HIGHWAY RESEARCH RECORD

Number 227

Snow and Ice Control

4 Reports

	Subject Area
26	Pavement Performance
31	Bituminous Materials and Mixes
34	General Materials
35	Mineral Aggregates
40	Maintenance, General

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Foreword

Maintaining adequate traffic flow in the snow belt during the winter months is a challenging assignment. Frequent or lengthy disruption to traffic during snow and/or ice conditions can seriously affect the economy of the country. More and more, snow and ice control is becoming a major problem for those who are charged with this responsibility.

In recent years, the use of chemicals in this operation has greatly increased. Questions have been raised as to the effect these chemicals have on auto body steel and in recent years, attention has been brought to focus on the effects the chemicals allegedly have on roadside vegetation and underground water supplies.

H. J. Fromm presents the facts relating to the corrosive effects of chemicals used in snow and ice control uncovered by extensive research performed under the auspices of the Department of Highways, Ontario, Canada.

W. E. Dickinson's paper, an abridgment of which is contained herein, was prepared and presented for the purpose of justifying the highway departments' use of these chemicals. The alleged pros and cons of chemical use and the benefits derived therefrom are explored extensively.

One of the original, but less sophisticated approaches employed for the maintenance of traffic under snow and ice conditions is the use of abrasives, i.e., crushed stone, cinders, etc. R. R. Hegmon and W. E. Meyer present the results of extensive research at the University of Pennsylvania with respect to the relative merits of different types of aggregates when employed as antiskid material. Those in charge of snow and ice control operations will find the facts revealed in this paper very interesting.

Snow and ice control by heating of pavements has been a subject of much research. Installation of various types of heat grids energized by steam, hot water and/or electricity have been studied extensively. L. David Minsk of the United States Army Cold Regions Research and Engineering Laboratory (U.S.S. CREEL) has investigated a new approach to the heating of asphalt surfaces. He has developed an asphaltic concrete which has been made electrically conductive by the addition of graphite directly into the mix. This theory was tested both in the laboratory and in the field; the field test performed satisfactorily over a two-winter observation period.

Those in charge of snow and ice control operations in all phases of transportation will find these papers of great interest.

—E. Donald Reilly

Contents

Corrosion of Auto-Body Steel and the Effects of Inhibited Deicing Salts

H. J. FROMM, Department of Highways, Ontario, Canada

Corrosion of auto-body steel was measured in eight representative areas of Canada. These areas varied from cold, dry to humid climates, and from low to high industrial concentrations. Atmospheric corrosion was measured by exposing test panels of standard auto-body steel in each selected area. Corrosion due to deicing salt was measured by mounting test coupons of the same steel on vehicles operating in the test area and by the use of traffic simulators in one test location. The traffic simulators were constructed and operated outdoors under completely natural conditions.

Cumulative corrosion curves were obtained using standard auto-body steel test coupons for unsalted, salted and salted with inhibitor conditions. This gave a comparative measure of the amount of corrosion occurring due to natural conditions, the increase due to the use of salt, and the effect of three different inhibitors in retarding the salt induced corrosion.

A laboratory test for evaluating inhibitor performance, carried out at both room temperature and at 32 F, is also described.

•CORROSION of automobile bodies has aroused public interest and protest over the past few years. It first became a problem in the late 1950's, and since that time, has caused considerable concern to automobile manufacturers and highway departments. Motorists have associated a large part of this damage with the salting of highways during the winter, and as a result, there is an ever-increasing demand for the incorporation of a corrosion inhibitor in the deicing salt. Before this can be done, several questions must be answered regarding the effectiveness of inhibitors and the economics of their use.

Stated in simple terms, the corrosion of auto-body steel is an electrochemical reaction (6) which occurs between the tiny anodic and cathodic areas on the surface of the steel plate. This reaction can be accelerated in several ways. Certain electrolytes, of which sodium chloride (salt), calcium chloride and ammonium nitrate are well-known examples, can also accelerate the reaction by increasing the electrical conductivity of the solution. The chloride ion is a small and very mobile ion which can readily penetrate the corrosion deposits and prevent them from slowing down the reaction (3).

Where heavy deposits of scale form, oxygen cannot reach the area under the scale, hence an oxygen concentration cell is set up. The metal under the scale then becomes anodic and goes into solution. This causes deep pits to form beneath the scale.

These reactions can be inhibited by preventing free access of oxygen atoms to the cathodic areas (cathodic inhibitors) or by providing ions which can react with the product of the anode reaction to form a film on the metal, which prevents further attack (anodic inhibitors). Two well-known cathodic inhibitors are calcium carbonate and polyphosphate (3). The latter inhibitor benefits, in building up its cathode protective film, from the presence of calcium and iron atoms. Two well-known anodic inhibitors are chromate and nitrites (3).

Paper sponsored by Committee on Snow and Ice Control and presented at the 47th Annual Meeting.

Another method of inhibiting corrosion is to coat the metal with another more electropositive metal. An example of this is zinc coating of steel or galvanizing. Here the coating is anodic to the base metal, and it corrodes, rather than the base metal.

