A Survey of Acidity in Drainage Waters and the Condition of Highway Drainage Installations

James H. Havens
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TO:  D. V. Terrell  
Director of Research  

Two years ago when we completed the presentation of our first progress report on a survey of acid water and drainage installations, the Research Committee asked that the work be extended throughout the state. That has been done, and in addition a special test installation of pipe in highly acid water has been an added feature of the project during the past 20 months.

In total, approximately 16,900 culverts on about 3,520 miles of road were investigated, and over 350 field acidity measurements were made. With these studies and the information produced thus far by the test installation as a basis, J. H. Havens, Research Chemist, has prepared the attached report. Included with the data from our work is very valuable information about studies conducted in other states over the past 25 years (See page 37), and also some material pertaining to corrosion in general as well as to corrosion in its relation to physiographic features of Kentucky.

As a result of all this evidence, some very definite conclusions have been drawn. These are enumerated, beginning on page 7 of the report. In essence, there is only one type of material (vitrified clay) now used in drainage pipe which is known to be absolutely resistant to acid corrosion. Other pipe at the test installation may be resistant enough to assure long life, but that cannot be shown one way or another in an accelerated test.

Corrugated metal pipe is worthless in the presence of acids, and concrete pipe is so severely affected by concentrated acids that it should be considered dependable for only 5 or 10 years under those conditions. The situation is uncertain with respect to bituminous coated metal pipe, but there is no doubt that the pipe is acid resistant as long as the coating remains intact.
Inasmuch as uncoated corrugated metal often corrodes even when it is not in the presence of acid, this type of material should not be used for installations that are considered permanent. Thus, the general policy of the past by which corrugated metal has been avoided in cross drains was a wise one. Performance of concrete pipe warrants the confidence it has been given for the past several years as a permanent installation in all but very acid locations. All the evidence indicates that bituminous-coated or coated-and-paved metal pipe is at least as dependable as concrete in all situations - and possibly more dependable in acid locations. At any rate, in my opinion, the Department would be justified in considering bituminous-coated metal pipe and concrete pipe equally desirable for drainage installations of all types.

With regard to the so-called asbestos-bonded metal pipe, our experience is too limited and the results from other investigations that we were able to collect are not sufficient to warrant a recommendation at present. Attention is called, however, to the statement on page 48 of this report which was taken from a Bureau of Public Roads report dealing with the Blue Ridge Parkway in Virginia. That was the only direct reference from another highway organization that developed from our studies of similar work elsewhere.

Unless there is some reason to do otherwise, we will consider this the final report on our general acid water study. We will, of course, continue inspections of the test installation at Morton's Gap and make occasional reports on its progress.

Respectfully submitted,

L. E. Gregg
Assistant Director of Research

LEG: ddc
Attached
Copies to: Research Committee Members
Mack Galbreath (3)
Commonwealth of Kentucky
Department of Highways

Progress Report No. 2

on

A SURVEY OF ACIDITY IN DRAINAGE WATERS AND THE CONDITION
OF HIGHWAY DRAINAGE INSTALLATIONS

by

James H. Havens
Research Chemist

Highway Materials Research Laboratory
Lexington, Kentucky

December, 1952
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During the summer of 1949, approximately one year after installation, serious corrosion failures were discovered in a series of galvanized metal entrance culverts on U.S. 60 south of Ashland near Princess. Because of a unique disparity in their performance at this location, the problem was referred to the Research Division for possible explanation. An impromptu investigation ensued, and the cause of the failure was attributed directly to acid drainage water flowing from extensive strip-mining operations within the immediate area. A report (1) describing the attendant conditions was made to the Research Committee in December of that year.

As an outgrowth of those findings and as a precaution against future recurrences, the Committee directed that a state-wide survey be made to determine whether drainage of this type would constitute a real problem in other parts of the state; and if so, to determine whether these corrosive conditions would be naturally restricted to particular areas within which it would be advantageous to require the use of acid resistant materials. Both of these provisions, of course, were somewhat contingent upon an inventory appraisal of in-service culverts and of necessity both phases would have to be conducted concurrently.

Areal Differentiation

Quite logically, attention was first directed toward those areas in the state offering the greatest potential capacity for the production of corrosive acids and salts by dissolution of mineral matter occurring in the soils and underlying deposits. Those areas, of course, were well delineated geologically, but they are more familiarly known as the Eastern Coal Field.

* Numbers refer to References at the back of this report.
and the Western Coal Field. Stratigraphically these two areas are characterized by sandstone deposits inter-bedded with coal and shale seams, both of which usually contain sulfurous materials capable of being converted by water and atmospheric oxidation into highly corrosive acids and salts.

In contrast, the central areas familiarly known as the Bluegrass and Pennyroyal are characterized by great limestone deposits which are practically free of those severely corrosive agents. Most of the drainage is internal as evidenced by numerous sink-holes and caves. Portions of both limestone areas, however, are overlain by impervious shales which confuse this otherwise clearly defined pattern. The western extremity of the State, known as the Purchase Area, is characterized by washed alluvial sands, silts, and clays deposited as a result of the great Mississippi River embayment and by silty materials originating through wind action. The composition of these deposits indicate that they should be free of highly soluble or severely corrosive mineral matter.

Even in the absence of actual field tests, this general knowledge of physiographic features and mineralogical composition offered a general criteria from which to adjudge the corrosivity of water in the principal areas of the state. To a large extent, the results of the field survey simply provided factual confirmation of these guiding generalities.

**Initial Phase**

The first phase of the survey demonstrated a random but frequent occurrence of critically corrosive waters within the Eastern and Western Coal Fields. It also demonstrated that water in those areas should be con-
sidered corrosive to galvanized metal, whereas only 0.2 percent of the concrete pipe of all ages had been noticeably affected despite the severity of conditions. None of the concrete pipe showed complete disintegration of the invert, but this condition was frequently observed in galvanized metal culverts.

An attempt was made to compile comparative performance records through these inspections of culverts in service, and from the records make a statistical evaluation of culvert materials for suitability under various service conditions. However, factors limiting the distribution of age groups and the variations in types of pipe used for cross drains made this objective impractical.

For example, the records showed that the vast majority of grade-and-drain projects on principal highways fell within the period 1928 to 1934. Also, there were very few galvanized metal cross drains installed on roads receiving Federal Aid in the period since 1928 or 1929. By the end of 1950, over 13,000 culverts had been examined and of those only 1155 were galvanized metal. Of the 1155 metal culverts that were found, only 296 were cross drains. The remaining 859 were entrance pipes which, because of uncertain influences - such as replacement in intervening years, lack of records on installation, exceptionally rigorous treatment causing structural failure, and similar things - were not reliable for a statistical analysis.

Hence, from the standpoint of evaluation of material performance, service records for galvanized metal pipe were extremely limited, while those for concrete pipe were abundant. That being the case, there was no basis
for comparison of different materials under in-service conditions at the
time surveys were completed in the coal fields late in 1950.

All of the data accumulated from this initial work was assembled
into a progress report (2) and distributed to members of the Research Com-
mittee in December, 1950. Prior to that report, but in conjunction with
data collected for it, the Department adopted a policy prohibiting the use
of uncoated galvanized metal pipe in 19 coal-producing counties for con-
struction being administered under the Rural Secondary program. This action,
of course, established a uniform practice with respect to cross drains for
those areas, but left the remaining areas in the state without factual
support for any action. The committee re-affirmed the directive that the
survey continue to completion.

Second Phase

Emphasis in the second phase was shifted not only to other parts
of the state but also to some other features of evaluation. Direct com-
parison of materials was relegated to a controlled test installation even
though acidity measurements and material performance studies were continued
and all types of pipe inspected. Among other things, entrance pipe were
eliminated from consideration entirely, particular attention was given to
selection of roads graded 23 or more years ago (in order to increase the
number of metal pipe represented in the data), and an arbitrary system for
rating metal pipe (comparable with but not the same as some used elsewhere)
was initiated. The last of these was adopted more as a means for correlation
with other studies rather than as an expression of confidence in any system for arbitrarily establishing a life expectancy.

For comparative evaluation of acid resistance, a site at Mortons Gap on U.S. 41 in Hopkins County was selected. This location afforded a continuous supply of highly acid mine drainage passing through the test insulation. Duplicate sections of each material were placed in a shallow ditch so that periodic inspections could be made.

At the end of the first month the invert of the galvanized metal was perforated, and at the end of the second month it was completely eaten away. After 18 months — or at the time of the inspection in October, 1952 — the concrete sections showed extensive etching of mortar about the coarse aggregate but no loss of the aggregate. Bituminous-coated and asbestos-bonded metal sections showed loss of metal only where the protective coatings were scarred during placement; otherwise, they were not noticeably affected. Vitrified clay, as expected, remained virtually unaffected.

In this phase, material performance surveys covered the Bluegrass area and the Pennyroyal, both of which — as borne out by actual tests on drainage waters — were completely free of severely corrosive agents.* In these areas, more so than in the eastern and western portions of the state, it was possible to obtain long-time performance records under fairly uniform service conditions. Also, it was possible to estimate a percentage deterioration for the metal pipe. This percentage divided by the age of the installation

* It should be borne in mind that nothing subjected to the so-called "elements" is ever completely free of corrosion. The terminologies and references above simply imply a relatively insignificant degree of corrosive action.
yielded an approximation of the annual rate of deterioration and, consequently, an estimate of the ultimate life-expectancy in years for each metal culvert examined.

