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BRIDGE CONSTRUCTION with UNPAINTED, HIGH-STRENGTH, LOW-ALLOY STEEL; EIGHT YEAR PROGRESS REPORT

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16. Abstract

In 1968 specimens of ASTM A-242, A-588, and copper-bearing and plain carbon steel were placed at two exposure sites in Newark, New Jersey for subsequent corrosion tests. One site is on the roof of a two story office building, representing fully open exposure conditions. The other site is beneath a nearby unpainted, A-242 steel highway bridge, where corrosion specimens are mounted on interior and fascia girders. To date, specimens have been removed and analyzed after 1,2,4,6½, and 8 years of exposure. Since the bridge was not opened to traffic for several years, the 1,2,4 and 6½ year specimens received no salt spray or exhaust fumes. Overall, the corrosion results, as well as the appearance of the unpainted bridge structure are encouraging. However, peculiarities in those results accentuate the importance of the 16-year specimens, and the additional specimens which were installed in 1978 to determine the influence of salt-spray and exhaust fumes from traffic.

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I. Introduction

With construction of the Interstate Highway network in New Jersey has come a massive increase in required annual highway maintenance. While some older portions of the network are already receiving major renovations, still other miles have barely been in use and contribute in a relatively minor fashion to the overall highway maintenance budget. This rapidly increasing mandated maintenance, coupled with the fiscal problems that annually beset an urban-suburban state such as New Jersey, has served to accent the need for a maintenance-efficient highway system. The realities of the maintenance burden are upon the State, and the "flood has yet to crest". With this in mind, design engineers should be taking a close, hard look at the long-term cost benefits of construction materials which may result in reduced maintenance. In this vein, in 1968, the Division of Research and Development undertook jointly with the Bethlehem Steel Corporation an investigation of the use of a relatively new steel for construction of highway bridges.

The subject steel is generally called "high-strength low-alloy" steel. The particular characteristic, however, that sets these steels apart from others is their relative resistance to corrosion when used in an unpainted condition. These steels, which fall under ASTM specifications A-242 or A-588, are said to have enhanced resistance to corrosion approximately four times that of plain carbon steel without copper (0.02% max). More importantly, these steels are expected to form, during the initial years of environmental exposure, a tight oxide coating that is to serve as a protective coating for ensuing years. Therefore, this protective oxide skin would act essentially as a coat of paint to prevent additional corrosion, and it would possess the further benefit of being "self-healing", much the same as the epidermis of a live organism. If such steel were used in our composite highway bridges, the obvious benefit to the State would be a savings in the cost of initial painting and all subsequent paintings. Intangible benefits (which are actually becoming more tangible as our society in general develops more sophisticated methods of evaluation) include a decrease in restrictions to traffic flow.

II. Objectives

The fundamental objective of this project is to determine the influence of soil and salt deposits, industrial and automotive air pollutants, and sheltering such as would exist under a bridge structure, upon the corrosion rate of such steels in the unpainted condition. Due to limited funds, important aspects such as the effects of stress corrosion, cyclic load on corrosion rates, reduction in fatigue strength, and loss of tensile strength could not be considered. Although it was not within the original scope of this project, the NJDOT has separately undertaken a second phase of investigation that deals with the esthetic problems associated with the use of unpainted structural steel in bridges. That phase is reported under separate cover.

III. Description of the Research

Complete details of the corrosion research were presented in a previous report entitled "Unpainted Low-Alloy Steels for Use in the Construction of Highway Bridges", 1968 (1) and subsequently published in a paper in the Highway Research Records #287 (2). Numerous specimens of ASTM A-242 Type 1 (Mayari R), ASTM A-588 Grade B (Mayari R-50) steels, and copper-bearing and plain carbon steels have been placed at selected locations in the vicinity of Newark, N.J., an area of intensive industrial pollution. Table 1 shows the composition of those steels. The site was selected to expose the specimens to what was considered this State's most corrosive atmospheric conditions. However, the most corrosive atmosphere in New Jersey is probably along the marine coastal shores where there are chlorides that tend to break down oxides. For that reason, the use of low-alloy high-strength steel in an unpainted mode is specifically not recommended in a marine environment.

The main effort of this research work is to determine the corrosion performance of A-242 Type 1 steel as compared with that of plain carbon steel in an industrial atmosphere as well as under conditions of direct exposure to fumes and salt spray due to highway traffic. To isolate the first condition, specimens were mounted on the roof of a New Jersey Department of Transportation office building. The latter exposure condition was achieved by mounting specimens on the steel superstructure of nearby Bridge #9, Route I-78, Section 5V. Bridge #9 is a small single-span bridge of composite construction, i.e., steel girders and a concrete deck. The steel used in its construction is ASTM A-242 steel Type 1. By mounting specimens on its superstructure, it was felt that the corrosion results obtained would typify the worst corrosion performance of this steel that could be expected on the vast majority of bridges throughout New Jersey.

The specimens on the office roof were mounted in three positions: vertical, horizontal, and 30^0 from the horizontal. Some of the latter mounts, corresponding to the usual positioning as in ASTM corrosion tests (ASTM G50-76), are for a comparison of the corrosivity of this area's atmosphere with the atmosphere of ASTM tests. Horizontal and vertical specimens were mounted to simulate the positions of the web and flange elements of Bridge #9 in order to determine what effect, if any, the orientation of the steel would have on corrosion rates. Specimens mounted on the bridge structure were in horizontal and vertical positions only. However, these bridge specimens were mounted at three different locations beneath the bridge in order to provide some insight into the effect of the degree of sheltering that occurs at various points among the girders. The locations on the bridge superstructure are denoted as follows: "L1", a fascia beam location at center-span of relatively open exposure, "L2", an interior beam location near the abutment, sheltered from washing by rain and open-air drying; and "L3", an interior beam location at center-span, sheltered from washing and drying.

During the eight-year exposure period, some specimens of each type of steel were removed at predetermined time intervals. They were cleaned in a molten bath of caustic soda with freshly generated sodium hydride (1-2%), weight losses were determined, and corrosion penetration and rates were calculated in mils and mils per year, respectively.

The project further called for the mounting of specimens at two different times, that is initially (soon after construction of Bridge #9) and several years later when the roadways were built and opened to traffic. The latter samples were installed to determine any additional effects of salt spray (from de-icing operations), soil, and automotive exhaust fumes.

To date all of the original specimens (installed May 1968) have been removed and tested, with the exception of the 16-year specimens. Those removed include the 1-,2-,4-, x-year (6-1/2 years) and eight-year specimens. The x-year specimens were removed in November 1974, when the roadway was opened to traffic. This removal was done in order to obtain a final evaluation of the steel specimens before the possible occurrence of exhaust fumes and salt spray. Prior to this time, the highly industrial atmosphere was the primary factor affecting the specimens, with a small amount of fumes and dirt from construction equipment being the remaining factor.

IV. Results and Significance

The corrosion results obtained thus far in the joint project are tabulated in Tables 2 to 6, and the data are plotted in corrosion-time curves in Figures 1 to 3. The data up to eight years show the following trends:

1. Each of Figures 1, 2, and 3 shows a corrosion-penetration curve for plain carbon steel from tests done previously by Horton (4) and similar curves for specimens of steels tested in this project. None of the plain carbon specimens in this joint effort display results with such dramatic penetration increases as obtained by others. That is, the corrosion rate of carbon steel specimens installed under this program were significantly less than corrosion rates of similar materials exposed in the industrial environment at Pittsburgh (4).
2. Figures 1, 2, and 3 show an envelope of curves for low-alloy steels previously tested in industrial atmospheres by others (5). Our A-242 Type 1 roof samples are well within this envelope. In Figures 1 and 2, the bridge-mounted A-242 Type 1 specimen curves lie close to or exceed the upper limit of the envelope.
3. In a comparison of the 30^0 from the horizontal specimens of our joint tests to the ASTM (3) tests previously conducted at Newark (Table 5), the plain carbon steel specimens from the joint tests yielded corrosion-penetration results substantially lower than those of the ASTM tests (3).
4. There were no significant differences in results due to specimen orientation, i.e., horizontal or vertical positioning.
5. Examination of sheltered specimens located at interior positions on the bridge structure revealed a comparatively heavy layer, or coating, of soil.
6. The A-242 Type 1 steel specimens exhibit roughly one-half as much corrosion penetration (mils) after eight years as the plain carbon steel (Figures 1, 2 and 3) for a given exposure location.