The problem of preventing corrosion on the underside of an automobile is a complex one. Any crevices where dirt and moisture collect can encourage and accelerate corrosion. Areas such as those around headlights or right angle corners of baffles and areas where two pieces of metal are crimped together are all traps for dirt and moisture. Vehicles built in the late 1950's had many of these debris collectors and severe damage from corrosion was evident within two years. Since then, automobile manufacturers have introduced improvements in automobile design that eliminate as many as possible of these undesirable pockets.

Corrosion can also be accelerated by some types of undercoating. Any undercoat, such as many asphalt-based undercoats which dry out and become brittle, can cause corrosion problems. These undercoats crack, and each crack becomes a trap where dirt and moisture can collect. A good undercoat is one which remains flexible and has excellent adhesion to the metal.

The corrosion reaction begins whenever moisture comes into contact with unprotected steel, since oxygen is already present in the atmosphere. The free energy change is such that this reaction is inevitable unless one of the three components oxygen, steel or moisture is removed. An automobile, therefore, will corrode at all seasons of the year whenever the three components are brought together. The corrosion reaction is accelerated by some atmospheric contaminants such as the gases from automotive exhausts and domestic heating units. The questions to be answered are: How much of the corrosion occurring to automobiles during a year can be attributed to the winter period? Will corrosion inhibitors, if effective, be economical?

It is very difficult to inhibit the accelerating effect of deicing salt on the corrosion of automobile steel. Inhibitors are usually coated on the outside of the salt granules. Hence, they are dissolved with the first quantities of salt and splashed to the sides of the road, leaving salt with a much lower concentration of inhibitor on the road. If a cathodic inhibitor such as a polyphosphate is used, time is required to build up the cathodic protective film (3) and before this can happen considerable corrosion can occur. The frequent rains and snowfalls in many areas of the snow belt during the winter will wet the underside of the car with water containing no inhibitor, thus removing some of the protective inhibitor left on the underside of the car. The steel is then subjected to the full effect of saline solutions the next time salt is used.

Noncorrosive deicants have been proposed for use. The cheapest and most readily available is urea but its effectiveness is limited by its solubility in water. Urea is of little use at temperatures below 20 F (4). Its cost is also too high (more than ten times that of sodium chloride). Other deicants such as formamide and calcium formate are reviewed elsewhere (4). These materials, due to their high cost, are only suitable for special purposes such as the deicing of airport runways.

A few corrosion inhibitors are currently available commercially. One of these is a combined anodic-cathodic inhibitor which contains hexavalent chrome, and two others have the cathodic inhibitor sodium polyphosphate as their major component. One of the latter was tested by Adair in Toronto during 1961 (1). This investigation used an accelerated test method. Test rigs were used which simulated the action of traffic. The rigs were run four times daily and at all times snow, deicing salt and inhibitor were present in the tracks. If no snow was available then city water was used. The test was of four months duration from January to April. Since the test rigs were wetted all the time, the test coupons received a mixture of water, salt and inhibitor whenever the rigs were in motion. This is not typical of actual road conditions where the coupons would be wetted only a small portion of the time and when wetted, the inhibitor would vary in concentration from full strength down to none at all.

Use of the inhibitor in this test reduced corrosion by approximately 50 percent. Assuming that 50 percent of the total corrosion occurring on a vehicle is due to road salt and 50 percent to natural conditions, the best that can be hoped for from the use of inhibitors is approximately 25 percent reduction in total corrosion. There have been doubts that this reduction would be achieved in practice and, as a consequence, the use of inhibitors has so far been avoided by highway and municipal authorites.

The cost of using a corrosion inhibitor in road salt will vary upward from $3.00 per ton of salt, depending on the type and amount of inhibitor used. The Ontario Department of Highways currently uses about 250,000 tons of salt per year on highways. The municipalities also use large quantities of salt; Metropolitan Toronto used 80,000 tons in one year (1). The cost, therefore, of incorporating an inhibitor in all of the salt used in the Province will vary upward from $1½ million. Before such an expenditure is contemplated, much more must be known about the effectiveness of corrosion inhibitors in deicing salt.

SCOPE OF THE STUDY

The study was limited to four principal points of interest: (a) to determine the amount of auto-body steel corrosion due to natural causes; (b) to determine the amount of auto-body steel corrosion due to natural causes and deicing salts used on the highways during the winter period; (c) to determine the atmospheric corrosion in the test areas; and (d) to determine if inhibitors would reduce the corrosion due to deicing salts.

Since the study was concerned with the corrosion caused by deicing salt and its possible inhibition, the testing period was selected to include two complete winters and the intervening period. This was done in an attempt to eliminate the weather variable, i.e., if one winter was extreme the other might present a more normal pattern. The second winter also permitted evaluation of the effect of inhibitors on heavily rusted test coupons.

The study was divided into the following three phases which were carried out simultaneously.