In all, 714 galvanized metal cross drains averaging 30.9 years in age averaged 47 percent deterioration. About 14 percent of these should be replaced. In these same areas 2,134 concrete, 586 vitrified clay, and 25 cast iron culverts averaging approximately 25 years in age were inspected, and in no case was there any evidence of corrosive deterioration. The life-expectancy for galvanized metal within these areas varied from just a few years to more than 100 years depending on whether the culvert carried water continuously, intermittently, or not at all.

Some roads such as U.S. 68 between Harrodsburg and Brooklyn Bridge follow along high elevations or ridges so that many of the culverts drain water originating within or immediately adjacent to the right-of-way. Rarely does the rainfall intensity cause water to rise to the threshold of the culvert. For culverts in these so-called "high places" life expectancies exceeded 100 years. In the "low places" subject to dampness and seepage or frequent wetting and drying, the expected life of many culverts fell under 20 years.

On a state-wide basis, without regard to area or location, it may be surmised that the life expectancy of uncoated galvanized metal may vary from 1 month to over a 100 years. On the same basis and charging 10 percent or even 20 percent deterioration to all concrete culverts even where no deterioration was perceptable, the life expectancy of that material projects well beyond the realm of realistic conception.
It should be recognized that data of this kind are contingent upon the judgement of the observer as well as on many indefinable complexities of nature. In any case, an attempt was made to furnish some degree of insight into the problem of culvert material evaluations. The life expectancy approach could be misleading if only average values were considered. If a material has an average life of 50 years in a particular area and in 80% of the cases its individual ratings exceed 60 years, the individual ratings for the remaining 20% would have to be as low as 10 years. From this standpoint, the value of the material would have to be judged on the basis of replacement risks; and it seems unlikely that any rational economic program could be resolved for any material overshadowed by the possibility of replacement within the anticipated life of the roadway it serves.

Conclusions

On the basis of data which have been accumulated through the test installation and surveys conducted since 1949, the following conclusions have been drawn:

1. Sulfur-bearing natural deposits such as shales and coals are the foremost, if not the only, sources of severely corrosive drainage waters of any consequence in the state.

2. Drainage waters within the coal fields vary from mild to extreme acidity, but the vast majority of waters carried by highway culverts are only mildly acid or not acid at all.

3. The acid potential is greatest in the Western Coal Field because of its predominately high-sulfur coal and vast areas wasted by stripping.
4. Severely acid drainage waters occur only within the Coal Fields, but mild acidity may occur at shale outcappings within the Knobs or along deeply entrenched stream valleys in the Pennyroyal.

5. Within potentially acid areas, concentrations of the acids are highest at the source but usually become diluted by other tributary water within a short distance downstream. Drainage structures contacting these waters near the sources are vulnerable to damage unless corrosion-resistant materials are used.

6. Uncoated galvanized metal pipe has no resistance to corrosion by acid waters and is vulnerable to corrosive deterioration even under mild conditions. Deterioration occurs through exposure to dampness and moderate flow — whether intermittent or continuous. Under non-acid conditions, the life expectancy may range from 10 to 100 years depending upon the exposure. Because of those characteristics, metal pipe should be regarded as:

1. Of no value where there is acid water

2. Unsuitable for use in non-acid water where flow is at least moderate and where the installation is designed for long life.

3. Suitable for use in non-acid water where the installation is designed for limited life or where ease of replacement justifies the risk of early failure.

7. Concrete pipe is resistant to corrosion except under conditions of extreme acidity. In the presence of highly acid waters the anticipated service period should be in the range of 5 to 15 years. Under
conditions other than these concrete pipe is suitable in any installation
designed for permanent use.

8. Bituminous-coated metal pipe is resistant to acid corrosion
as long as the coating insulates the metal from contact with acids.
Limited examples in the field surveys and limited time of exposure in the
test installations do not provide a basis for estimating life expectancy.
On the basis of information available from other sources, a bituminous
coating properly applied should have an anticipated service period of at
least 15 years. The service life of coated pipe in acid waters should be
comparable with the life of the coating, and in non-acid waters the service
life should range upward from 15 years depending on the conditions at the
site.

9. Vitrified clay pipe is the only culvert material now in use
that is totally inert to corrosion by even the most severe drainage waters.
Aside from normal use as an independent drainage structure, its use as a
lining material for concrete affords promising possibilities where con­
ditions of high acidity are known to exist.

10. From the standpoint of overall conditions influencing culvert
performance, silting was the major cause of improper function. Structural
failures in cross-drains were of negligible importance, but in entrance
pipe they were more widespread. This was due primarily to the conditions
under which the pipe were installed.
FIELD SURVEYS

Field itineraries were planned in such a way as to give maximum areal coverage of the primary road system. The survey of each road consisted of a cursory inspection of each accessible culvert, and conductivity tests on drainage waters at selected locations. Often the condition of the culvert or some feature of the surrounding area guided the selection of water samples. In numerous cases water was not available for sampling, and in other cases, a single sample was considered sufficient to describe the conditions prevailing within the area. Within the coal regions, the tell-tale features attendant to severely corrosive conditions were easily recognized. An attempt was made to sample all such locations encountered. The water survey was also influenced by weather conditions to the extent that natural ground waters were often exhausted by prolonged dry weather or natural drainage was diluted by recent rains.

Originally, it was intended to spot all the locations of severe acidity on detailed county maps, but the idea was later rejected because of their random occurrence and because it was foreseen that future mine-openings or roadway cuts could produce additional sources and invalidate the record. Instead, sample locations were simply recorded by speedometer readings and type of drainage, whether mine water or residual surface water. The degrees of acidity were so variable that data from even the most detailed sampling could only serve to indicate in a general way whether or not corrosive conditions would be encountered on future construction within the area.
In conjunction with the water survey covering the two Coal Fields and the Purchase Area (made in 1950), a record of culvert conditions was believed to be of great value not only from the standpoint of assessing the extent of damage caused from corrosive drainage waters but also from the standpoint of a comparative assessment of damage from other causes. For this record, each culvert examined was identified by type and assigned to one of the five condition categories listed below:

Excellent - No deterioration, cracking or structural defects; no stoppage of any sort; and seemed to be functioning properly.

Silting - Structurally sound, but the passage of water impeded by residual deposits of silt, sand, gravel, rock or organic matter.

Caving In - Any portion of the culvert broken or bent to the extent that the flow of water was impeded.

Undermined - Water flowing other than through the culvert due to faulted sections or seepage channels.

Miscellaneous - Etching, or corrosion, and abrasion.

A statistical summary of these data is included elsewhere in this report. (See section on Results).

In conjunction with the water survey covering the Bluegrass and the Pennyroyal (made in 1952 - a particularly dry season), a percentage material deterioration was estimated for each culvert examined. Since conditions were expected to be more uniform in these areas, it was thought that such data on even a limited number of each type of culvert of known
age would furnish valuable information on the average and minimum life-expectancies of each type. Although various rating systems had been developed for each type of material in similar investigation elsewhere, it was decided that a simple visual rating ranging from 0 to 100 percent would afford more comparable and usable data. A depreciation of 10 percent was categorically charged to all culverts even when no deterioration was visible. Since none of the concrete, vitrified clay, or cast iron pipe encountered in the Bluegrass and Pennyroyal region ever showed any visible deterioration, the problem of judging degrees or stages of deterioration was limited entirely to corrugated metal. Very generally, depreciation was charged to those in the following manner:

<table>
<thead>
<tr>
<th>Deterioration Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Spelter in good condition, no visible evidence of deterioration.</td>
</tr>
<tr>
<td>25</td>
<td>Rust stains showing through spelter.</td>
</tr>
<tr>
<td>40</td>
<td>Spelter gone, or slight rust scale in invert.</td>
</tr>
<tr>
<td>60</td>
<td>Heavy rust scale in invert.</td>
</tr>
<tr>
<td>80</td>
<td>Invert perforated.</td>
</tr>
<tr>
<td>100</td>
<td>Invert completely corroded away.</td>
</tr>
</tbody>
</table>

Acidity Measurements

Acidity determinations were made by the electrical conductivity method generally used in "water purity meters." This method was favored over the more conventional pH determinations because it is more indicative of the combined salt and acid impurities or total electrolyte content.
Whereas pH simply represents the log \(1/\text{H}^+\) concentration, total electrolyte content was believed to be more indicative of the corrosivity of the water. Perhaps these essential differences could best be clarified by describing the basic principles of the conductivity method.

**Note:** pH is a logarithmic expression of the reciprocal of the hydrogen ion concentration in gram-moles per liter. At a pH-7, neutrality the hydrogen ion concentration is \(1 \times 10^{-7}\), gram-moles. Thus, a pH-6 is 10 times more acid than pH-7, and pH-1 is 1,000,000 times more acid than pH-7.

Electrical conductance is a measure of the ease with which current may flow through a particular medium. It is also the counter-part of electrical resistance which is described by Ohm's Law as \(R = E/I\). If two parallel, non-polarizing electrodes were constructed to embrace exactly a 1 centimeter cube of an aqueous solution between them, it would be possible to measure the specific resistance of the solution. It might be imagined that the ease with which the current flows would depend upon the number of current-carrying ions present in the solution. Actually, that is the case. Mathematically the relation may be expressed as:

\[
\text{Conductance (ions)} = \text{Conductance (solution)} - \text{Conductance (water)}
\]

Since distilled water may exhibit a specific resistance of 300,000 ohms, then the conductance of water in the equation above is equal to \(1/300,000\) which is an insignificantly small value. Neglecting the water, the equation then attributes all conductance of the solution to the ions.
The ultimate objective of the conductivity measurement is to relate measured specific resistances to the concentration of the ions. To accomplish this, it must be imagined that specific resistance (resistance per cm$^2$) x 1000 would give the resistance of 1000 cc. of the solution. This resistance divided by concentration, C (expressed in gram-equivalents per liter), would give the resistance of a volume of the solution necessary to contain exactly a 1 gram-equivalent of the ions. The reciprocal of this value would then have the dimensions of equivalent conductance. Knowing equivalent conductance values for specific solutes, or by assuming an average value for all solutes likely to be present (approximately 400 for strong acids and 100 for inorganic salts), concentration may be calculated from:

$$C = \frac{1000 \times \frac{1}{R} \times K}{A}$$

where:
- $C$ = concentration in gram-equivalent weights per liter
- $R$ = measured resistance in ohms
- $A$ = equivalent conductance
- $K$ = cell calibration factors (1.17)

Typical equivalent conductance values usable for determining "A" for the above equation are listed in Table 1.