7. For a given material, roof specimens exhibit about two-thirds as much corrosion penetration as bridge-mounted specimens.
8. For a given material, the rate of corrosion for roof specimens has decreased substantially more than the rate for bridge specimens (Table 6).
9. For a given location, the rate of corrosion for A-242 Type 1 specimens varied from about 20% to 50% of the rate for plain carbon steel during the time period from 6-1/2 to 8 years (Table 6).
10. Roof specimens of A-242 Type 1 steel and of plain carbon steel indicate a trend toward a continually decreasing corrosion rate.
11. In the case of bridge-mounted specimens, the corrosion rate for all the plain carbon steel specimens showed an increase for the period of 6-1/2 to 8 years as compared to the 4 to 6-1/2 year period. A-242 Type 1 specimens in most (4 of 6) cases, however, exhibited a slightly decreased rate during the same period. There were 2 of 6 cases that showed a slightly increased rate.
12. No significant pitting was observed on any of the steel samples.

The results indicate that within eight years under environmental exposure conditions such as those in Newark, the corrosion rate of A-242 Type 1 steel can be expected to decrease. The rate for boldly exposed A-242 Type 1 roof specimens has come very close to leveling off, but the rate for A-242 Type 1 bridge-mounted specimens has not decreased to the same extent. This behavior is thought to occur due to two factors.

First, the bridge specimens are closer to the ground than the roof specimens and the bridge specimens were found to possess a heavy coating of dirt. These specimens are also in more sheltered locations, a factor that lengthens drying times when the samples get wet and is known to cause a more severe corrosion problem. For example, it was estimated by Horton (4) that corrosion rate may increase by approximately 50% as a result of sheltering. Therefore, it may be expected that these specimens would require a little longer to "stabilize", i.e., form a tight and protective oxide coating, and that corrosion will, therefore, continue during this stabilization period.

The second factor that may have contributed to the continued corrosion penetration on the bridge specimens is the opening to traffic of the roadway beneath Bridge #9. Since at the time of opening, the oxide coating of the specimens was not yet stable (4 to 6-1/2 year period on Figures 1 and 2), the specimens were left somewhat vulnerable to the more severe effects of salt spray as well as to the increased and prolonged wetness that would occur because of traffic spray. The question that arises in view of the foregoing discussion is the necessary time for the A-242 Type 1 specimens on the bridge to acquire a stable, protective oxide coating. The analysis of the [illegible] year samples should better define or answer this question. Another important question that arises from this discussion relates to how the A-242 Type 1 specimens would have corroded if they had been subjected to the salt-and-traffic spray conditions from the beginning. Some light will be shed on this matter with the continuation of the project and the installation of new specimens.

There are other questions as well that may not be answered by this research. A comparison of the eight-year corrosion-penetration results (Tables 2, 3, and 4) for the different specimens showed that the A-242 Type 1 steel corroded up to one-half as much as the plain carbon steel. This is not yet in conformance with the requirements of ASTM A-242 Type 1, where it is stated by definition that "(These) steels have enhanced atmospheric resistance of approximately two times that of carbon structural steels with copper...." and "...four times (that of) carbon structural steel without copper (copper 0.02 max.)". This apparent non-conformity may be partially explained through comparison of our plain carbon steel tests with tests of plain carbon done by others.

For example, Table 5, where results from 30^{0} from the horizontal roof specimens are compared to those of the ASTM tests in Newark (3), shows that the plain carbon specimens of this program exhibit a corrosion rate substantially lower than in the ASTM tests. For some reason the plain carbon steel specimens that were used for our tests are not providing results typically representative of plain carbon steel in an industrial environment as Pittsburgh for example (Figures 1, 2, and 3). Additional insight is provided by comparing the curves shown in Figure 4 to that in Figures 5 to 7 (data from tests conducted by Bethlehem Steel). These figures show corrosion curves for A-242 Type 1, copper-bearing, and plain carbon steel specimens in different test sites and different atmospheric conditions. Each type of steel had the same chemical composition for each site. Figures 4 and 5 represent industrial atmospheres, whereas Figures 6 and 7 represent rural and marine environments, respectively. Interestingly, the A-242 Type 1 specimens show only minor corrosion variation from site to site, with the exception of the marine atmosphere. Even then, the A-242 Type 1 steel appears to perform relatively better when compared to the other steels. By contrast, the copper-bearing steels, and more so the plain carbon steels, show marked variation from site to site. It is, therefore, apparent that plain carbon steel is highly sensitive to atmospheric conditions. Conversely, A-242 Type 1 steel is relatively insensitive, showing significant changes only in the presence of the most corrosive atmospheric conditions. While this does not explain why our plain carbon steel corrosion rates were lower than expected, it does point out the caution required in making a simple, direct comparison of corrosion rates between plain carbon and A-242 steels.

From the figures it appears, then, that the atmospheric conditions at the roof location in Newark are not as severe as originally thought. Questions now remaining pertain to how severe an environment the sheltering of a particular bridge structure may present and under what conditions A-242 Type 1 steel can safely and efficiently be used in an unpainted condition for bridge structures.

Our tests have shown that a bridge structure, through its sheltering or other causes,presents a more severe corrosion condition to some extent. With specific reference to the Eight-Mile Road Bridges (constructed of A-242 Type 1 steel) at Detroit, Michigan, (6,7) it is obvious that the sheltering provided beneath a bridge can be extensive enough to cause unpainted low-alloy steel to continue to rust, with flaking and scaling in evidence. The determination of whether or not a similar condition will occur beneath any particular bridge is a subjective evaluation. Since the object of using said steels is to avoid painting maintenance costs, it seems appropriate that a definite method of assuring adequate corrosion performance be employed.

Bolted connections and similar places where moisture could penetrate and would not readily dry also warrant consideration. To that end, reference is made to exposure tests conducted by Bethlehem Steel, where plates of unpainted low-alloy steel were bolted together to represent bolted connections. These connections were boldly exposed in a marine atmosphere only 800 feet from shoreline for a period of 11 years. After careful dissection and subsequent disassembly of these bolted connections, it was obvious by visual inspection that corrosion in the crevices or spaces of the bolted connections was minimal (Figure 8). There was no evidence that the interior interfaces experienced more severe deterioration than the fully exposed, exterior faces of the steel parts. Other exposure specimens at this marine site verify that the atmosphere at this site was several times more severe than the industrial atmosphere at Newark. Therefore, it appears that well-formed standard bolted connections do not pose a special problem with regard to corrosion.

The effects of pitting are also of concern since pits serve as stress raisers, and under some corrosive conditions brittle failures may occur. Visual evaluation of the specimens from the tests has not revealed any extensive, deep pits after eight years of exposure.

Since a plate, or wide-flange, girder on a typical bridge is basically comprised of horizontal flange and vertical web elements, it was desired to determine the effect of orientation on the corrosion rate of steels. Therefore, the corrosion tests include exposure of horizontal, as well as vertical specimens. The results, as may be seen by comparing Figure 1 to Figure 2, indicate that orientation is not a significant factor.