Phase 1: Vehicle Tests—Phase 1 was designed to determine the amount of corrosion to unprotected auto-body steel fitted to vehicles traveling on highways in eight representative areas of Canada (Fig. 1). The five Ontario areas were chosen to obtain results that were representative of conditions throughout the Province (they would also be applicable to the major part of Canada and a large part of the northern United States). The three areas outside of Ontario were included so that the results obtained would be representative of all of Canada and the northern United States. Although each area is designated by the major city or town, the test vehicles (light maintenance trucks or station wagons) ran largely on the highways of the particular area.

Small test coupons of auto-body steel were carried behind one wheel of each of the test vehicles. The vehicles were then allowed to resume their routine highway work.

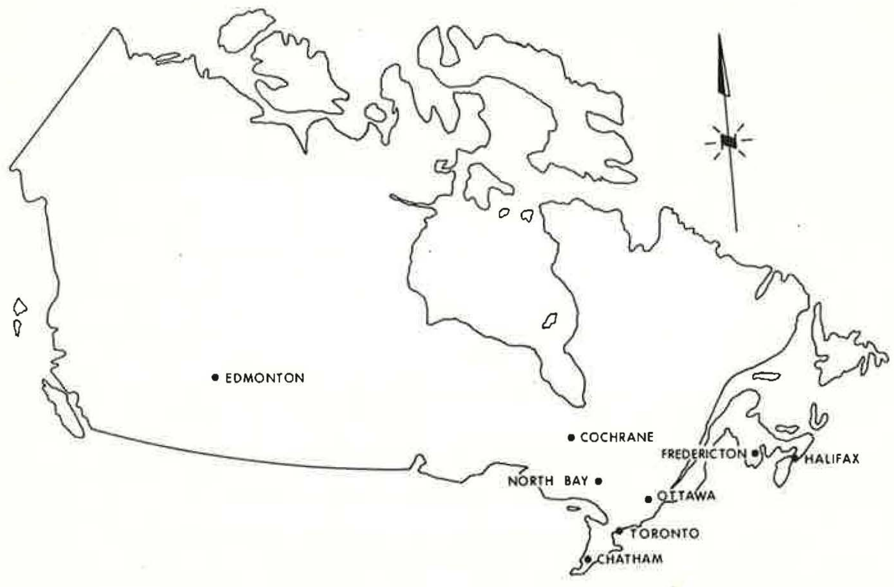

Figure 1. Vehicle and atmospheric test locations.

TABLE 1

EIGHT TEST AREAS

Area	Remarks
Edmonton, Alberta	Very cold winters, low humidity both winter and summer. Largely a farming area.
Cochrane, Ontario	A cold Northern Ontario area, more humid than Edmonton, little industry.
North Bay, Ontario	Less cold and more humid than Cochrane, two main heavily traveled highways in area, low industrial concentration.
Ottawa, Ontario	Weather somewhat similar to North Bay, but much higher population and industrial concentration.
Toronto, Ontario	Moderate winters, high humidity, very high industrial and population density.
Chatham, Ontario	Possibly one of the warmest areas of Southern Ontario, mild winters, high humidity, moderate industrial and population density, largely agricultural.
Halifax, Nova Scotia	Sea coast area, subject to salt drift from sea spray at all seasons of year. Moderate winters, high humidity, moderate industrial and population density.
Fredericton, New Brunswick	Similar to Halifax but located inland from the ocean; considerably less vulnerable to sea salt spray drift. This was the comparison area for the sea salt corrosion area of Halifax.

Some of the coupons were withdrawn at regular intervals to determine a cumulative corrosion curve for each area. New coupons were used to replace those removed. The eight areas were selected for the reasons given in Table 1.

Phase 2: Atmospheric Corrosion Tests—Atmospheric corrosion tests were also undertaken in the same areas. Test coupons similar to those used in the vehicle tests were exposed to the atmosphere in a central part of each test area. The coupons were periodically withdrawn and replaced to determine the corrosion rate and compile the cumulative corrosion curve for each area.

Phase 3: Corrosion Inhibitor Tests—Phase 3 consisted of five traffic simulators or "test rigs" which were designed and installed in Metropolitan Toronto. Each test rig (designed to simulate a motor vehicle) consisted of four automobile wheels (complete with tires) which were driven within the confines of a circular track (see Fig. 9). The test coupons of auto-body steel were mounted beneath fenders which partially enclosed each wheel. The test coupons were mounted so that they were in the wheel splash area at all times. The test rigs were operated outdoors under prevailing weather conditions. The testing was not accelerated by adding snow or water to the tracks. The conditions for each test rig are given in Table 2.

The results from these tests show comparatively how much corrosion was due to natural weather conditions alone (Test Rig No. 1), how much the use of deicing salt accelerated the corrosion (Test Rig No. 2 less Test Rig No. 1), and finally if any reduction in corrosion was achieved by the use of corrosion inhibitors (difference between Test Rig No. 2 and Test Rigs Nos. 3, 4, and 5).