Ordinary "water purity meters" are based upon an average equivalent conductance for some salt such as sodium or calcium chloride, and usually they have a dial calibrated to read directly the total amount of impurities expressed as parts per million of that salt.
The instrument used in the study was a Conductivity Bridge, Model RC-16, with a platinized dip-type electrode assembly manufactured by Industrial Instruments, Inc. A picture of the equipment is shown in Fig. 1. During the survey, measured resistance values were taken as such without attempting to translate them into absolute concentrations. Frequently, it was necessary to screen a large number of samples, and unless the measured resistance was less than 2000 or 3000 ohms, the sample was classified as non-critical. Samples testing less than 2000 ohms were reserved for spot-tests for calcium, iron, magnesium, sulfates, and chlorides. In particularly interesting cases, total acidity was determined by titration using phenolphthalein indicator. Total acidity was then translated into pH values. Some pH measurements were made using pH indicating paper (pHhydrion paper manufactured by Micro Essential Laboratory, Brooklyn, New York). Both methods gave pH values of the same order of magnitude, but the paper usually gave a slightly higher value.

Hindsight, of course, is always better than foresight; but as a result of the experience gained in this survey, it is believed that a more fundamental approach to the evaluation of drainage waters could be developed on the basis of combined pH measurements and conductivity measurements. A discussion of these possibilities is presented as being of collateral interest from the standpoint of interpretation of conductivity data.

If it is assumed that all the impurity in the water is there as sulfuric acid or if it were desirable to express the combined impurities as being equivalent to concentrations of sulfuric acid having equal resistance,
then concentration of the acid could be expressed in terms of pH and related directly to measured resistance. Such a relationship is given graphically in Fig. 2. The assumption that all the impurity is acid is, of course, invalid if qualitative tests show the presence of ions such as iron, calcium, or magnesium. Also, the assumption would be altogether misleading when testing drainage waters such as those in the Bluegrass which contain calcium carbonate as the principle impurity. A relationship of the type shown in Fig. 2 does have some advantages, however, and they may be illustrated by the following example:

Suppose that a sample of water has a measured resistance of 250 ohms. Then according to Fig. 2, it should have a pH of 2. But a direct pH measurement using a pH meter or pH indicating paper showed an actual pH of 4. The difference could only be accounted for by the amount of salts present. For a pH-4 the corresponding resistance should have been 28,000 ohms. The difference may be described by the following approximate equation:

\[
\text{Conductance (Salts)} = \text{Conductance (Solution)} - \text{Conductance (Acids)}
\]

Or, since conductance \(= \frac{1}{R}\)

\[
\text{Conductance (Salts)} = \frac{1}{250} - \frac{1}{28,000}
\]

Substituting this value for \(\frac{1}{R}\) in the equation:

\[
C = \frac{1000 \times \frac{1}{R} \times K}{A}
\]

and assuming 100 to be an average value for A, the salt concentration may be calculated within an accuracy of about 90 percent.
<table>
<thead>
<tr>
<th>Solute</th>
<th>Equivalent Conductance at 18° C</th>
<th>Milli Formula Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>1/2 MgSO₄</td>
<td>109.6</td>
<td>107.6</td>
</tr>
<tr>
<td>1/2 CaSO₄</td>
<td>115.5</td>
<td>114.0</td>
</tr>
<tr>
<td>1/2 Na₂SO₄</td>
<td>109.7</td>
<td>108.8</td>
</tr>
<tr>
<td>1/2 K₂SO₄</td>
<td>130.5</td>
<td>129.8</td>
</tr>
<tr>
<td>1/2 (NH₄)₂SO₄</td>
<td>130.5</td>
<td>129.8</td>
</tr>
<tr>
<td>1/2 ZnSO₄</td>
<td>109.6</td>
<td>107.6</td>
</tr>
<tr>
<td>1/2 CaCl₂</td>
<td>115.1</td>
<td>114.3</td>
</tr>
<tr>
<td>NaCl</td>
<td>107.8</td>
<td>107.6</td>
</tr>
<tr>
<td>KCl</td>
<td>128.8</td>
<td>128.6</td>
</tr>
<tr>
<td>NH₄Cl</td>
<td>129.3</td>
<td>128.9</td>
</tr>
<tr>
<td>HCl</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1/2 H₂SO₄</td>
<td>-</td>
<td>374.4</td>
</tr>
<tr>
<td>H₃PO₄</td>
<td>-</td>
<td>330.4</td>
</tr>
<tr>
<td>HNO₃</td>
<td>-</td>
<td>330.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solute</th>
<th>Equivalent Conductance at 25° C</th>
<th>Milli Formula Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>124.6</td>
<td>124.2</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>-</td>
<td>117.9</td>
</tr>
<tr>
<td>H₃PO₄</td>
<td>-</td>
<td>366.8</td>
</tr>
<tr>
<td>HNO₃</td>
<td>-</td>
<td>416.2</td>
</tr>
<tr>
<td>1/2 Ca(HCO₃)₂</td>
<td>109.5</td>
<td>106.3</td>
</tr>
<tr>
<td>NH₄HCO₃</td>
<td>-</td>
<td>91.4</td>
</tr>
<tr>
<td>NH₄H SO₄</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 1 - Conductivity Bridge, Dip-Type Electrodes, and Set of Qualitative Reagents. Burette at center was used for total acidity determinations.
Fig. 2 - Theoretical Relationship between pH of Sulfuric Acid Solutions And Their Electrical Resistivity.
1950 Survey (Eastern and Western Coal Fields)

The 1950 condition survey covered 52 counties and 2,376 miles of road in eastern and western Kentucky. A total of 13,161 culverts and entrance pipe were examined and rated according to five condition categories. A limited statistical summary of the results is presented in Table 2. This summary was made without regard to age of the culverts or service conditions. However, since the majority of the installations were located within the Coal Fields, the results are typical of conditions prevailing there. Also, since the dates of installation for most of the roads are shown on the map at the back of this report, certain inferences as to the material value of each type of culvert may be deduced. Aside from that, other conditions influencing performances are in evidence.

All these may best be judged from the following interpretations and general results in each category:

**Excellent** - As a general average, 82.3 percent of all cross drains and 58.8 percent of all entrance pipe are giving excellent performance. Exclusive of silting, a factor somewhat extraneous to the permanence of the installations, 99.1 percent of the cross drains and 88.7 percent of the entrance pipe are in excellent condition materially and structurally.

**Silting** - This was the major cause of imperfect performance. An average of 16.8 percent of the cross drains and 29.9 percent of the entrance pipe were affected. Actually, these figures are probably too severe since the extent of the condition ranged from moderate impediment to complete obstruction of the culvert.
Silting and the circumstances causing it are admittedly somewhat outside the scope of this study. It is, most certainly, related to erosional features of the soil, particularly where erosion control is not practicable for some reason. Certain construction or design features may be accountable in many cases. Cleaning a silted culvert will, of course, restore its proper function; but it does not necessarily promise permanent protection.

Caved In - Structural failures in cross drains were not only rare but of negligible importance. With entrance pipe there were obvious reasons for a much higher casualty rate. Either the ends had not been protected by headwalls or there was insufficient cover material to afford adequate protection. In many of these cases the cost of a more permanent installation may not even be justifiable. Although the results from this survey show only about 10 percent failures for entrance pipe, there was no way to determine how many installations had preceded the ones surveyed.

Undermining - This condition was even less prevalent than caving-in, and certainly could not be considered of any consequence in the overall performance of the culverts surveyed.