In addition to the evaluation of test samples, we periodically inspected and determined the performance of the A-242 Type 1 bridge superstructure. After weathering for 9-1/2 years, during two of which the bridge members were exposed to traffic fumes and water spray and soil, the steel surface in all locations is, apparently, performing as expected and has developed a thin, tight, adherent oxide, or rust, layer. In some cases this was difficult to see as the surface was covered with a light film of soil. However, in no instance was there any evidence of flaky, or scaly, rust.

V. Conclusions

The conclusions reflect the information gained after eight years of exposure of corrosion specimens at the two sites (office roof and bridge) in Newark and 9-1/2 years of weathering of bridge members.

1. The results from the exposure of plain carbon steel specimens imply that atmospheric conditions (with respect to corrosivity) in the test vicinity during the Bethlehem Steel/New Jersey Department of Transportation tests

were not as particularly severe to carbon steel as was originally expected. This observation was indicated from comparison with ASTM tests at Newark (3) and at other locations.

2. Roof-mounted specimens of A-242 Type 1 steel have yielded results that are in excellent agreement with the envelope of low-alloy steel corrosion curves obtained by others. On the basis of this observation, it is reasonable to conclude that all the A-242 Type 1 specimens of this test are materially representative of such steels and the results obtained are significant.

3. On the basis of the results from roof-mounted specimens and from comparison of these results with those obtained at three other exposure sites, it appears that plain carbon specimens are very sensitive to environmental conditions -- unlike A-242 Type 1, which does not vary widely.

4. The degree of sheltering that occurs among the girders of a typical composite bridge in New Jersey's highway network causes, as expected, a worse corrosion condition than the open-atmosphere bold exposure.

5. After eight years, the ultimate effect of such sheltering still remains undetermined. The causes behind the results obtained from these tests for the 6-1/2 to 8-year exposure period are obscured by the additional occurrence, during this period, of water-salt spray from highway traffic.

6. The rate of corrosion during the 6-1/2 to 8-year period was expected to decrease from the rate during the 4 to 6-1/2 year period. For the most part, such behavior did occur with the bridge-mounted A-242 Type 1 specimens. However, the reduction was less than expected. This appears to indicate that the traffic spray and sheltering combined can cause a more severe corrosion condition than the sheltering alone. The ultimate effect of the combined condition will hopefully be resolved with continued tests.

7. There is no evidence from these tests that the corrosion resistance of A-242 Type 1 steel is affected by orientation, i.e., horizontal or vertical positioning of the steel. Therefore, it is concluded that flange (horizontal) and web (vertical) elements, as well as other orientations having various slopes, will all possess approximately equal resistance to corrosion penetration, given the same environmental exposure conditions.

8. There was no significant pitting of the steels after eight years' exposure.

9. On the basis of other exposure tests conducted by Bethlehem Steel Corp., tightly bolted connections do not appear to present any formidable problems with regard to crevice corrosion.

10. While A-242 Type 1 steel is rather insensitive to different atmospheric conditions as compared to plain carbon steel, there are, nevertheless, certain conditions under which this steel should not be used in an unpainted condition. Currently, however, there does not appear to be an adequate method for determining unsuitable site environments.

11. The A-242 Type 1 bridge members have developed a thin, tight, adherent rust layer after 9-1/2 years' exposure.

VI. Recommendations

Although this is an interim status report on the subject research project, a considerable amount of information has been obtained and some additional questions have been raised. Accordingly, some important recommendations are offered.

1. Continuance of the project is essential with the A-242 Type 1 steel and a new series of tests with A-588 Grade B steel.

2. It is important that an accurate means of predicting the performance of weathering steel be developed.

3. Although the use of A-242 and A-588 steels is intended to reduce costs through decreased painting maintenance, the use of these steels for construction of New Jersey Department of Transportation bridges may result in increased initial construction costs. Use of weathering steel may also result in staining problems. This problem, however, does not appear to be insurmountable, and solutions are being sought in a parallel investigation.

4. At this time it is recommended that a thorough cost-benefit analysis commence in order to bring this project to a successful conclusion in forthcoming years.

5. Since the beginning of this research project there has been concern over structural joints, welded connections, stress corrosion cracking, and reduced fatigue capabilities. The performance of the bolted connection in the severe marine environment (as discussed in the Results and Significance section) serves to allay concerns involving crevice corrosion. It may be cited that the absence of the other phenomena on existing structures (built of unpainted low-alloy steel) is evidence of positive performance characteristics of this material. It is recommended, however, that a detailed, comprehensive inspection program be undertaken in order to confirm, as much as is practically possible, such evidence.

DISCUSSION BY N.J.D.O.T. AUTHORS

While, in general, the performance of low alloy steels in an unpainted mode is encouraging, the NJDOT has reservations about the general approval of its use as a primary structural element in our transportation network. Essentially, these reservations represent a cautious approach, to which we feel our driving public is entitled.

The corrosion results presented in the 8-year progress report were very interesting in two respects. First, the plain carbon roof samples (and similarly the bridge samples) led us to believe that the overall atmospheric conditions of the Newark vicinity were rather mild, in spite of the fact that the Newark site was chosen because of anticipated high atmospheric corrosivity. In view of this unanticipated mildness it was a little surprising that the corrosion results from the A-242 bridge samples were near the upper boundary of the corrosion envelope for low alloy steels. Since the bridge site was not open to traffic for the first 6½ years (following installation of the specimens), and therefore no salt spray occurred, we believe that this is an indication of an increased severity which is due to the nature of the bridge itself. This bridge is not atypical; we can reasonably expect other bridges to perform similarly. Also, in view of the performance of at least one other structure (8-mile road bridge in Michigan)[6,7] we cannot assume this to be a worst case situation.

The foregoing discussion accentuates a need for a method of accurately quantifying atmospheric corrosivity for any particular bridge, with regard to performance of unpainted, low alloy steel. This is of key importance to the design engineer, particularly in the case of transportation, whereby structures often incur loads in excess of those intended, and major in-service maintenance is very expensive and difficult. A quick practical method for predicting corrosion rates, other than in a general fashion, is not available, and unfortunately, materials specifications such as AASHTO M-161 and M-222 do not properly address themselves to this aspect.

While the difficulties in developing a specification are realized, it is nevertheless contended that AASHTO specifications M-161 and M-222 are ambiguous, misleading, and inadequate. The problem basically stems from the promotion of said steels as a structural material which need not be painted. Although the low alloy steels are promoted for such use, these specifications do not sufficiently address themselves to the matter. And while the specifications do not state that the steel is for use in an unpainted condition, they do allude to such use via their definitions, and also through a later statement whereby the manufacturer shall supply evidence of corrosion resistance satisfactory to the purchaser.

By definition the specifications state that the corrosion resistance of the low alloy steels is at least two times that of copper steel, and at least 4 times that of plain carbon steel without copper (Cu. 0.02 max.). After 8 years of exposure, our test specimens indicate corrosion resistance of only twice that of plain carbon steel. By "corrosion resistance" it is assumed that absolute amount of weight loss due to corrosion expressed as a percentage of the original specimen thickness, is the basis of comparison, although the "specifications" do not spell this out. Furthermore, there is no time duration over which the specified resistance must be achieved. Extension of the corrosion curves of Figure 1 to 20 years yields a comparative corrosion resistance (for roof samples) of only 2.6. Admittedly, this occurs because of the abnormally low corrosion of the plain carbon steel specimens (the low alloy specimens are well within expected corrosion levels). However, our point is that the definition of the specifications has been shown, via normal and accepted test procedures, to be factually incorrect, and hence misleading.

In order for the specifications on low alloy steels to be useful to the structural engineer, they must provide more truly definitive information. The following suggestions should help to clarify our concerns:

1. First, it is emphasized that a significant percentage (as much as 50%) of the A-242 and A-588 steels in use are actually used in an unpainted mode. Therefore, we think that the definitions in ASTM A-242 and A-588, and AASHTO M-161 and M-222 should be changed to directly state the inclusion of such use in a

conditional manner. Also, the statement regarding relative corrosion resistance (four times that of plain carbon steel without copper) should be removed. That statement is not necessarily (as required by definition) factually correct, nor does it provide the engineer with pertinent information.