TABLE 2

CONDITIONS FOR TEST RIGS

Test Rig	Conditions
No. 1	Natural weather conditions, snow plowed but no addition of deicing salts.
No. 2	As above but with the addition of deicing salt to clear the tracks.
Nos. 3, 4 and 5	As for test rig No. 2, but each of these test rigs had a different corrosion inhibitor added to the deicing salt.

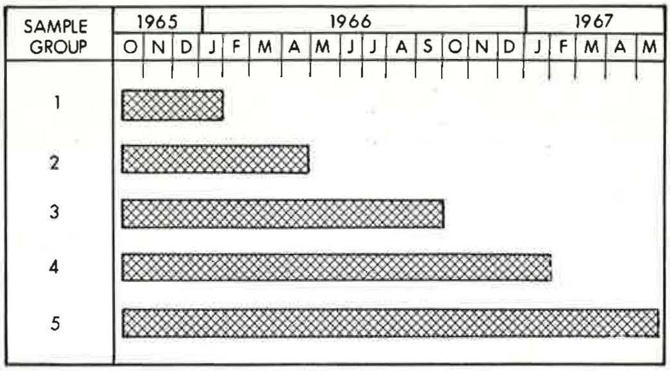

Figure 2. Vehicle corrosion coupon withdrawal plan.

EXPERIMENTAL DESIGN

The underside of an automobile consists of smooth flat areas, such as the sides of the fenders, where no dirt or water tends to accumulate, and creviced areas, such as lips at the edges of the fenders and around headlights, where dirt and water can accumulate. The creviced areas remain moist after exposure to water much longer than the smooth flat areas, hence corrosion is likely to be more severe. The test coupons were always exposed in pairs consisting of one flat and one creviced type, except for the atmospheric corrosion tests where flat coupons only were used. Similar shapes of coupons have been used by previous researchers to simulate conditions on an automobile (1, 2).

Results from the work cited (1, 2) indicated that considerable variation could be expected in the metal losses due to corrosion when test coupons are exposed for similar lengths of time under similar conditions. Because of this the study was designed to permit a very high degree of replication.

The coupon pairs were withdrawn successively throughout the 19-month test period to determine the cumulative corrosion curve for each area. When each pair of coupons was withdrawn it was replaced by a new coupon pair. The coupon withdrawal plan is shown in Figure 2. The analysis of the replacement coupons yielded additional information which was not obtainable from the cumulative curve, i.e., the amount of corrosion occurring during the second winter on the new coupons.

The coupon racks were designed for only 5 pairs of coupons because additional coupons would have to have been placed outside of the main splash pattern. Also, coupon changes were made at the required times by field personnel of the districts involved and simplicity was necessary to avoid serious disturbance of normal duties.

For the atmospheric corrosion tests, 20 flat coupons were mounted on a board and were exposed to the atmosphere in each test area. The coupons were withdrawn, 2 at a time, every 2 months throughout the duration of the tests. Metal losses for each pair of coupons were determined and then averaged to obtain the average metal loss due to atmospheric corrosion for each 2-month period. The withdrawal plan is shown in Figure 3.

The two positions on the board from which coupons were to be withdrawn at each withdrawal period were determined by using a table of random numbers. This was done to eliminate, as far as possible, any position variables (such as drainage across the board) which might exist. The cumulative corrosion curve was then plotted from the mean corrosion losses of groups 1 to

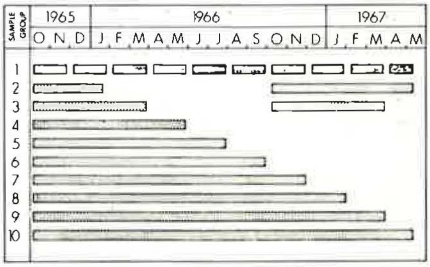

Figure 3. Atmospheric corrosion coupon withdrawal plan.

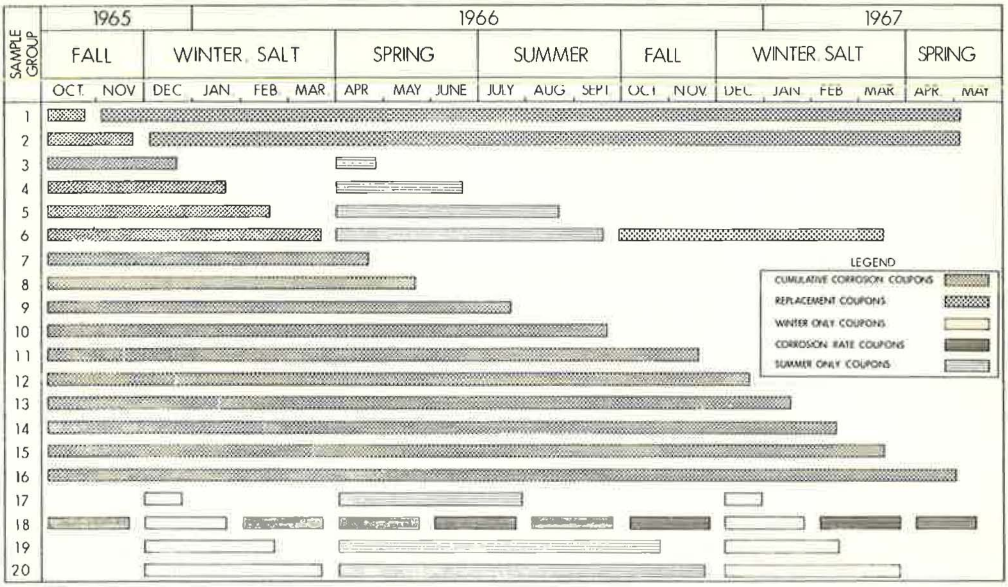

Figure 4. Traffic simulators corrosion coupon withdrawal plan.