Miscellaneous - This category consisted almost entirely of instances of corrosive deterioration. About 20 percent of the corrugated metal cross drains were affected by corrosion. For all cross drains taken collectively, this type of damage did not exceed 1 percent. In view of evidence accumulated from the test installation and elsewhere, it may be surmised that by judiciously limiting the use of plain galvanized metal pipe in the Coal Fields widespread damage to highway drainage facilities has been avoided.
Table 2 - Summary of Results From 1950 Survey.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Drain</td>
<td>Concrete Pipe</td>
<td>6,203</td>
<td>4,676</td>
<td>75.4</td>
<td>1,506</td>
<td>24.3</td>
<td>8</td>
<td>0.13</td>
<td>1</td>
<td>0.02</td>
<td>12</td>
<td>0.20</td>
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<tr>
<td></td>
<td>Concrete Box</td>
<td>3,782</td>
<td>3,640</td>
<td>96.2</td>
<td>127</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Concrete Slab</td>
<td>120</td>
<td>116</td>
<td>96.7</td>
<td>4</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>Stone Slab</td>
<td>108</td>
<td>95</td>
<td>86.0</td>
<td>13</td>
<td>12.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Corrugated Metal</td>
<td>296</td>
<td>183</td>
<td>61.8</td>
<td>145</td>
<td>45.2</td>
<td>8</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>20.3</td>
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<tr>
<td></td>
<td>Vitrified Clay</td>
<td>1,123</td>
<td>858</td>
<td>76.4</td>
<td>256</td>
<td>22.3</td>
<td>9</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Wood &amp; Cast Iron</td>
<td>6</td>
<td>6</td>
<td>100.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Total</td>
<td>11,638</td>
<td>9,574</td>
<td>82.3</td>
<td>1,951</td>
<td>16.8</td>
<td>25</td>
<td>0.2</td>
<td>12</td>
<td>0.1</td>
<td>76</td>
<td>0.65</td>
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<tr>
<td>Entrance Pipe</td>
<td>Concrete Pipe</td>
<td>524</td>
<td>366</td>
<td>69.8</td>
<td>131</td>
<td>25.0</td>
<td>14</td>
<td>2.7</td>
<td>1</td>
<td>0.2</td>
<td>12</td>
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<td>20</td>
<td>16</td>
<td>80.0</td>
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<td>20.0</td>
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<tr>
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<td>Concrete Slab</td>
<td>1</td>
<td>1</td>
<td>100.0</td>
<td>-</td>
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<td>50.0</td>
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<td>50.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Corrugated Metal</td>
<td>859</td>
<td>439</td>
<td>51.1</td>
<td>282</td>
<td>32.8</td>
<td>123</td>
<td>14.3</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>1.8</td>
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<tr>
<td></td>
<td>Vitrified Clay</td>
<td>106</td>
<td>68</td>
<td>64.2</td>
<td>33</td>
<td>31.1</td>
<td>5</td>
<td>4.7</td>
<td>-</td>
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<td></td>
<td>Wood &amp; Cast Iron</td>
<td>9</td>
<td>4</td>
<td>-</td>
<td>3</td>
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<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Total</td>
<td>1,523</td>
<td>896</td>
<td>58.8</td>
<td>155</td>
<td>29.9</td>
<td>144</td>
<td>9.5</td>
<td>1</td>
<td>-</td>
<td>27</td>
<td>1.8</td>
</tr>
</tbody>
</table>
1952 Survey (Bluegrass and Pennyroyal)

Culvert condition surveys in the second phase of the project covered 1145.7 miles of road and included 3,791 cross-drainage culverts of which 2181 were concrete, 984 were corrugated metal, 601 were vitrified clay, and 25 were cast iron. Entrance pipe were not included in this phase of the project. Since most of this survey was made during a particularly dry season, it was frequently necessary to make a detailed search of some areas for representative water samples. A total of 123 samples were taken, none of which was more than slightly acid. Those slightly acid are probably attributable to shale outcroppings. Sample locations, type and location of culverts, and installation dates are shown on the map in the pocket at the rear of this report.

Of the 984 corrugated metal pipe examined, sufficiently reliable installation dates were available for life-expectancy evaluations on 475. These data are summarized in Table 3. Some of the 948 pipe could not be inspected satisfactorily, and only 714 of them were rated for material deterioration. The over-all average percentage deterioration was 4.7 percent. Of the 714 pipe rated, 104 exceeded 80 percent deterioration. Percentagewise this means that at least 14.6 percent of those inspected have reached a state where they should be replaced.

All of the other types of culverts - concrete, vitrified clay, and cast iron - were conspicuously free of visible material deterioration. Considering that the average age would be at least 20 years (See enclosed map), it seems unlikely that a realistic estimate could be made of the expected life for those materials within the Bluegrass and Pennyroyal Areas.
Table 3 - Summary of In-Service Performance Data For Galvanized Metal Culvert Pipe (1952).

<table>
<thead>
<tr>
<th>Road and Location</th>
<th>Age At Time of Inspection</th>
<th>No. of Pipe Inspected</th>
<th>Avg. Percent Material Deterioration</th>
<th>Average Life-Expectancy in Years</th>
<th>No. of Pipe Exceeding 80% Material Deterioration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ky. 35 Danville-Mercer Co. L.</td>
<td>31</td>
<td>7</td>
<td>35.7</td>
<td>86.8</td>
<td>1</td>
</tr>
<tr>
<td>U.S.66 Harrodsburg-Ky. River</td>
<td>30</td>
<td>12</td>
<td>20.8</td>
<td>114.2</td>
<td>0</td>
</tr>
<tr>
<td>Ky. 73 Jct. Ky. 100 - Tenn. L.</td>
<td>22</td>
<td>16</td>
<td>40.3</td>
<td>51.6</td>
<td>2</td>
</tr>
<tr>
<td>U.S.60 Hardinsburg-Meade Co. L.</td>
<td>30</td>
<td>14</td>
<td>52.1</td>
<td>57.6</td>
<td>3</td>
</tr>
<tr>
<td>Ky.198 Lincoln Co. L.-Yosemite</td>
<td>31</td>
<td>10</td>
<td>27.0</td>
<td>144.8</td>
<td>1</td>
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<tr>
<td>Ky. 35 Liberty-Russell Co. L.</td>
<td>41</td>
<td>28</td>
<td>63.5</td>
<td>61.3</td>
<td>12</td>
</tr>
<tr>
<td>Ky. 53 Willisburg-Springfield</td>
<td>23</td>
<td>41</td>
<td>33.5</td>
<td>65.7</td>
<td>2</td>
</tr>
<tr>
<td>Ky.152 Springfield-Mackville</td>
<td>24</td>
<td>20</td>
<td>40.5</td>
<td>59.3</td>
<td>3</td>
</tr>
<tr>
<td>U.S.150 Danville-Perryville</td>
<td>33</td>
<td>9</td>
<td>30.6</td>
<td>107.8</td>
<td>0</td>
</tr>
<tr>
<td>U.S.60&amp;52 Perryville-Marion Co. L.</td>
<td>35</td>
<td>22</td>
<td>44.0</td>
<td>79.5</td>
<td>4</td>
</tr>
<tr>
<td>Ky. 55 Jct. U.S. 60-Finchville</td>
<td>34</td>
<td>10</td>
<td>42.0</td>
<td>81.0</td>
<td>0</td>
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<tr>
<td>Ky. 53 Southville-Mt. Eden</td>
<td>17</td>
<td>23</td>
<td>39.0</td>
<td>143.6</td>
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<tr>
<td>U.S.60 Woodford Co. L.-Frankfort</td>
<td>40</td>
<td>70</td>
<td>48.3</td>
<td>82.8</td>
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<tr>
<td>Ky. 35 Owenton-Sparta</td>
<td>35</td>
<td>70</td>
<td>25.6</td>
<td>138.7</td>
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<tr>
<td>Ky. 35 Anderson Co. L.-Harrodsburg</td>
<td>32</td>
<td>13</td>
<td>16.9</td>
<td>189.3</td>
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<tr>
<td>Ky. 35 Danville City L.-Jct. Ky. 300</td>
<td>32</td>
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<td>60.0</td>
<td>53.3</td>
<td>0</td>
</tr>
<tr>
<td>Ky. 35 Lincoln Co. L.-Liberty</td>
<td>28</td>
<td>32</td>
<td>79.3</td>
<td>35.3</td>
<td>20</td>
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<tr>
<td>Ky. 35 Albany-Tenn. L.</td>
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<td>25</td>
<td>42.0</td>
<td>54.5</td>
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<tr>
<td>U.S.90 Jct. Ky. 64-Hardinsburg</td>
<td>29</td>
<td>18</td>
<td>43.5</td>
<td>66.6</td>
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<tr>
<td>Ky.100 Alien Co. L.-Jct. Ky. 63</td>
<td>21</td>
<td>20</td>
<td>31.8</td>
<td>66.0</td>
<td>0</td>
</tr>
<tr>
<td>Ky.100 Jct. Ky. 63-Tompkinsville</td>
<td>21</td>
<td>13</td>
<td>52.1</td>
<td>46.1</td>
<td>2</td>
</tr>
<tr>
<td>U.S.58 Edmonston-Green Co. L.</td>
<td>23</td>
<td>23</td>
<td>63.9</td>
<td>36.0</td>
<td>2</td>
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<tr>
<td>U.S.1450 Jct. U.S.60-Scott Co. L.</td>
<td>36</td>
<td>7</td>
<td>94.2</td>
<td>64.4</td>
<td>3</td>
</tr>
<tr>
<td>U.S.62 Bourbon Co. L.-Jct. U.S. 27</td>
<td>34</td>
<td>9</td>
<td>50.0</td>
<td>54.6</td>
<td>1</td>
</tr>
<tr>
<td>U.S.62 Cynthiana-Robertson Co. L.</td>
<td>21</td>
<td>13</td>
<td>49.2</td>
<td>42.6</td>
<td>0</td>
</tr>
<tr>
<td>U.S.25 Fayette Co. L.-Georgetown</td>
<td>35</td>
<td>4</td>
<td>60.3</td>
<td>52.8</td>
<td>1</td>
</tr>
<tr>
<td>Ky. 177 South of Covington</td>
<td>21</td>
<td>11</td>
<td>59.5</td>
<td>35.3</td>
<td>4</td>
</tr>
</tbody>
</table>

Total 475 45.2 73.44 0

Average 28.4 73.44 13.9

Note: Life-Expectancy = 100 x Age/Percent Deterioration
TEST INSTALLATION

The need for a test installation was not recognized until it was discovered from field surveys in the first phase of the project that in-service performance records, particularly within the Coal Fields, were conspicuously limited to concrete culverts. Scattered occurrences of vitrified clay and plain galvanized metal were found but they were usually insufficient in number and distribution and were, for the most part, considered inconsequential for comparative purposes.