2. The above referenced specifications are "Materials" specifications, and not "Use" specifications. Ideally, these specifications should include a statement regarding a method of test to determine how well the unprotected steel will perform in its intended environment. The lack of any such short term, or accelerated, test method was stated in the report. Therefore, the current statement whereby "the manufacturer shall supply evidence of corrosion resistance satisfactory to the purchaser", must suffice as a test method for material requirements. However, at this point in the specifications, a cautionary statement should direct the user to "Use" type specifications.

3. "Use" specifications such as AISC Manual of Steel Construction, 7th Edition, and AASHTO Standard Specification for Highway Bridges (1977) currently allow the use of the low alloy steels. Nowhere in either of those standards are there any meaningful statements regarding the use of said steels in an unpainted, exposed condition. These specifications should incorporate some statements of guidance. These could include comments with regard to "acceptable" environments, allowable

minimum thickness of sections, allowance for "full-life" sectional thickness loss due to corrosion, final surface preparation of the unpainted steel, and protection of appurtenant structural components from subsequent rust staining.

Aside from the apparent inadequacies of specifications, and aside from the slightly peculiar corrosion results, the authors wish to offer some concluding commentary. While we have some reservations about the full scale, general acceptance of the subject steels (unpainted), it must be emphasized that the concept of unpainted bridges is well worth the research efforts. The ever-expanding transportation network, the increasing demand upon the existing network, and the increasingly stringent controls for environmental protection during field painting would appear to make the use of said steel very attractive from an economics viewpoint. A cost-benefit analysis is, therefore, strongly recommended for the New Jersey Department of Transportation.

Finally, a considerable number of unpainted, low alloy steel bridges have been constructed during the past two decades. Since these structures are distributed throughout at least 25 states and in light of this research findings, the researchers believe that a special independent inspection team should be assigned to perform a detailed, in-depth inspection of selected structures in order to gather objective, concise information regarding the field performance of such structures.

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TABLE 1. COMPOSITION OF STEELS EXPOSED AT NEWARK, N.J.

	Composition, Percent by Weight									
Steel	C	Mn	P	S	Si	Ni	Cr	Cu	V	Mo
A-242, Type 1	.09	.65	.110	.032	.29	.66	.52	.270	-	.01
A-588, Grade B	.13	1.02	.008	.018	.22	.27	.64	.210	.062	-
Copper-Bearing	.02/.023	.34/.35	.003/.006	.011/.014	.01	.02	.02	.210	-	-
Plain Carbon	.07	.35	.009	.020	<.001	.01	.02	.021	-	-
Plain Carbon (ASTM Test)	.09	.34	.007	.018	.005	.02	.03	.024	-	.01

TABLE 2 EIGHT-YEAR CORROSION PERFORMANCE OF STEELS AT VARIOUS LOCATIONS, NEWARK, NEW JERSEY

(VERTICAL PANELS)

Steels	Location	Corrosion Penetration - Mils. (Average of 2 Specimens)				
		1 Year	2 Years	4 Years	6-1/2 Years	8 Years
A-242, Type 1	Roof- (Open Exposure)	1.23	1.51	1.86	2.13	2.22
	Bridge-L1 (Facia)	1.16	1.64	2.11	2.56	2.91
	Bridge-L2 (Sheltered)	0.96	1.50	2.42	3.13	3.63
	Bridge-L3 (Sheltered)	0.93	1.50	2.32	3.03	3.44
Plain Carbon	Roof- (Open Exposure)	2.06	2.92	3.86	4.56	4.90
	Bridge-L1 (Facia)	1.66	2.67	4.14	5.24	5.95
	Bridge-L2 (Sheltered)	1.29	2.29	4.12	6.03	7.29
	Bridge-L3 (Sheltered)	1.30	2.38	4.28	6.13	7.32

TABLE 3 EIGHT-YEAR CORROSION PERFORMANCE OF STEELS AT VARIOUS LOCATIONS, NEWARK, NEW JERSEY

(HORIZONTAL PANELS)

Steels	Location	Corrosion Penetration - Mils. (Average of 2 Specimens)				
		1 Year	2 Years	4 Years	6-1/2 Years	8 Years
A-242, Type 1	Roof (Open Exposure)	1.30	1.52	1.72	1.99	2.05
	Bridge-L1 (Facia)	1.15	1.72	2.40	2.93	3.19
	Bridge-L2 (Sheltered)	1.00	1.56	2.28	2.99	3.31
	Bridge-L3 (Sheltered)	0.94	1.49	2.30	2.94	3.26
Plain Carbon	Roof- (Open Exposure)	2.24	2.91	3.52	4.29	4.44
	Bridge-L1 (Facia)	1.69	2.69	4.56	5.81	6.83
	Bridge-L2 (Sheltered)	1.33	2.39	4.30	5.99	7.21
	Bridge-L3 (Sheltered)	1.30	2.31	4.30	6.11	7.22

TABLE 4 - EIGHT-YEAR CORROSION BEHAVIOR OF MATERIALS EXPOSED ON THE OFFICE ROOF, NEWARK, N.J.
(30^{o} FROM THE HORIZONTAL)

Steels	Corrosion Penetration - mils			
	1 Year	2 Years	4 Years	8 Years
A-242, Type 1 Avg.	1.06/1.06/1.08 1.07	1.30/1.34 1.32	1.60/1.64 1.62	1.77/1.99 1.88
A-588, Gr. B Avg.	1.29/1.40/1.57 1.42	1.70/1.80 1.75	2.00/2.12 2.06	2.46/2.57 2.52
Cu-Bearing Avg.	1.37/1.40/1.41 1.39	1.66/1.68 1.67	2.12/2.12 2.12	2.60/2.70 2.65
Plain Carbon	1.97/1.97/1.98 1.97	2.50/2.60 2.55	3.20/3.20 3.20	4.02/4.10 4.06

TABLE 5 - COMPARISON OF NJDOT/BETHLEHEM TESTS WITH ASTM TESTS AT NEWARK, N.J.

Material	Corrosion Rate, mils/year (based on 2 year results)	
	NJDOT/Bethlehem	ASTM (3)
Plain Carbon	1.28	2.00

TABLE 6 - COMPARATIVE PERFORMANCE OF STEELS AT NEWARK, N.J.

Steel	Location	Corrosion Rate (mils per year)				
		Vertical		Horizontal		30° from horizon
		4 to 6-1/2 yr.	6-1/2 to 8 yr.	4 to 6-1/2 yr.	6-1/2 to 8 yr.	4 to 8 yr.
Plain Carbon	Roof (open)	.28	.23	.31	.10	.22
	Bridge-L1 (open)	.44	.47	.50	.68	
	Bridge-L2 (sheltered)	.76	.84	.68	.81	
	Bridge-L3 (sheltered)	.74	.79	.72	.74	
A-242, Type 1	Roof (open)	.11	.06	.11	.04	.07
	Bridge-L1 (open)	.18	.23	.21	.17	
	Bridge-L2 (sheltered)	.28	.33	.28	.21	
	Bridge-L3 (sheltered)	.28	.27	.26	.21	
A-588, Grade B	Roof (open)					.12
Copper-Bearing	Roof (open)					.13