10 (Fig. 3) against time. Since the corrosion on the metal coupons introduced some degree of passivation, it is not possible to estimate accurately the corrosion rate for any given period from a cumulative curve. In order to circumvent this problem new coupons were placed into Group 1 (Fig. 3) every 2 months. The analysis of these coupons then gave the corrosion occurring on new steel for that 2-month period and from this a better estimate of the corrosion rate could be obtained than that estimated from the cumulative curve.

The replacement coupons in Groups 2 and 3 duplicate for the second winter the periods covered by original coupons in Groups 4 and 3, respectively, for the first winter. This was done to enable a good comparison to be made between the natural corrosive conditions existing in the two winter periods in each test area.

The experimental design used for the traffic simulator (test rig) tests was based on a statistical model so that all results could be analyzed by regression analyses and analysis of variance techniques. This was necessary in view of the high degree of variation expected in the individual results.

Each wheel of the test rigs was designed to contain 40 pairs of coupons (one flat and one crevice per pair) mounted beneath the fender (see Fig. 10). This was to minimize variations so that at each coupon withdrawal two coupon pairs could be taken from each fender, making a total of 8 pairs withdrawn from each test rig at every withdrawal period. It was expected that the average of 8 coupons of each type would result in smoother cumulative corrosion curves.

It was known from previous work (1, 2) that a distinct splash pattern existed under the fenders and that all coupon positions did not receive equal quantities of spray from the wheels. To minimize this undesirable effect a randomization technique was used to select the positions in each fender from which coupons would be withdrawn. Once the withdrawal pattern was established it was kept the same for all of test rigs. Thus each sample group withdrawn consisted of 8 flat and 8 crevice coupons per test rig. The plan for the withdrawal of the sample groups of all five test rigs is shown in Figure 4.

The coupons from sample groups 1 through 16 provided the data to construct the cumulative corrosion-with-time curve for each test rig. These coupons are those which were put in at the beginning of the test in October and withdrawn monthly.

No deicing salt was used in the traffic simulator tracks until December of each winter period and none was used after the end of March in either of the two winters. Thus the initial coupons in Groups 1 through 16 were exposed to normal weather for two months (during which time some corrosion occurred) before they were exposed to deicing salt. The coupons in Groups 17 through 20 were exposed under somewhat different conditions. They were placed in the fenders at the beginning of December of the first winter, thus they received no corrosion before they were exposed to the salt. These coupons were used to form a cumulative corrosion-with-time curve for the winter period only. This gave a comparison of the effect of the corrosion inhibitors in preventing further corrosion on pre-rusted steel (Sample Groups 3 to 6) and on a new steel surface (Sample Groups 17 to 20). These effects were also obtained for the second winter by again placing new coupons in Groups 17 to 20 and comparing the results of Groups 12 to 15 and 17 to 20.

It was expected that the results obtained from Sample Groups 17 to 20 for the two winters, when subjected to the analysis of variance, would indicate the following: (a) the difference in amount of corrosion determined for each winter; (b) the difference in amount of corrosion determined for uninhibited and inhibited salt; and (c) the difference in the effectiveness of the three inhibitors on the corrosion of new steel.

The coupons in Sample Group 18 were withdrawn and replaced every two months in the unsalted test rig only. As in the atmospheric corrosion test, these coupons were used to determine the bimonthly corrosion rate.

At the beginning of April (end of the first winter) new coupons were placed in Sample Groups 3, 4, 5, 6, 17, 18, 19, and 20 in the unsalted test rig only. These coupons when analyzed provided data to form a cumulative corrosion-with-time curve for that part of the year when no deicants were used.

Finally, the coupons from Sample Group 16 provided a measure of the corrosion occurring over the entire period. Originally it was hoped that this group could be duplicated in order to obtain a better measure of the total corrosion. This was not possible with the test-rig design used, but a method was adopted that proved almost as good. New coupons were inserted in the positions occupied by Groups 1 and 2, when these groups were withdrawn at the end of October and November. Thus, when the tests were concluded these coupons had been subjected to an exposure that was only 1 or 2 months less than Group 16. This provided a relative measure of total corrosion and when averaged with the results of Group 16, a more accurate estimate of the corrosion and difference between the test rigs was obtained.