Inasmuch as corrugated metal pipe had not been used to any extent as cross drains on projects receiving Federal Aid since about 1928 or 1929, there were few opportunities to observe this material. Cases where coated or paved pipe had been used were even more rare. There was a considerable amount of metal pipe installed under the Rural Secondary program, but they had not gained sufficient age to be of significance in this project.

In some of the few cases where metal cross drains (coated or uncoated) were found, patching of the pavement or settlement of backfill indicated a replacement since the time of original construction. Under circumstances such as these where there was doubt concerning the date of installation, the only recourse was to disregard the culvert entirely.

All these things in combination led to the decision that direct comparisons, at least with respect to acid resistance, must be made through a controlled test installation. The series of entrance pipe at Princess had many attributes of a test installation for galvanized metal. Pipe located on the north side of the road were subjected to severely acid mine
water while pipe on the south side carried water which was essentially non-acid. Failures in the former case were eminent at the end of one year, but no serious corrosion had taken place in the case of the non-acid water. Had similar conditions been found for other materials such that comparisons could have been drawn, the need for a planned test might not have arisen.

The test should, therefore, be regarded as an expedient attempt to overcome limitations of in-service performance data. It should be recognized too that the test represents the most severe conditions known to exist anywhere in the state. To that extent, it is an accelerated test. Under conditions more favorable to longevity, tangible results probably could not have been achieved within the next 15 to 20 years.

The installation was made April 25, 1951, at a selected location adjacent to U.S. 41 in Hopkins County at the south city limit of Morton's Gap. The site was chosen on the basis of: concentrated acidity measured in the earlier field survey; the apparently continuous supply of drainage water from a nearby spring; and accessibility from a major highway. An easement on the property was secured from the West Kentucky Coal Company for a period of five years expiring September 25, 1955.

Duplicate sections of 24-inch diameter pipe including reinforced concrete, vitrified clay, galvanized metal, and galvanized metal with five different protective coating modifications were placed in a shallow ditch leaving the upper section exposed to facilitate inspection.

The general appearance of the installation is shown in Fig. 5, and a layout in Fig. 7 shows the arrangement of the different sections.
Actually the photograph in Fig. 5 was taken April 29, 1952, approximately one year after installation. Because of heavy rains on April 15, it was necessary to re-set the pipe and restore the channel, and that work was under way at the time this photograph was taken. In order to minimize any differences due to their respective positions, duplicate samples of each pipe were placed in reverse order. Beginning at either end, the sections were placed in the following order:

1. Reinforced concrete
2. Vitrified Clay
3. Corrugated metal, asbestos bonded
   bituminous coated and paved
4. Corrugated metal, 1/2-coated and paved
5. Corrugated metal, plain galvanized
6. Corrugated metal, full double coating
   without paving
7. Corrugated metal, full coated and
   paved according to Ky. Special Spec.
   No. 1-R
8. Corrugated metal, galvanized, asbestos
   bonded with bituminous seal coat

Originally considerable thought was given to the possibility of including bituminous-coated concrete sections in the test. However, the idea was abandoned because it would have been necessary to improvise coating and methods of application. It was thought that unless the concrete sections were coated in exactly the same manner and to the same depth as companion metal sections, the implied comparison might reflect undue discredit upon the coated concrete.

Developments in the test and general results of periodic inspections in chronological sequence were:
Fig. 3 - Photograph Taken May 22, 1951, Approximately One Month After Installation; Shows Condition of Plain Galvanized Metal Test-Section. Spelter was completely gone in the channel, and the base metal was perforated within a few days after the above date.

Fig. 4 - Photograph taken July 16, 1951, Showing Condition of Same Culvert as Shown Above.
Fig. 5 - Photograph of Test-Installation Taken April 29, 1952, After Pipe Sections Were Re-Set Following Heavy Rain. Plain galvanized metal sections were not re-set.

Fig. 6 - Photograph Showing Condition of Plain Galvanized Metal Sections When Removed April 29, 1952, Approximately One Year After Installation.
KEY

A. Plain Reinf. Conc. Pipe  
B. Vitrified Clay Pipe  
C. Asbestos Bonded Corr. Metal 
D. Corrugated Metal 
E. Corrugated Metal (double strength) 
F. Corrugated Metal (plain galvanized) 
G. Asbestos Bonded Corr. Metal (seal coated only) 
H. Corrugated Metal (double full coated only)

Note: All pipe is 24-inches in diameter. Corrugated Metal Pipe are placed in pairs 6-inches apart and wrapped with roofing paper.

Fig. 7 - Plan-View of Experimental Culvert Installation.
April 25, 1951. Date of installation. Specific resistance of water - 280 ohms.

May 22, 1951. Date of first inspection. Specific resistance of water - 260 ohms. Spelter gone from plain galvanized metal (See Fig. 3).

July 16, 1951. Water tested 235 ohms. Invert eaten out of plain galvanized metal sections (See Fig. 4). Concrete showed slight etching.

August 20, 1951. Water tested 240 ohms.

October 18, 1951. Routine Inspection. No significant changes noted.

March 9, 1952. Water tested 300 ohms.

April 15, 1952. Heavy rain dislodged several sections of pipe and deposited silt in the channel.

April 29, 1952. Installation restored (See Fig. 5). Galvanized metal sections not replaced (See Fig. 6). Water tested 290 ohms.

June 18, 1952. Routine inspection, no significant changes.


August 28, 1952. Routine Inspection, no changes noted.

October 5, 1952. Water tested 265 ohms. Concrete pipe beginning to show visible evidence of progressive corrosion. Aggregate exposed in the invert, but no appreciable reduction in material thickness observed.

At the last inspection, the vitrified clay sections and variously coated metal sections remained virtually unaffected except in the case of the metal pipe where the protective coatings had been scarred during placement. The half-coated galvanized metal sections showed some staining where the uncoated portion was in contact with fill material. This was interpreted as a mild form of corrosion.
Several conclusions may be drawn from the results attained thus far in the test. The obvious ones probably do not require any further comment or qualification. It may be generally stated, however, that:

1. The failures in plain galvanized metal confirm the findings of the situation at Princess, and present a rather spectacular demonstration of the performance of the material under highly acid conditions. In a sense, they demonstrate failures that could be expected in this material at each location of mine drainage or any point of concentrated acidity throughout the coal-bearing regions.

2. The performance of concrete pipe indicates that although the material is not entirely free of corrosion the present rate of deterioration projects the usable life of the material well beyond 10 years. It will be possible, of course, to make a more accurate estimate after 2 or 3 more years.

3. The value of protective coatings over metal is unreservedly demonstrated despite the early age of the installation. It is not possible, however, to project these short-term performances with any degree of accuracy. As a result of experiences gained elsewhere by others, it is expected that the life of the bituminous coatings will be at least 15 years.
Physiographically, Kentucky is divided into six major regions as outlined by the approximate boundaries drawn in Fig. 8. From an academic standpoint, these natural boundaries are correlative with the types of rock materials underlying the surface and their geologic development (3). In simple terms, it is inferred that the entire state was once uniformly stratified or laminated as the pages in a book. Later the central areas popularly known as the Bluegrass and Pennyroyal (4), were arched upwardly, and the protruding layers were eroded away exposing successively deeper and older strata. Toward the east and west these exposed strata, consisting of massive limestones, dip under outcropping of those formerly continuous layers. The eastern and western slopes of the arch are still covered with massive sandstones interbedded with shales and coals. These general cross-sectional features are illustrated diagrammatically in Fig. 9.

Mineralogically, the limestone of the central areas are, for all practical purposes, free of severely corrosive mineral matter. Some phosphatic minerals associated with limestone may even act as corrosion inhibitors. Sandstones themselves rarely contain such mineral matter but interbedded shales and coals almost invariably contain sulfurous minerals either in the form of sulfides of iron and calcium or as free sulfur. These sulfurous materials are capable of being converted by water and atmospheric oxidation into highly corrosive acids and salts. Surface
GENERALIZED GEOLOGIC CROSS-SECTION OF KENTUCKY

Figure 9
waters infiltrating through typically porous sandstones eventually arrive at an impervious strata and then must seek an outlet laterally. Roadway cuts, drift mines, and strip mines provide artificial outlets. Numerous natural outlets of this type have gained considerable fame in the past as mineral springs. Many of the small towns in the coal fields obtain their water supply from deep wells which frequently contain fairly high concentrations of mineral salts. As a consequence, corrosion of utility pipes constitutes a rather serious problem.

In 1948, the State Department of Mines and Minerals (5) listed 4,312 coal mines as being in production. It might also be presumed that at least as many abandoned mines are scattered indiscriminately throughout the areas. With the continued development of rural roads in these areas, it is expected that the number of entrances will continue to increase. Many small truck mines abandon operation after two or three years, but the openings continue to drain these highly corrosive waters. According to studies by the Ohio River Sanitation Commission and the U.S. Public Health Service, it has been estimated that the equivalent of 2,500,000 tons of sulfuric acid originating in underground mines is discharged every year into the Ohio River Basin.

Acid intensity, of course, is highest at the source and diminishes successively with each stage of downstream dilution. Hence, when a highway culvert is in contact with the water close to the source the corrosion which results is usually great. However, observations in field surveys showed that the percentage of culverts which are too close to acid sources to benefit from dilution is actually small.
In the Eastern Coal Field stream gradients are typically steep, and the channels are frequently flushed by heavy rains. Streams in the Western Coal Field have relatively flat gradients, and great reservoirs of mine drainage may collect in the channels. During particularly dry seasons, evaporation further concentrates the salts and acids to a point approaching saturation. Surface runoff in this territory is rarely sufficient to flush the stream; as a result, the water usually looks red or yellow. This factor, in combination with predominately higher concentration of sulfur in the coal itself, suggests a higher degree of corrosivity for this area.