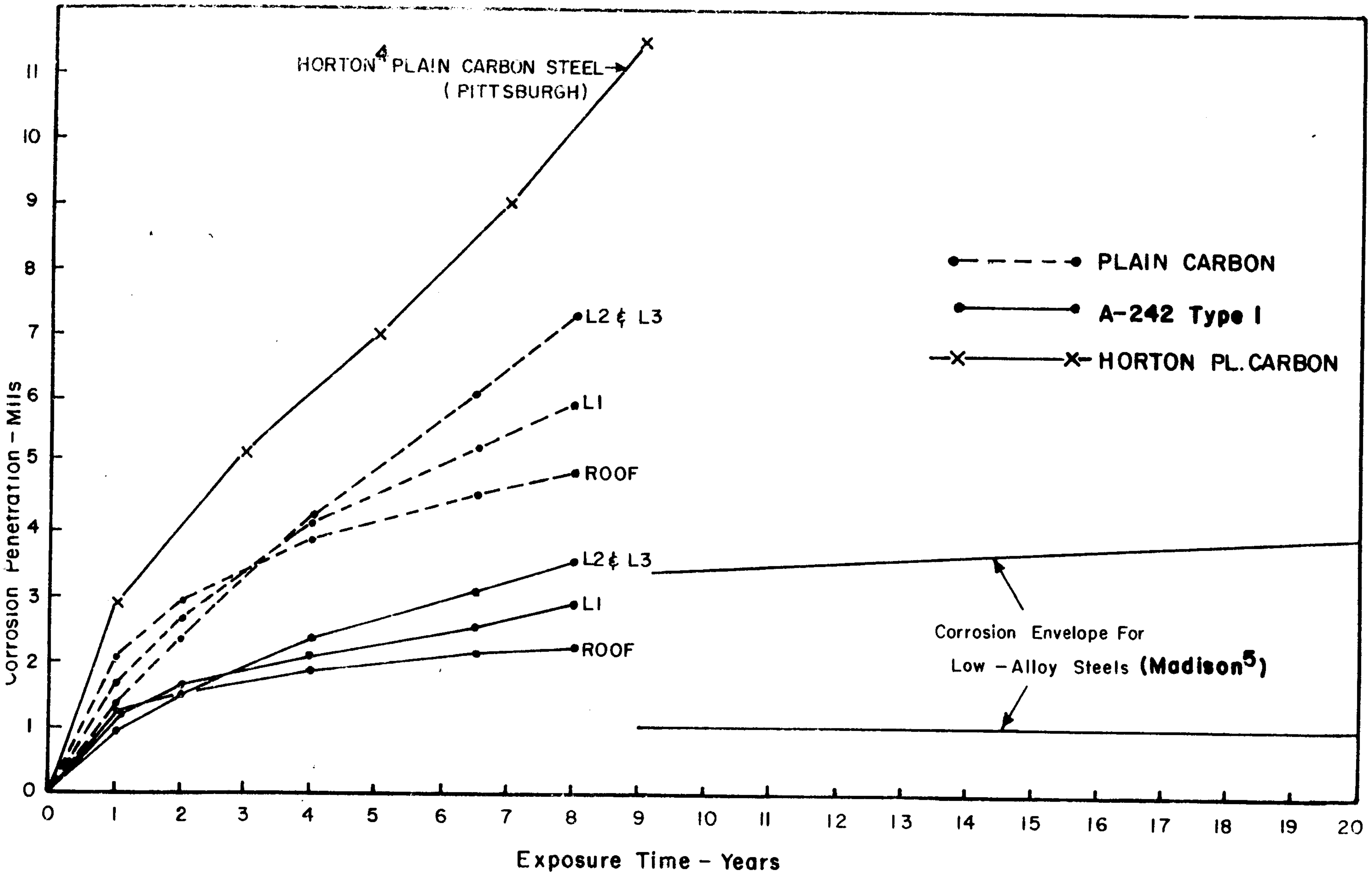


Figure I. Corrosion Penetration vs Time (Vertical Specimens)

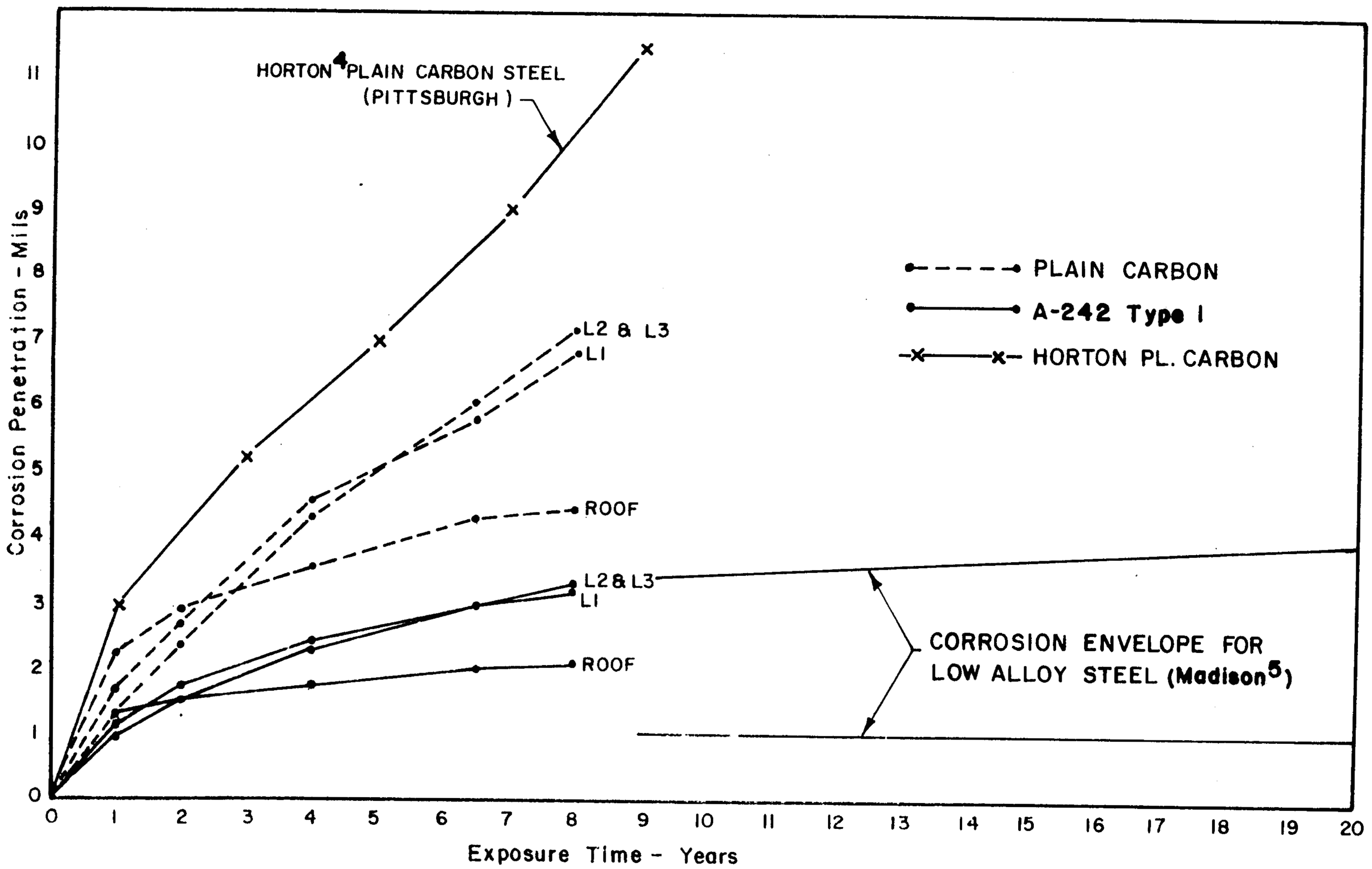


Figure 2 . Corrosion Penetration vs Time (Horizontal Specimens)