At no time during the test were any sample group positions allowed to remain vacant. Had this occurred, the splash and drip pattern within the fender might have been changed. Although Figure 4 shows no coupons in Sample Groups 17 to 20 for the first two months, these groups were actually filled with new coupons which were removed at the end of November to make way for the new first winter coupons. Some of the coupons removed were analyzed and the results tested by the analysis of variance to determine if there were any significant differences in corrosion between the rigs which might be caused by some structural difference. All other vacant spaces (Fig. 4) were filled with used coupons to maintain the splash and drip pattern constant at all times.

No heated compartments were used to simulate storage of a vehicle in a heated garage. This has been done (1, 2) and the results showed conclusively that marked increases in the amount of corrosion occur.

TEST EQUIPMENT

Corrosion Test Coupons

In order to maintain continuity and comparability with other similar investigations (1, 2) the same type of equipment and coupons were used. The corrosion test coupons were made to the same dimensions as those used elsewhere (1, 2) and were made from the same batch of auto-body steel used by Craik (2). The dimensions of both the flat and creviced coupons were 2 by 4 in. The ends of the flat and the sides and back of the creviced coupons were protected by three coats of a baking urethane lacquer. They were baked after the application of each lacquer coat and, prior to lacquering, were

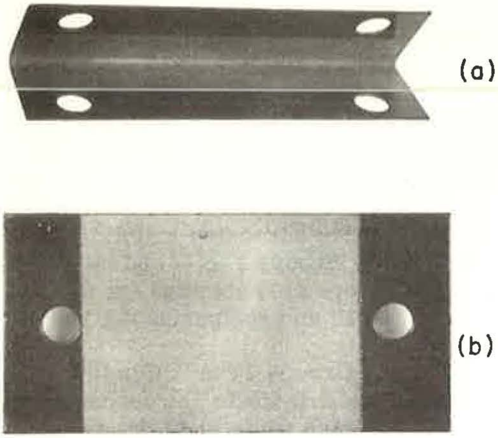

Figure 5. Test coupons: (a) creviced coupon and (b) flat coupon.

degreased, sand blasted and weighed. The coupons (Fig. 5) were produced by the same manufacturer that made the coupons used by Craik (2). The analysis of the steel used to make Craik's coupons was as follows: steel type—SAE 1010, 20 gage, aluminum killed, cold rolled and annealed; carbon—0.090 percent; sulfur—0.043 percent; phosphorus—0.004 percent; manganese—0.37 percent; silicon—0.14 percent; copper—trace; nickel—nil; chromium—nil; and molybdenum—nil.

The exposed area on the flat coupons was 2 by 3 in. on each side of the coupon—a total of 12 sq in. On the creviced coupons only a strip on the upperside of the coupon was exposed, this was 1 by 4 in. in size for a total of 4 sq in.

The coupons used in the test rigs were mounted in groups of 5 pairs (Fig. 6). Steel drill rod covered with polyethylene tubing was used to support the coupons. The coupons were separated from each other by polyethylene spacers to electrically insulate them from each other and other sections of the test rigs.

The coupons used for the atmospheric test were the same as the flat coupons except for one modification; the backs of these were covered with lacquer to prevent corrosion occurring on the back when it was attached to the test board.

As soon as the coupons were removed from the test vehicles, atmospheric board, or test rigs, they were brushed lightly to remove any dirt or loose rust, and were then dried immediately. The Toronto coupons, after drying, were stored in a desiccator until they were processed. The coupons from the areas outside of Toronto, after drying, were placed in plastic bags and mailed to the author for processing.

The method of processing the coupons was very similar to that used by Adair and Craik (1, 2). The coupons were first brushed to remove all loose rust. They were then immersed in a lacquer remover until the film was softened and could be removed by brushing. After rinsing off the lacquer remover, the coupons were immersed in a

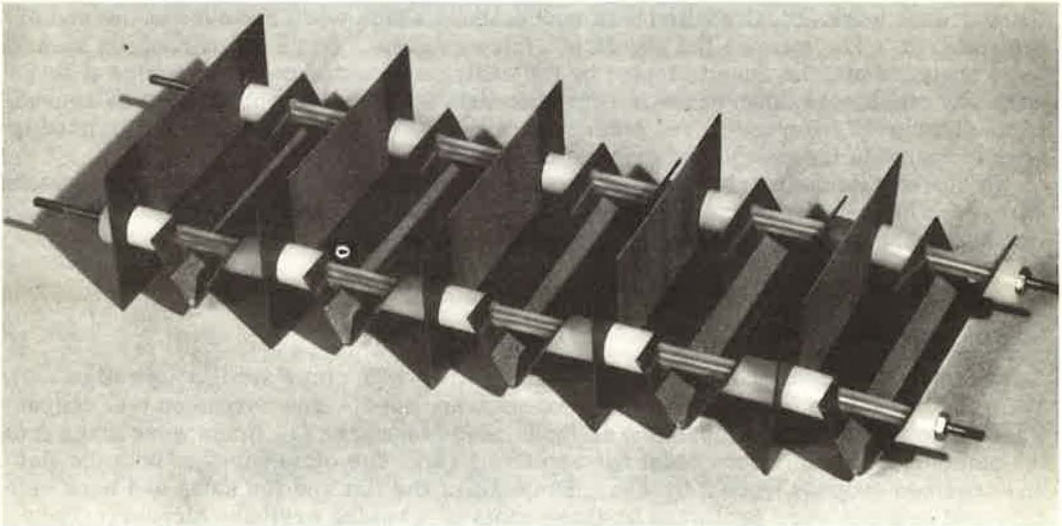

Figure 6. Test coupon assembly.

