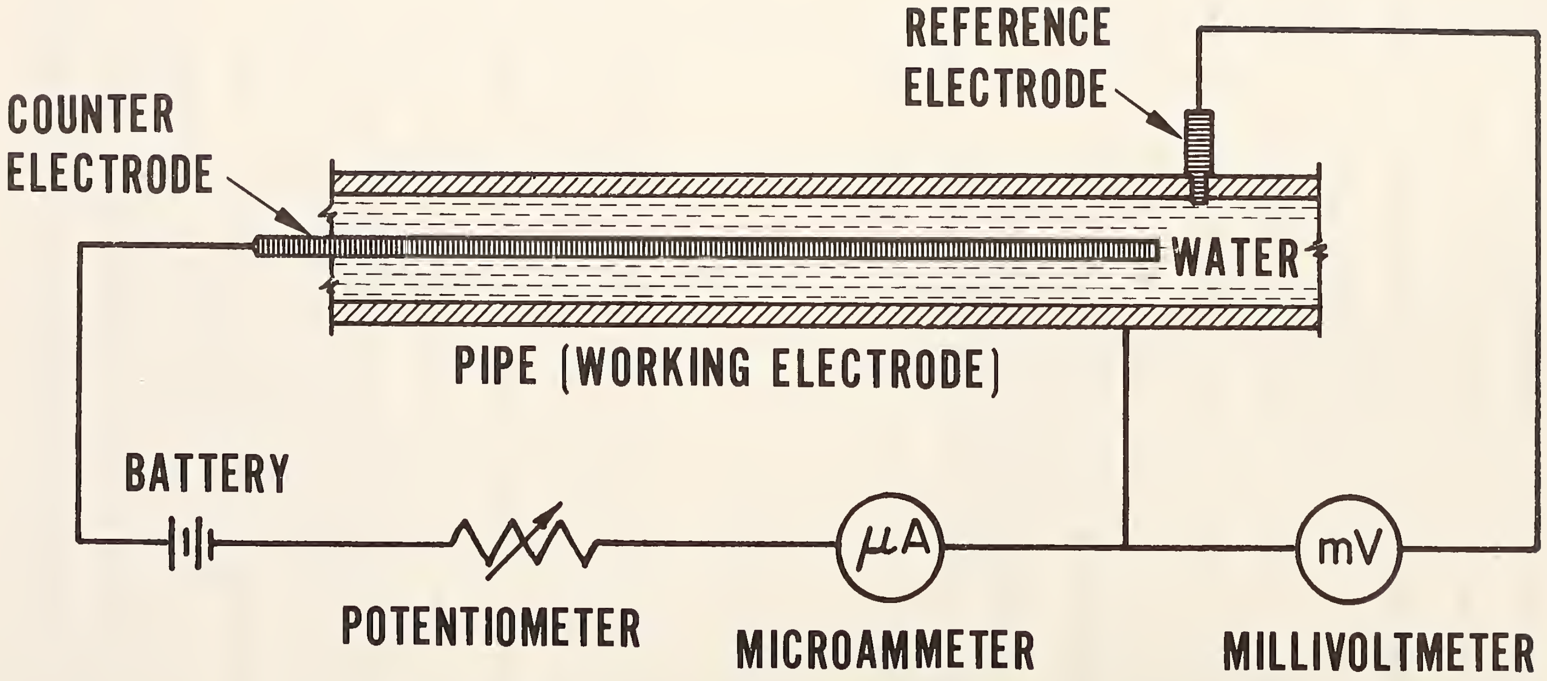


Figure 6. Schematic of Circuit for Making Polarization Resistance Measurements

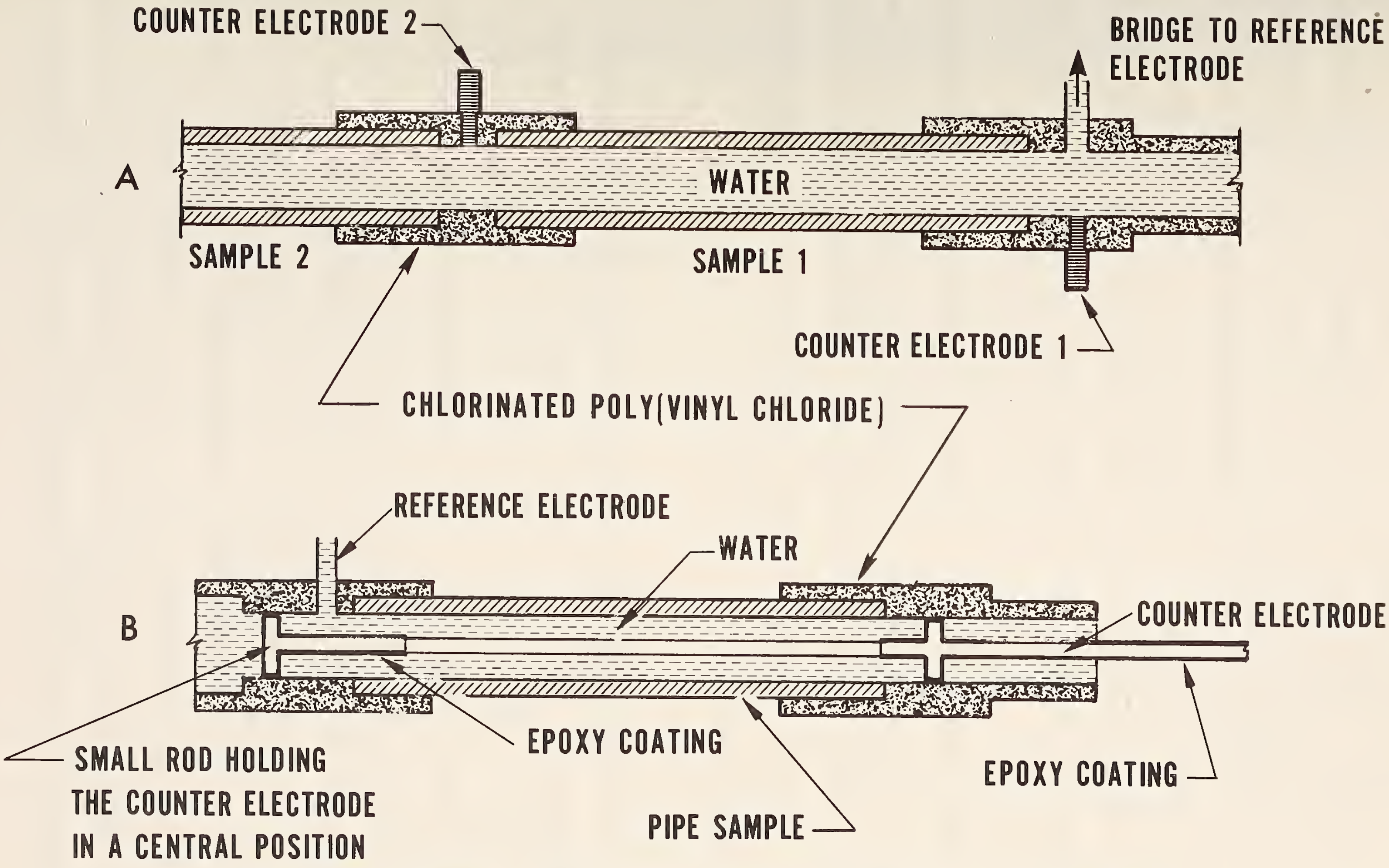


Figure 7. Schematic Indicating Location of Reference and Counter Electrodes. Position of Counter Electrodes in A gave Rise to High IR Drop. No Noticeable IR Drop was Detected with the Counter Electrode being Located as Shown in B.