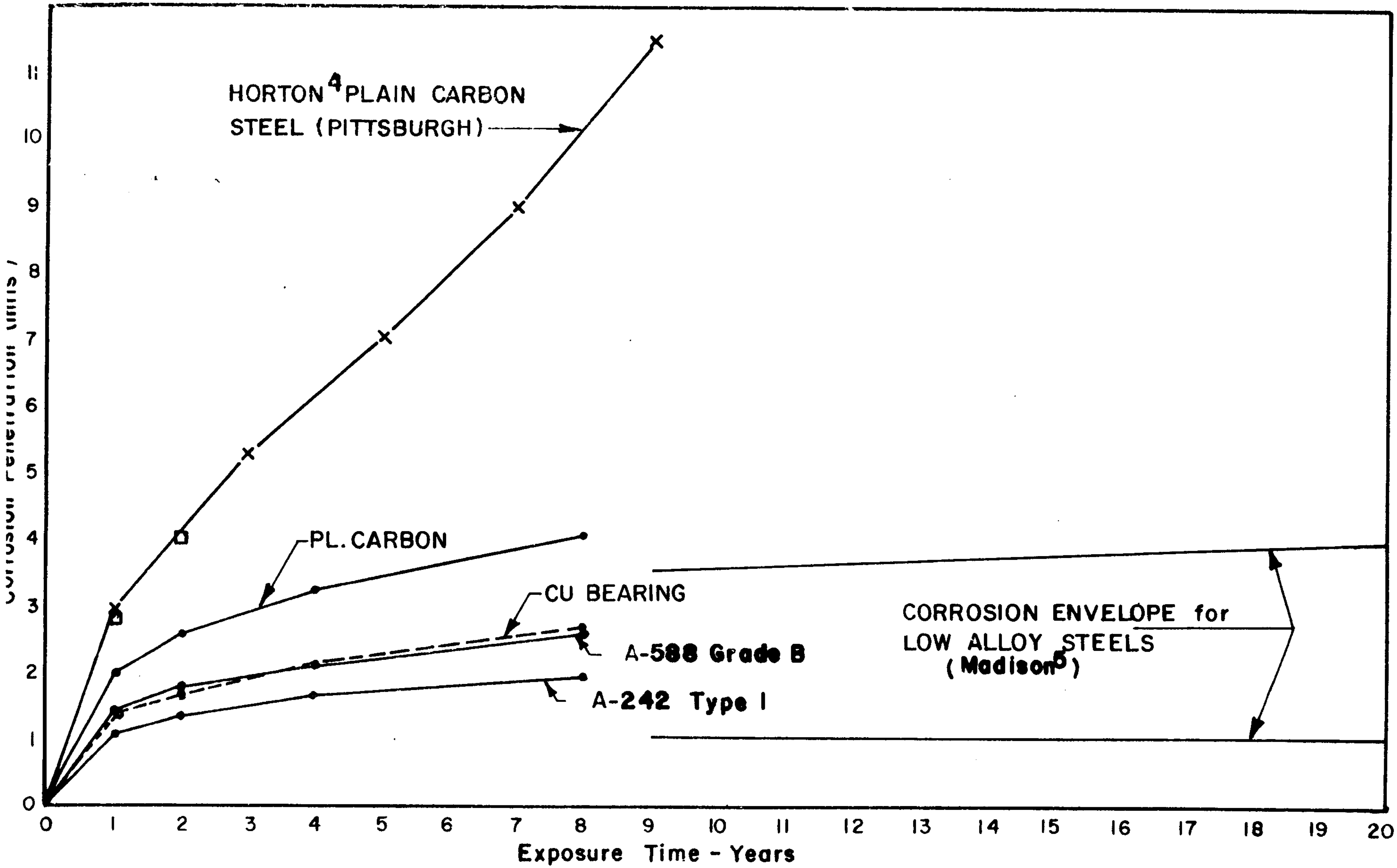


Figure 3. Corrosion Penetration vs. Time (30° to Horizontal, Roof Specimens)