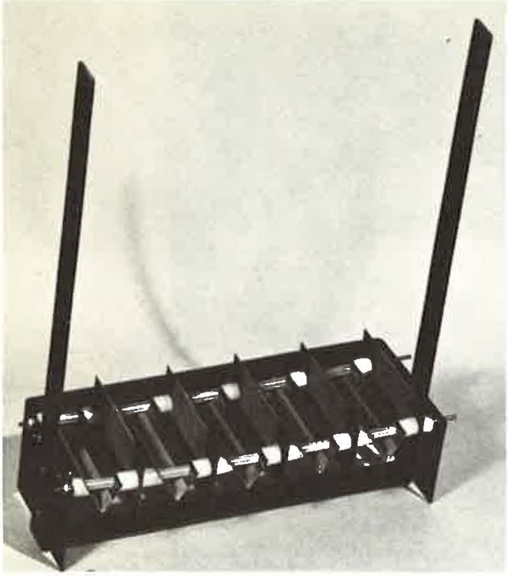

Figure 7. Vehicle test coupons mounted in bracket assembly.

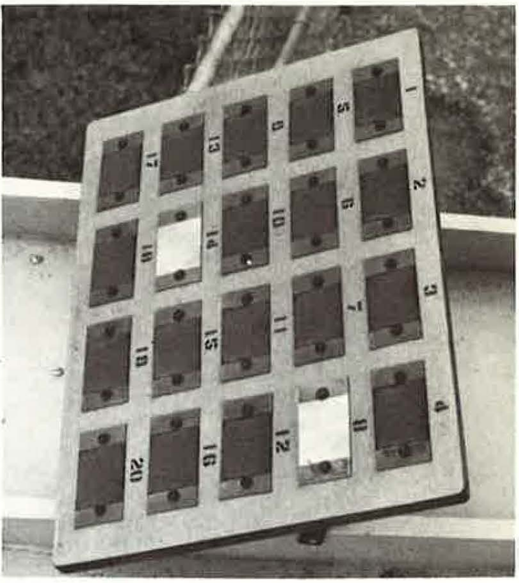

Figure 8. Atmospheric test coupons mounted in exposed position.

heated bath of inhibited hydrochloric acid (pickling acid). When the rust was all dissolved, the coupons were neutralized, washed with water, immersed in alcohol, dried in the oven, cooled in a desiccator and weighed. The difference in weight between the initial and final weights of the coupon after applying the "blank correction" was the amount of metal lost due to corrosion. This loss of metal was calculated as milligrams per square decimeter.

All results were recorded on punched cards so that the required statistical tests and evaluation of the results could be performed by computer.

Vehicle Corrosion Tests

In each of the eight districts, six highway service vehicles were used to carry the test coupons. These were mostly half-ton pickups, maintenance panel trucks and station wagons. In the Toronto area, the emergency patrol trucks operating on the Toronto bypass section of the MacDonald-Cartier Freeway were used. The 5 pairs of corrosion test coupons were mounted on a steel bracket (Fig. 7). The brackets were usually attached behind the right-rear wheel of the vehicle. Where they could not be mounted in this position, they were placed behind the right-front wheel.

When changing the coupon pair, the right-hand (outside) pair was removed and the remaining coupon pairs were slipped along the rods to fill the space; a new pair of coupons was then added to the left-hand end of the rods. This procedure was followed for all coupon changes; thus, the coupon pairs slowly progressed in time across the bracket from left to right, from which point they were removed. At the conclusion of the test the entire bracket was removed and returned to Toronto where all coupons, the remaining original coupons and the replacement coupons, were analyzed.

The operation of the test vehicles was not controlled, but they were restricted to the test area. At the conclusion of the test, a history of each vehicle was forwarded to the author and this included miles traveled, approximate operating hours and days per week, and whether they were garaged in or out of doors.

The atmospheric corrosion test coupons were mounted on a board which was placed in a clear, unobstructed area, facing south and inclined upward at an angle of 30 deg to horizontal. Each board contained 20 flat coupons. Figure 8 shows a set of these coupons in their exposed position at Toronto.