Even with specimens as short as 10 cm, it appears that a homogeneous potential field was not induced by the applied current. In subsequent experiments, the system was modified. The counter electrode consisted of a cylindrical stainless steel rod, 3 mm diameter, placed along the axis of the specimen (Figure 7B). That portion of the counter electrode which extended beyond the specimen was covered with an epoxy coating. The reference electrode was positioned as near as possible to the edge of the sample. The calculated weight losses from polarization resistance measurement of galvanized steel and copper test specimens using this arrangement were within a factor of 2 of the measured weight losses (Table 1). These results are very encouraging considering the assumptions made in calculating weight losses based on polarization resistance measurements. It does appear, however, that a few weight loss measurements need to be made to calibrate the polarization resistance technique if it is to be used for quantitative measurements of the corrosion rate.

A few other difficulties were encountered during making the electrochemical measurements. One problem which is inherent in electrochemical measurements carried out in flowing hot water, is the instability of the open circuit corrosion potentials. Random fluctuations of sometimes more than 10 mV were observed. These fluctuations necessitated changing the electrical potential by more than 10 mV during polarization resistance measurements. This introduces an additional error in the determination of the corrosion current. When the open circuit potential was highly unstable, a potential change higher than the usual value of ±10 mV was imposed; however, the potential change was kept as low as possible so that the conditions for valid polarization resistance measurements could be met. Measurement of

TABLE 1. COMPARISON BETWEEN CALCULATED AND MEASURED WEIGHT LOSSES

	Composition of Test Water[1]	Flow Rates (m/s)	Weight Loss Determined by Weighing Samples (g)	Weight Loss Calculated from Resistance Polarization Measurements (g)
Galvanized steel	$CaCO_3$, 80 ppm $NaHCO_3$, 225 ppm NaCl, 60 ppm $MgSO_4 \cdot 7H_2O$, 20 ppm pH, 6.0	≈0.07	1.68	2.7
		0.46	0.46	0.3
		2.7	1.40	0.6
	10 ppm of sodium silicate added to above	≈0.07	0.86	0.9
		0.46	0.47	0.3
		2.7	1.1	0.9
Copper	CaCO3, 50 ppm $NaHCO_3$, 225 ppm NaCl, 50 ppm $MgSO_4 \cdot 7H_2O$, 128 ppm pH, 7.5	≈0.07	.119	.101
		0.37[2]	.106	.178
		1.5[2]	.140	.211
	10 ppm of sodium silicate added to above	≈0.07	.103	.124
		0.37	.100	.107
		1.5	.107	.114

[1] Experimental temperature was 60°C, pH measured at 23°C.

[2] Inside surface of copper pipe was scaled with a continuous carbonate film.

potential changes were made when the potential was sufficiently stable, generally 10 to 60 seconds after the current was applied.

4. SUMMARY AND CONCLUSIONS

The effects of the composition of water (characterized by pH, dissolved salts and dissolved gases), the flow rate of the water and a silicate inhibitor on the corrosion of galvanized and copper pipes have been investigated. The experimental test design and testing apparatus developed for this investigation provides a reasonable simulation of field conditions and contains considerable flexibility. The advantages of such laboratory testing are that selected variables can be studied in a relatively short test period and at modest cost. Certainly field use is the ultimate test; however, laboratory data are needed to develop performance criteria to form the basis of selecting durable materials for field use.

The polarization resistance technique gave satisfactory results in this preliminary study of the corrosion of metallic pipes transporting water. Furthermore, it appears that the polarization resistance technique is a useful tool which may be used in a variety of corrosion studies on pipe carried out in aqueous media [20, 21]. However, the results from polarization resistance measurements should be correlated with results from actual weight loss measurements and with visual inspection of test specimens for the detection of localized corrosion, especially pitting.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Many factors affect both the form of and the corrosion of pipes transporting potable water including the composition, temperature and flow rate of the water, type of metal and the physical condition of the pipe. A pipeline was constructed and experimental methods developed to determine the effects of the above factors on the corrosion of pipes. Components of the pipeline were carefully selected or designed to prevent the occurrence of extraneous corrosion.

The rate of corrosion of galvanized steel and copper pipes were measured by direct weight losses measurements and by polarization resistance methods. It appears that the polarization resistance technique is a useful tool which may be used in a variety of corrosion studies of pipe in aqueous media.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Copper pipe; corrosion; corrosion measurement; galvanized steel pipe; metal pipes; potable water; resistance polarization.

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