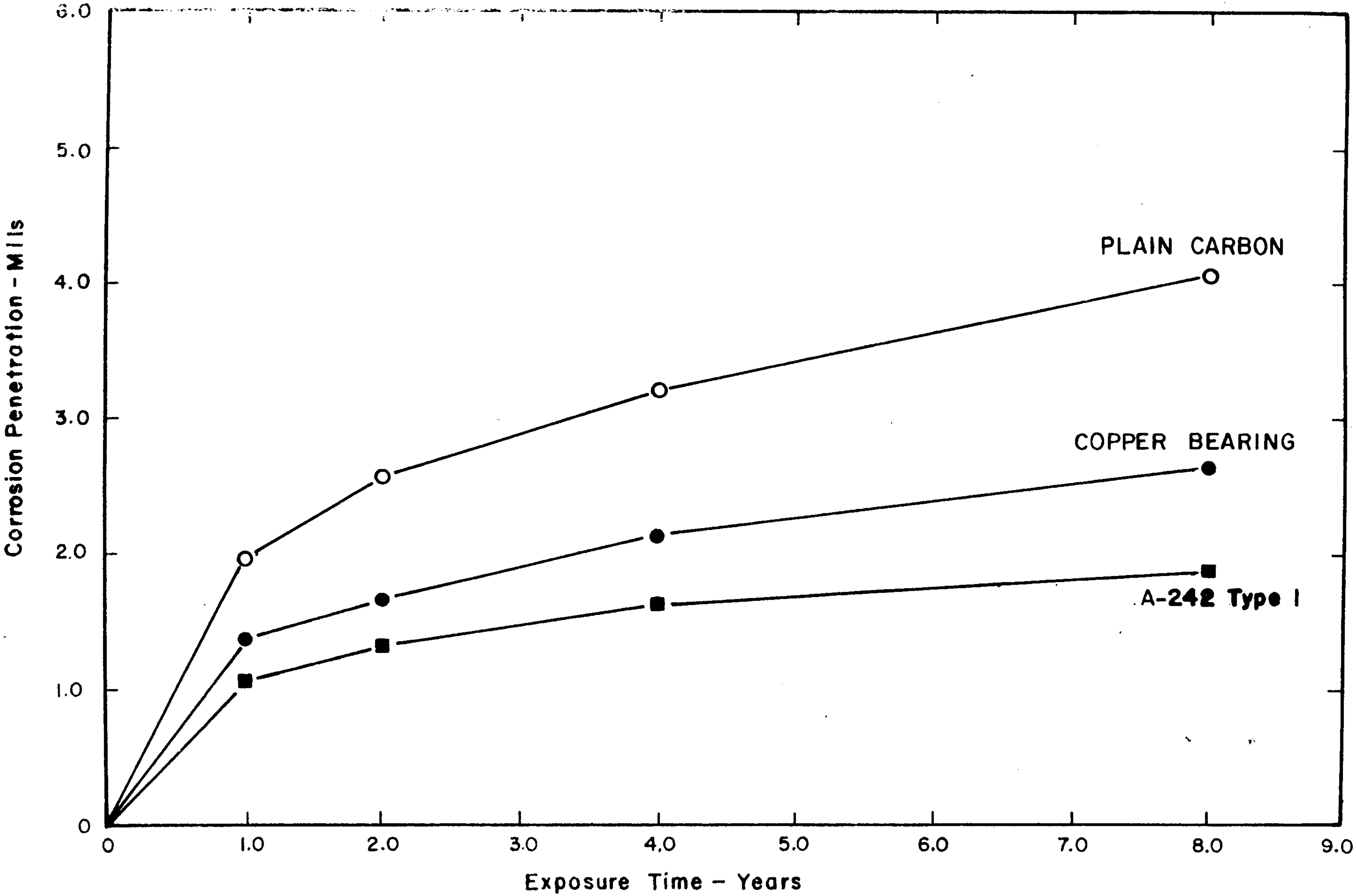


Figure 4. Corrosion Performance of Steels at Newark, N.J.
30° FROM HORIZONTAL

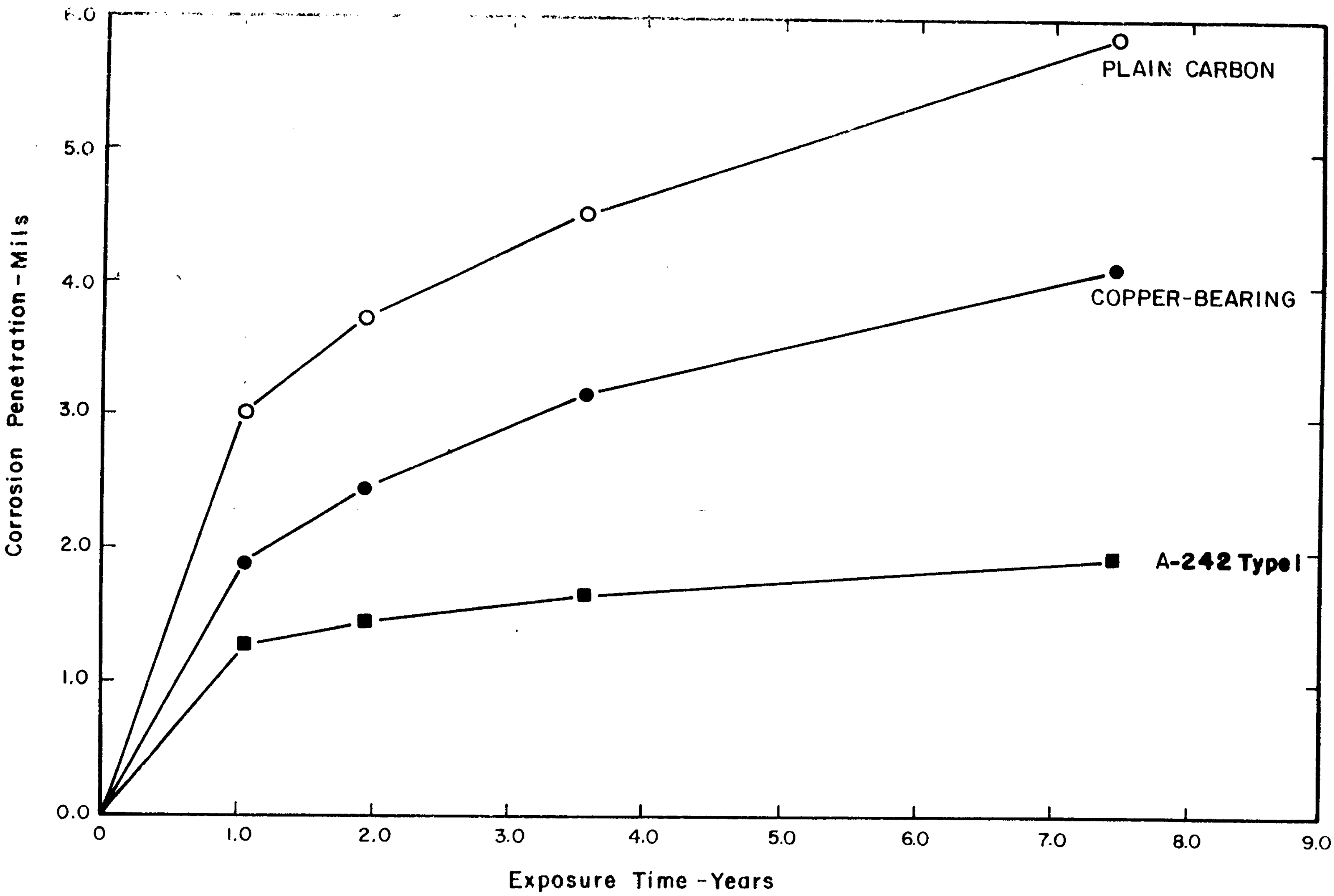


Figure 5. Corrosion Performance of Steels at Bethlehem, Pa.
30° FROM HORIZONTAL

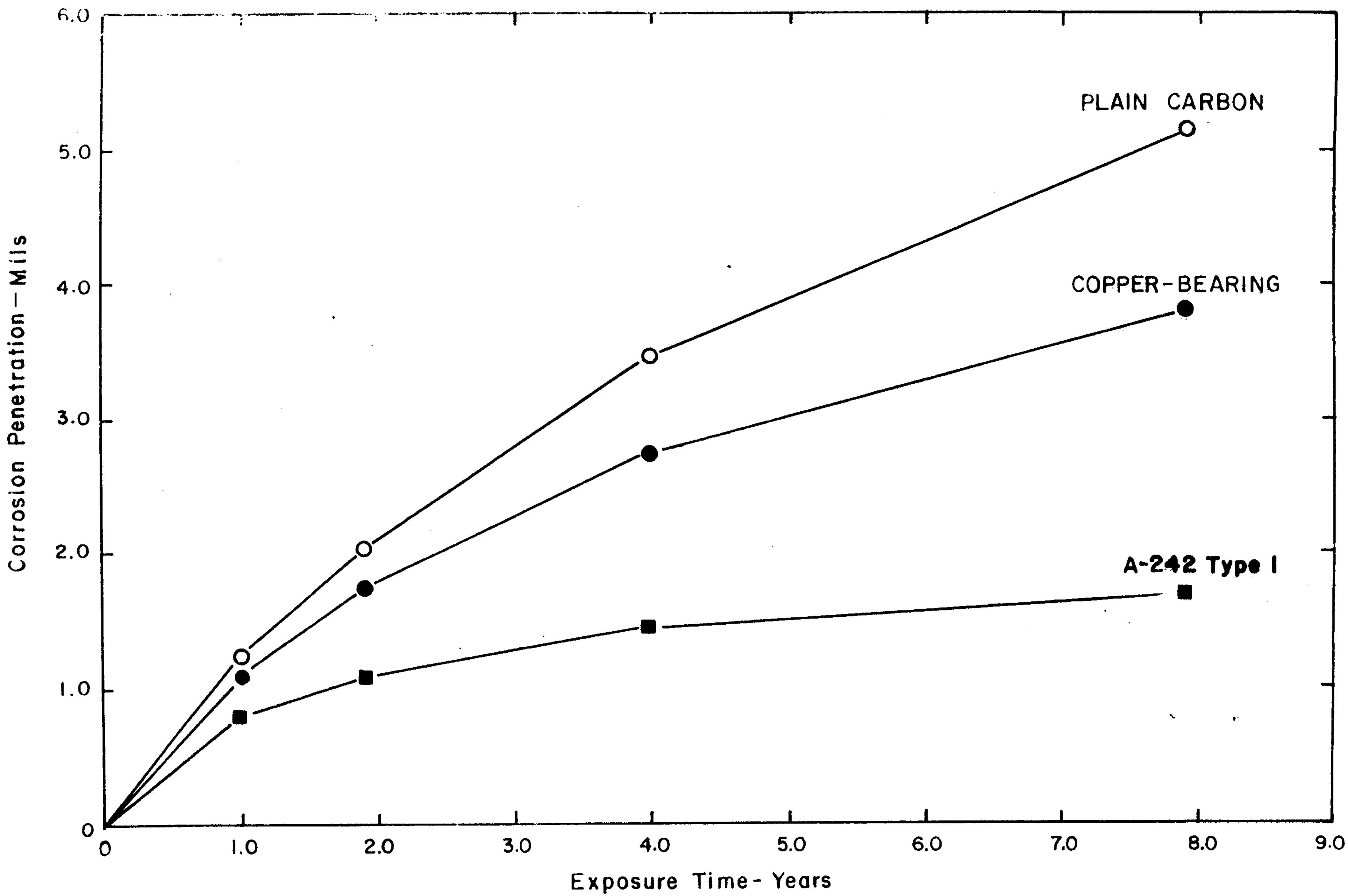


Figure 6. Corrosion Performance of Steels at Saylorsburg, Pa.
30° FROM HORIZONTAL