On the assumption that the combined influences of sulfur content and the volume of coal production are also indicative of prevailing corrosive capacity of each county, an attempt was made to integrate these data. A plot of average percent sulfur (weighed according to the number of seams and the number of mines working each seam) versus total annual production is shown in Fig. 10. The various counties tend to group into three distinctive categories. On this basis, Hopkins County, by virtue of both high production and high sulfur content, represents the ultimate in corrosivity to be encountered in the state.

The Knob Region (6) surrounding the Bluegrass is characterized by conical hills which are erosion remnants or outliers of the limestone uplands to the south and west of Muldraugh's Hill, and of the sandstone of the Coal Field on the east. Geologically it is the region of outcrop of the Ohio-Waverly formations. More simply, it is the shale country
Fig. 10.—Grouping of Counties by Production and Sulfur Content of Coal
between the limestone of the Bluegrass and the bordering Pennyroyal and Cumberland Plateau (Eastern Coal Field). Where porous sandstones overlie impervious shales or clays, shallow wells usually yield fairly pure water. Where the water has seeped through joint planes of the underlying shales, numerous mineral springs have resulted. This is particularly true along the outcroppings of the Ohio shale overlain by the Waverly sandstone.

Shallow wells penetrating outcroppings of the black shales near Berea yield sulfurous water. Waters permeating magnesian limestones and shales of Silurian age yield mineral waters at Crab Orchard in Lincoln County. Several springs from the Ohio shales have gained passing notoriety. Some of the better known are:

- Sulphur Springs - Near Lebanon, Marion County,
- Alum Springs and Linetta Springs - Near Junction City, Boyle County,
- Springs at Mitchellsburg and Shelby City - Boyle County,
- Hales Well - Near Stanford, Lincoln County,
- Dripping Springs - Garrard County,
- Estill Springs - Near Irvine, Estill County,
- Oil Springs - Near Indian Fields, Clark County,
- Olympian Springs - Bath County,
- Fox Springs - Fleming County,
- Esculopia - Lewis County,

These springs are predominately sulfurous in character and should not be confused with so-called "salt licks" such as the Blue Lick in Nicholas County which rise by artesian effect from great depths.

Natural brines containing predominately chloride salts are known to exist within localized areas of some sandstone strata underlying Eastern Kentucky. A few of these sources nearer the surface were commercialized.
in earlier days, but have now fallen into obscurity. The general tendency, it seems, is for brines of that type to occur well below the depths of lateral drainage outlets due to local relief. Consequently they can not have a significant bearing on the present problem.

By further reference to Fig. 8, the crest of a second arch may be noted dipping eastwardly under the Western Coal Field and dipping westwardly under the Mississippi River. The westward slope of the arch, comprising the Jackson Purchase Area, is now covered by washed alluvial sands, silts, and clays deposited as a result of the Mississippi River embayment, representing the northern-most extremity of a former Gulf Coastal Plain. Because of the manner in which this overlying material was deposited it should be relatively free of highly soluble or severely corrosive mineral matter. Because of the flat terrain and generally porous character of the material, drainage is largely internal.

Although this approach to the problem might well be pursued into much greater detail, it is easily surmised from the information given here that extreme conditions of corrosivity are fundamentally related to the mineralogic character of the substrate and that such potentially corrosive materials occur in abundance within the two coal fields and, to a lesser degree, in the Knob Region.
THEORY OF CORROSION AND CORROSION PREVENTION

Corrosion is defined as the disintegration of metallic and other solid surfaces by chemical action.

Every year inestimable damage is caused by this "gnawing" action on construction materials and industrial equipment. There is no single explanation for why corrosion occurs nor is there a definite scale of relative corrodibility of materials. Most instances of resulting damage can be explained by careful study of existing conditions. Often a knowledge of chemistry, careful planning, and protective measures commensurate with the cost of an installation will prevent or avert damage. Such matters are very important to manufacturers and design engineers who bear the responsibilities of qualifying a material to perform satisfactorily under severe exposure conditions. This brief digest on causes and preventions is offered as a collateral record of the generally recognized physico-chemical principles involved in corrosion.

Acid Corrosion

Most of the corrosion that is of industrial importance takes place in mildly acid solutions where oxygen is a cooperating agent. Acids reacting with metal liberate hydrogen in the form of a gas. As an example, a piece of iron immersed in a glass of water has a tendency to dissolve until the water becomes saturated with Fe\(^{++}\) ions; but in order for an ion to leave the electrically neutral surface of the metal (Fe\(^{0}\)), it must lose two electrons (Fe\(^{0}\)-2e → Fe\(^{++}\)). Without a receptor for these electrons, the solution process can not progress. If H\(^{+}\) ions are present in the
water (slightly acid) the iron may force them to accept the electrons. Since each \( \text{H}^+ \) liberated must gain one electron \((2\text{H}^+ + 2e \rightarrow \text{H}_2^0)\), the two reactions progressing simultaneously will preserve the electrical balance of the system. However, the hydrogen gas liberated may be reabsorbed on the metal surface creating an electro-positive barrier against any further exchange of electrons and stop the reaction. If there is sufficient oxygen dissolved in the water, it will react with this absorbed hydrogen \((2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O})\), break down the barrier, and permit corrosion to proceed.

Between pH-6 and pH-9, according to McKay and Worthington (7), the rate of corrosion is practically determined by the oxygen concentration. If the water is more acid than pH-5, corrosion will proceed whether oxygen is present or not. Above pH-12 there will not be enough hydrogen ions present to cause measurable corrosion even if oxygen is present. These facts are presented graphically in Fig. 11.

It may be assumed that the tendency to dissolve is an inherent characteristic of all metals. Generally, those metals which are most active in liberating hydrogen are also most active in combining with oxygen to form oxides (rust). Except for the fact that some metals form thin oxide coatings which are very resistant to corrosion of any sort, metals might be rated as to their susceptibility to corrosion by their position in the electro-chemical series. This series is based upon the electrical potential existing between the solid metal and a solution containing a 1 normal concentration of its ions as compared to the potential between hydrogen and a 1 normal solution of its ions (arbitrarily set at
Fig. 11 - The Influence of pH and Oxygen Concentration on the Rate of Corrosion of Iron. From McKay and Worthington.
zero). The so-called normal electrode potentials for most of the familiar metals are:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>-2.38</td>
</tr>
<tr>
<td>Aluminum</td>
<td>-1.67</td>
</tr>
<tr>
<td>Zinc</td>
<td>-0.76</td>
</tr>
<tr>
<td>Chromium</td>
<td>-0.56</td>
</tr>
<tr>
<td>Iron</td>
<td>-0.44</td>
</tr>
<tr>
<td>Cadmium</td>
<td>-0.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>-0.25</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>-0.20</td>
</tr>
<tr>
<td>Tin</td>
<td>-0.14</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.13</td>
</tr>
<tr>
<td>Copper</td>
<td>+0.52</td>
</tr>
<tr>
<td>Silver</td>
<td>+0.80</td>
</tr>
<tr>
<td>Platinum</td>
<td>+1.2</td>
</tr>
<tr>
<td>Gold</td>
<td>+1.68</td>
</tr>
</tbody>
</table>

Metals preceding magnesium in the series react violently with water while magnesium itself will react noticeably with hot water but only slightly with cold water. Other metals in the series react less spectacularly, and finally gold and platinum are practically non-reactive to ordinary corrosive agents.

Air and water are the most important natural carriers of corrosive agents. Rain falling through the air absorbs oxygen and carbon dioxide. Over industrial areas where coal is the major source of power and heat, rain water may contain appreciable quantities of sulfuric acid (SO$_3$ from burning sulfur-bearing coal + H$_2$O $\rightarrow$ H$_2$SO$_4$). As a philosophical assumption, metals could not corrode if their surfaces were sealed from contact with these so-called "elements."
Protective coatings of some type seem to be the only practical way to prevent corrosion of industrial metals. Bitumens, paints, varnishes, and lacquers afford temporary to semi-permanent protection. Vitreous enamels (glass) afford permanent protection for many specialized uses. Electroplatings and dip-platings of less corrosive metals afford adequate protection under mild conditions, but may actually accelerate corrosion of the base metal under highly acid exposure, due to galvanic action (See later discussion on galvanic corrosion).

The relative merits of cast iron versus wrought iron are frequently debated. The question is probably of little importance to the present problem; but as an adjunct to this discussion, the following citations may be of interest:

"Cast iron corrodes by so-called graphitic corrosion, whereby the iron constituent of the alloy is converted to corrosion products, these acting as cement for residual graphite flakes. A corroded cast-iron pipe, therefore, may have lost most of its mechanical strength, but is serviceable for the purpose first intended. In this respect, it may last longer in some applications than steel or iron." (8)

"The microscopic structure of wrought iron consists of filaments of almost pure ferrite separated by films of slag which in its physical properties is a glass. The intermixed slag helps to prevent slip bands from spreading and also to stop corrosion. The function of the slag in this latter respect may be roughly compared with that of the fused silicate enamel on steel cooking utensils and cast iron bath tubs." (9).