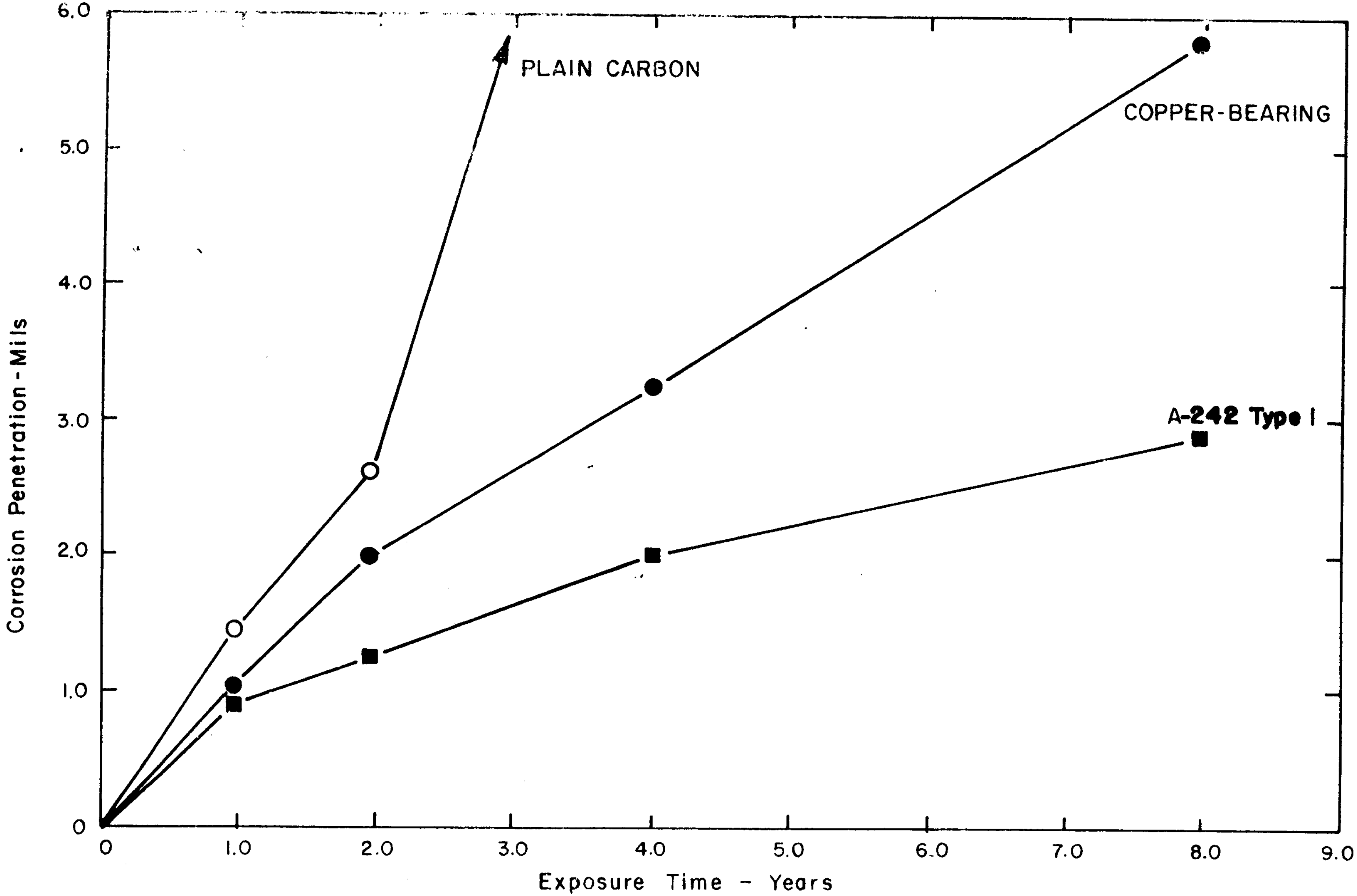
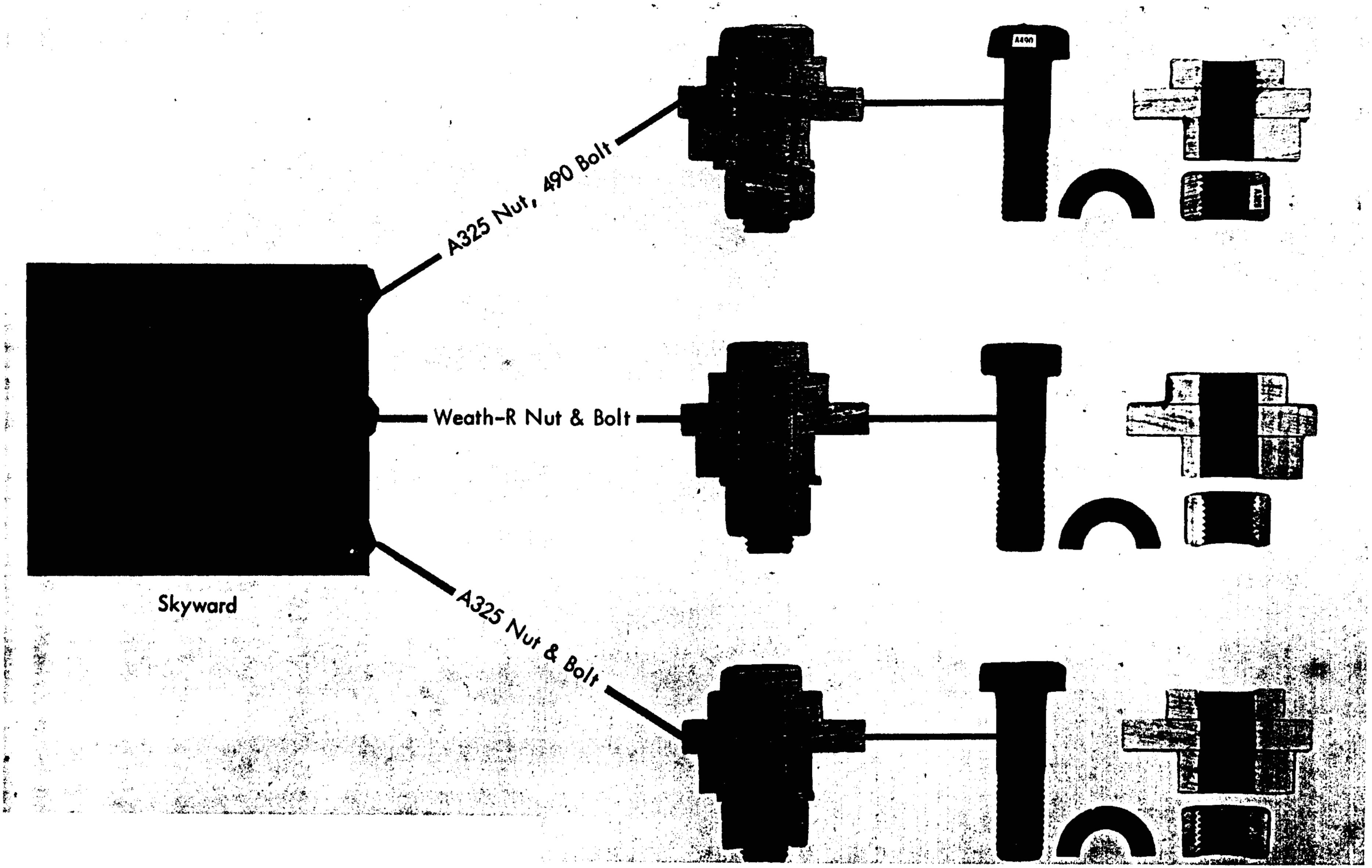


Figure 7. Corrosion Performance of Steels at Kure Beach, N.C.
30° FROM HORIZONTAL



STRUCTURAL FASTENERS ON MAYARI R PLATE AFTER 11 YEARS
AT THE 800 FOOT LOT, KURE BEACH, NC

(Weath-R, A325 - Type 1 Plain Carbon and A490 Fasteners)