**Galvanic Corrosion**

Galvanic corrosion is comparable to the electrode decomposition that takes place in an ordinary automobile battery while it is
being discharged. It results from electrical contact between two dis-
similar metals immersed in solutions containing their ions. Generally,
those metals differing greatly in their normal electrode potential
(already discussed under acid corrosion), exhibit appreciable galvanic
action. As an hypothetical example, if a copper rod and an iron rod
were partly immersed in a solution containing equal concentrations of
copper sulfate and iron sulfate and these rods were connected by a wire
outside the solution, the iron would probably corrode while the copper
would grow due to its ions being plated out of the solution. On the
other hand, if magnesium were used in place of the copper, it would be
corroded and the iron would grow.

Metals closely adjacent in the electro-chemical series, such
as iron and cadmium, have no strong tendency to produce galvanic action
on each other. Platings, therefore, should form resistant oxide films
and should not create strong galvanic tendencies with respect to the base
metal. Zinc coatings, for instance, are slightly anodic with respect to
iron; and, while its oxide film affords added protection to atmospheric
exposure, the zinc actually corrodes sacrificially in acid conditions.

Advantage has been taken recently of this galvanic action to
preserve metal piles and structural members by bonding them to a buried
mass of some metal that will corrode sacrificially. The same idea is
used to preserve home-type hot water tanks by inserting a magnesium rod
in the tank and bonding it to the wall of the tank. Supposedly the iron
or steel tank can not corrode until all the magnesium rod has corroded
away.
Concentration Cell Corrosion

Concentration cell corrosion is more-or-less a variation of the two fundamental types already discussed. It usually shows up as pitting or localized corrosion. It is likely to show up most prominently under conditions of frequent wetting and drying where water contacting the metal at different places contains differing concentrations of oxygen, salts, or acids. The merits of stainless steels and some platings are sometimes attributed to their very smooth surfaces and thin resistant oxide coatings which prevent the formation of concentration cells. An otherwise porous surface would be vulnerable to this type of corrosion. The condition shown in Fig. 12 is, in part, a manifestation of this type of corrosive attack.

Corrosion of Hydrated Calcium Silicate Cement Concrete

Hydrated calcium silicate cements are termed "hydraulic cements" because of their low solubility in water— that is, they harden or "set" in the presence of water and produce water-insoluble hydration products of high strength. In common usage they are typified by portland cement.

Soluble calcium hydroxide, formed as a by-product of hydration, is crystallized from interstitial water and is trapped within the hardened cement. The strength of the cement, in binding aggregate particles together as concrete, is dependent upon the amount of the hydration product present and its density (absence of voids). Porous concrete, for instance, not only has low strength due to the corresponding decrease in effective cross-
Fig. 12 - Plain Corrugated Metal Cross-Drain Located on Ky. 36 in Bath County. According to the best records available the date of installation was 1926. It is located in a limestone region and apparently accommodates only surface runoff. A sample of residual water taken below the exit showed a specific resistance of 1880 ohms at 25 degrees Centigrade. Although this is a comparatively low value, it cannot be attributed to acidity or the severely corrosive salts.

The water filling the corrugations demonstrates the oxygen and concentration-cell corrosion. Obviously, there has never been appreciable concentration of acid here. The type of rusting or corrosion shown here is very slow in comparison with severely acid exposure.

This type of corrosion is distinguishable from critically acid corrosion by the presence of oxide scale or rust and the absence of a clean-cut channel through the invert.
section but it is vulnerable to internal decay by infiltration of corrosive agents and by freeze-and-thaw weathering.

Note: Air-entraining concrete usually has slightly reduced strength but the air bubbles or "voids" are not communicating with the outside and, therefore, do not permit infiltration of water.

Acid attack on dense impervious concrete is limited more-or-less to a surficial type of corrosion, and is outwardly visible. Corrosive action on porous concrete may result in a "honeycombed" structure, and the corresponding loss of cementing material from the interior would be accompanied by loss of strength.

Acids reacting with the hydrated cement cause the calcium of the calcium silicate to be converted into soluble salts and leaves gelatinous silica which may be subsequently washed away. In the presence of drainage waters containing appreciable quantities of iron sulfates and sulfuric acid, the naturally alkaline condition of the concrete tends to neutralize the acid at the surface of contact; and, as a result, the iron may be precipitated on the surface as a very red ferric hydroxide gel acting to insulate the surface against further corrosion, unless washed away by turbulent water.

As to the possibilities for preventing concrete corrosion, it seems reasonable to assume that coatings of bituminous materials would be capable of affording the same protection to concrete as they do to metal.
OTHER INVESTIGATIONS

At one time or another, practically every state in which coal is a major resource has found it necessary to investigate the durability of various culvert materials in relation to corrosive drainage waters. During the late 20's and early 30's several states conducted field surveys of in-service culverts. Some of the resulting information developed in Georgia, Tennessee, Virginia, and California was summarized in a report published in the 1932 Proceedings of the Highway Research Board (10). Many of the various reports were never published, and copies of the original manuscripts are either no longer available or are yet held confidentially by the states. After almost a decade of fruitful research, interest in the problem apparently subsided.

**Austin - San Antonio Post Road (1915-1929) (11)**

Probably the first attempt to evaluate culvert materials on the basis of in-service performance was begun in 1915 on the Austin-San Antonio Post Road. Originally the installation included 3 each of five types of corrugated galvanized metal and five types of black (ungalvanized) metal, 14 gauge, 24-inch diameter. Within the first few years several conflicting reports regarding the relative performances of different base metals were disseminated unofficially.
In 1929, after 14 years of service, this situation led to a cooperative evaluation of the project by several public service agencies including the Bureau of Public Roads, Highway Research Board, and a number of interested highway departments. (In those early days, it seems that the base-metal issue gained considerable prominence; and even now is not entirely clarified.)

Within the limitations of the tests and under the prevailing conditions of service (predominately alkaline, ranging from pH-7 to pH-8.8), galvanized pipe was rated as superior to ungalvanized pipe, and ungalvanized copper-bearing steel and ungalvanized copper-bearing iron were favored over other black (ungalvanized) pipe.

**Georgia (1926-1928) (12)**

Approximately 3,300 in-service culverts of known ages, ranging from 5 to 12 years, were rated both materially and structurally in the Georgia survey. Life expectancies were estimated by a method — adapted from a system originally developed by California — which credits a maximum rating of 90 percent to apparently perfect culverts over four or five years old, and zero percent rating to all failures. Intermediate ratings were based upon the judgment of the inspector.

The calculations were empirically formulated and are included here as a point of interest:

\[ F = L + \frac{H - L}{K} \]
where \( F \) = final rating, or percentage worth of the structure at time of inspection.

\( H \) = higher rating, whether material or structural.

\( L \) = lower rating, whether material or structural.

\( K \) = (a somewhat arbitrary constant)

From the final ratings, the annual rate of deterioration was calculated by:

\[
U = \frac{100 - F}{A}
\]

where \( U \) = unit deterioration (per year).

\( A \) = age at time of rating.

\( F \) = final rating.

Life expectancy \( E \) was then obtained by:

\[
E = \frac{100}{U}
\]

Note: In one respect, the structural adequacy of a culvert pipe at any age is related to the amount of material deterioration that has taken place. Structural conditions such as faulted joints, cracks, silting, etc. are not necessarily the result of material deterioration but may reflect some fundamental disadvantage of the type of culvert or even poor construction and maintenance practices. In the equations above, all these contributing influences are more-or-less averaged together in a single numerical rating. Such a rating may indicate the overall condition of a culvert, but it fails to credit any cause to the condition.
As a result of the survey, corrugated metal culverts were discontinued in certain parts of southern Georgia due to their rapid deterioration under acid conditions. The actual data on life expectancies is rather difficult to summarize. As a notable observation, there was a surprising number of failures in what were originally considered permanent installations. A number of installations rated in 1926 were re-rated in 1928, and the average expectancies, particularly for vitrified clay, were somewhat higher. This indicates that the rating system probably gave conservative results.

A third investigation was begun in 1930, and was expected to include about 4,000 installations; however, it is not known whether the work was ever completed or the results reported.

**Tennessee (1925, 1926, 1927)(1941)**

Although copies of the Tennessee report, made by E. W. Bauman in 1928, were not available; the work has been summarized by Slack (13) and Crum (10) in published reports. It seems that the Tennessee investigation preceded the Georgia survey by almost a year, and some of those early developments were incorporated into the plans for the Georgia Survey. A total of 2,924 culverts of all types commonly used in Tennessee were included in the inspection. Quoting Slack's summary:

"It was early seen that all culverts ultimately failed structurally but that two distinct paths of deterioration led to final failure. The corrugated metal or flexible type usually but not always deteriorated more rapidly materially than it did structurally. The rigid type, including vitrified clay and concrete pipe, usually but not always deteriorated more rapidly structurally than materially."
In recent correspondence (14) from Mr. P. I. Edwards, Engineer of Materials and Tests, attention was called to a survey (unpublished) made in Tennessee in 1941, which covered all existing state highways in that state. An excerpt showing the type of information developed appears below. This is part of the report covering Route 11, Robertson County, Tennessee.

"Project SAP 382-E begins at the city limits of Cedar Hill, Tennessee and ends at the city limits of Adams, Tennessee. The small drainage structures on this project are concrete boxes and corrugated metal pipes. They were installed under a State Aid Project in 1930. Six pipes on this project were examined. Two of these were in good condition. The bottom part of the remaining four pipes were rusted or pitted. Nine samples of water on this project were available for tests. These nine samples tested slightly acid. Since the above mentioned pipes have been in service for only two years, it is evident that the rust on the bottom part of these pipes is due to the slightly acid water."

Note: Acidity measurements were made using pH-indicating paper, probably pHydrion paper.

Virginia (Approximate Date, 1925)(1946)

Copies of an original report by Shreve Clark, at that time Engineer of Tests in Virginia, were not available. Crum's summary of the report (10) is quoted "en toto."

"The outstanding result of the Virginia culvert investigation was the elimination of the use of corrugated metal culverts in Tidewater, Virginia, east of the 'Fall' line. It was found that on account of the
brackish waters in the tidal area, the lives of these culverts were too short to justify their use in comparison with other types."

"North and west of the 'Fall' line no appreciable difference in the service of vitrified clay, concrete, or corrugated metal pipe was found, and these types are therefore on a parity for construction in this region."

Recently (1946) studies were made of the performance of bituminous coated metal pipe in the Tidewater area (15). Whereas the average life of plain galvanized metal pipe in the area had been in the order of 10 years, bituminous coated pipe already in service 10 years at the time of the survey, appeared capable of giving many additional years of service.

Correspondence with Mr. T. E. Shelburne, Director of Research (16), indicated that conditions in the Bristol District, particularly in Scott, Wise, Dickenson, and Buchanan Counties, very closely resemble those encountered in Eastern Kentucky. Although plain galvanized pipe are presently being used there, they have numerous examples of damage due to acid drainage waters.

California (1925-1927), (1929-1930)

No report on the original 1925-1927 survey in California was ever compiled for distribution. According to a summary (17) of the unpublished work, prepared in July, 1950 by T. E. Stanton, then Materials and Research Engineer, the 1925-1927 survey failed to furnish conclusive data as to the comparative merits of different base metals,
and that report was held confidential. As an outgrowth of the inconclusive status, a long-time (20-year) performance test on a variety of corrugated metals was started in 1929-1930. At the conclusion of the 20-year period (in 1950), there were still no outstanding differences in corrosion resistance for any of the base metals. Some of the conclusions from the earlier survey, as cited in the above summary, are also of interest.

"The average indicated life of corrugated metal culverts in California, in fresh water and with intermittent flow, based on observations of 2500 such structures, is about eighty years."

"Deterioration in corrugated metal culverts is due almost exclusively to corrosion, is preventable in many cases, and may be greatly reduced in others."

"Spelter alone does not provide sufficient protection against corrosion, except under most favorable conditions of exposure, and bituminous and other protective coatings are usually desirable even where spelter is used."

"Concrete culverts have not been extensively used on California State Highways, but a study of a limited number shows an indicated average life of 96 years. Well-made reinforced concrete pipe meeting present specification requirements will probably be "permanent" structures under conditions prevailing in this state."

"Under favorable conditions of exposure the value of corrugated metal culverts, --- ---, may be only 25 to 75% of the value of permanent structures. Economic considerations should control under these circumstances, as in all others, and the selection of some type not affected by these destructive conditions may thus be found desirable."

"Monolithic reinforced concrete culverts have been found to depreciate very slowly under conditions prevailing in California and the average performance of these culverts justified classifying this type"
as permanent. They are not greatly affected by unfavorable conditions which accelerate corrosion in corrugated metal and are, therefore, suitable for use where the unfavorable conditions can not be eliminated and where there is economic justification for their use."

According to Mr. Stanton (18), California Specifications now permit the use of five kinds of base material as listed in Table 1 of A.A.S.H.O, Standard Specification M36-47. Under severe scouring or other adverse conditions, bituminous coated and paved pipe are specified.

West Virginia (1921) (1928-1929)

In 1934, the State Road Commission of West Virginia, in cooperation with the University of West Virginia published a report (19) of a culvert survey made in the state in 1931, which is by far the most comprehensive treatise yet reviewed. The author, W. S. Downs, described the West Virginia situation as follows:

"A major portion of the state's area contains valuable coal deposits consisting of numerous seams which differ somewhat in the mineral content. Many such coal deposits are being operated or have been operated. In either event the oxidizing effect of the air in contact with the workings causes the drainage water from the mines to be highly impregnated with mineral salts. Most of them show an acid reaction due to the sulfur and iron (free sulfur and sulfur in combination with iron, never iron alone) in the coal so that the effect upon metal or even upon concrete can not be ignored. Under such conditions, it is necessary to exercise discretion in the selection of the culvert type. In certain localities it may be advisable to reject the use of a culvert type which under different conditions has proven highly economical."
Approximately the same system of evaluation as used in Georgia, Tennessee, and California was used in this survey except that the structural factor was not averaged with the material factor. The lower rating was simply used to calculate the life expectancy. The age of the culverts included ranged from 3 to 12 years. The statistical results of the survey are shown (in part) in the following tabulation:

<table>
<thead>
<tr>
<th>Culvert Type</th>
<th>No. of Culverts Observed</th>
<th>Avg. Expected Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Iron Pipe</td>
<td>130</td>
<td>105 Years</td>
</tr>
<tr>
<td>Corr. Metal, General</td>
<td>1277</td>
<td>27</td>
</tr>
<tr>
<td>Corr. Metal, Plain</td>
<td>832</td>
<td>22</td>
</tr>
<tr>
<td>Corr. Metal, Paved Invert</td>
<td>445</td>
<td>49</td>
</tr>
<tr>
<td>Rein. Conc. Pipe, General</td>
<td>1758</td>
<td>50</td>
</tr>
<tr>
<td>R.C.P, Cast</td>
<td>1185</td>
<td>47</td>
</tr>
<tr>
<td>R.C.P. Machine Made</td>
<td>430</td>
<td>59</td>
</tr>
<tr>
<td>Rein. Conc.Box</td>
<td>303</td>
<td>43</td>
</tr>
<tr>
<td>Stone Box</td>
<td>49</td>
<td>108</td>
</tr>
<tr>
<td>Vit. Clay Pipe</td>
<td>169</td>
<td>54</td>
</tr>
</tbody>
</table>

These results should not be taken without qualification since it was acknowledged that in the cases of cast iron pipe and the stone box, both were located in areas unusually favorable to culvert longevity. In the case of vitrified clay pipe, structural failures contributed prominently to the low life expectancy.

With regard to the effect of acid water on culvert longevity, it was found that in water having a pH less than 3, concrete showed an average rate of deterioration roughly four times as great as when the pH was around 7. Quoting again from this report:

"...It is conclusively shown that mine drainage which possesses a low pH value (highly acid) will rapidly disintegrate the invert of any exposed metal pipe.

...As a general rule, however, this survey shows..."
values ranging from 6 to as low as 2.7. The survey further shows that pipe deterioration (concrete and metal) increases as the pH value of the water decreases.

In 1928 and 1929, West Virginia also attempted to resolve a solution to the base-metal problem (20). A series of test sections of various metal pipes were installed in a flume carrying highly acid mine water. Though the report on this work too has been held in confidence for some 20 years, the conditions of the test were very similar to those at the Kentucky test installation at Morton's Gap. In their tests, bare metal in contact with the acid water lasted only 36 days, and there was little difference observed in the life of the different base-metals. (At Morton's Gap the plain galvanized metal sections did not last quite that long.)

**Pennsylvania (Probably about 1930)(21)**

A copy of the Pennsylvania report has been reviewed; but because of the uncertain date and volume of the data, no attempt was made to summarize it. However, the following excerpt from recent correspondence (22) with Mr. W. H. Herman, Chief Research Engineer, should be of current interest:

"The type of pipe primarily used by the state of Pennsylvania in our mining sections where drainage structures are subjected to acid mine waters is concrete pipe with terra-cotta lining or corrugated metal pipe with an asphalt coating. We have found these two types to give satisfactory performance."
From time to time, the Armco Drainage and Metal Products Company has participated in surveys conducted in several states, either in cooperation with highway departments or on an independent basis.

During the fall of 1951, the company conducted an independent survey of some 500 culverts in Kentucky. At the request of Mr. A. M. Snyder, ARMCO District Manager in Kentucky, a committee of Department Representatives was appointed to hear the findings of that survey (June 18, 1952). Most of the concrete and galvanized metal installations cited had already been included in the Department's survey, there being only 33 bituminous-coated metal pipe installed on Rural Secondary projects in 1949, and 4 others installed in 1940 which were not considered in the Highway Department Survey.

Note: Rural Secondary projects were not included in the Department survey because those installations had not gained sufficient age for an evaluation of performance.

Conclusions drawn in the ARMCO survey were, in part:

"It is quite evident that bituminous coated and paved invert corrugated metal pipe has a material life that is long enough to justify it being used under practically any drainage conditions......"

"If drainage conditions indicate a low pH value, 6.0 to 2.5, every consideration should be given to using Asbestos Bonded, full coated and paved invert pipe..."
Blue Ridge Parkway (1946)(24)

In 1945 inspections were made by the Public Roads Administration of a series of variously coated, paved, and asbestos bonded metal pipe installed between 1936 and 1941 on certain sections of the Blue Ridge Parkway. One of the resulting conclusions bears directly upon points emphasized in the ARMCO report:

"The culvert pipes in which asbestos-bonded metal was used appeared to have the greatest resistance to deterioration. Even though there was some loss of asphalt coating, the asbestos sheet appeared to give added protection to the metal."
REFERENCES


2. "A Survey of Acidity in Drainage Waters, and The Condition of Highway Drainage Installations," Research Laboratory Progress Report No. 1; by Havens, Young, and Field; presented to Research Committee February 1, 1951.


18. Direct Correspondence from California Division of Highways, November 6, 1950.


22. Direct Correspondence from Pennsylvania Department of Highways, November 8, 1950.


REFERENCE SUPPLEMENTS