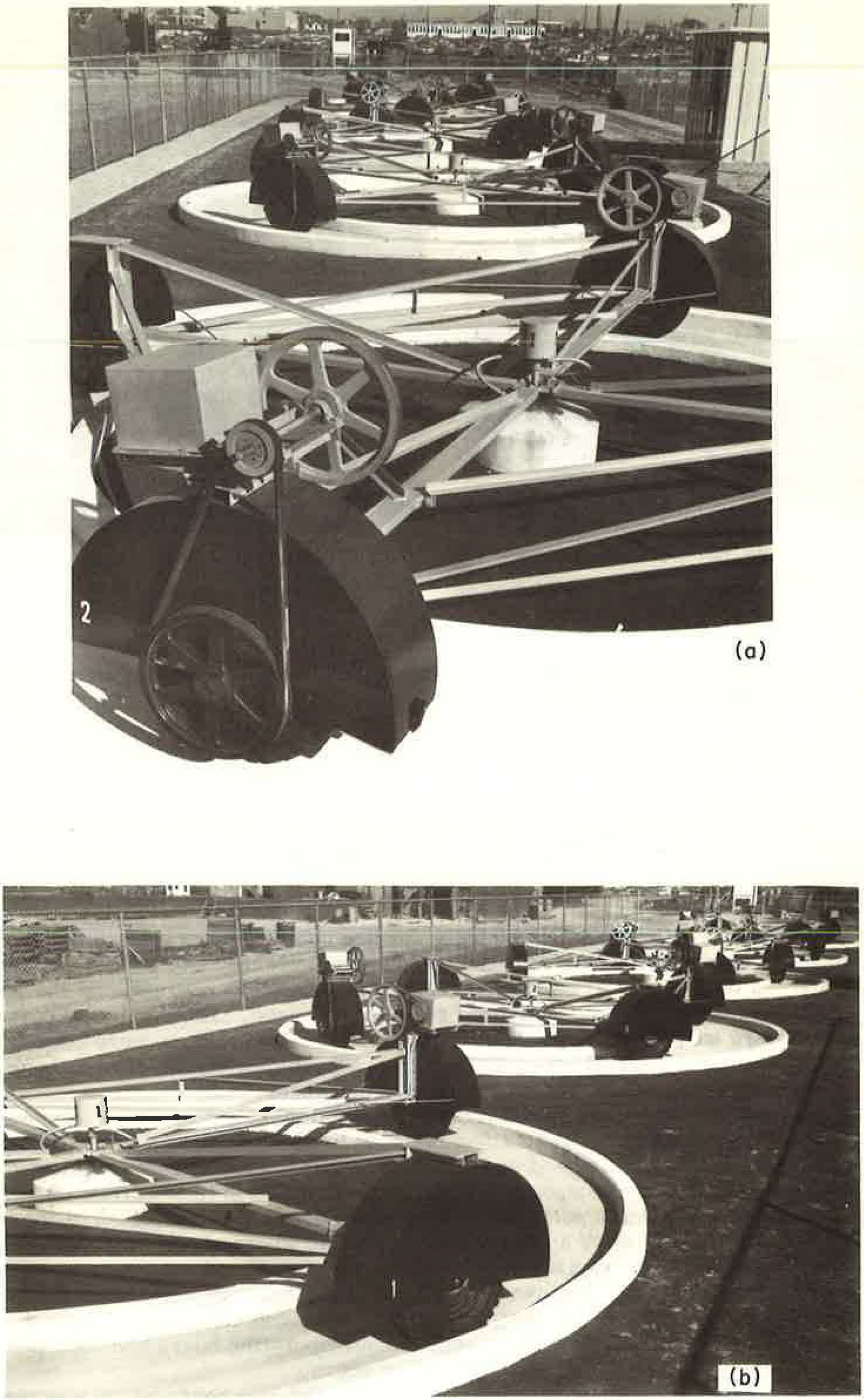

Figure 9. The traffic simulators (test rigs) showing (a) drive mechanism and (b) wheelpaths.

Traffic Simulators

The design of the traffic simulators (test rigs) was similar to those of Adair (1) and Craik (2) with certain modifications. The fender design was virtually the same as Adair's. The design and the method of pivoting the arms, so that each could rise and fall independently of the others, was that of Craik.

The simulators used by Adair had a speed, in the tracks, of approximately 25 mph which was much too fast since it threw the solutions out of the tracks too rapidly. Craik reduced this speed to approximately 18 mph which, in the author's opinion, was still a little too fast. The simulators used at Toronto were designed for a mean speed of 12.5 mph. The diameter of the track was 24 ft and it was constructed of doubly reinforced concrete with a burlap drag finish. Drain holes were cast into the curbs so that solutions would drain away as they do from roads and highways. Two views of the test rigs are shown in Figure 9.

The test rigs were driven by electric motors mounted on two of the four wheels of each test rig and the power was transmitted to the wheels by a belt reduction drive (Fig. 9a). The wheels ran in three paths (Fig. 9b); wheel 1 ran in the outermost track; wheels 2 and 4, the drive wheels, ran in the center path while wheel 3 ran in the innermost path. This arrangement helped to move the snow back and forth and mix in the deicant in much the same way as traffic does on the highway. Later in the first winter, scrapers were added behind each wheel to assist further in mixing the snow and, in the interest of safety, guardrails were built around each track. These features are shown in the winter photographs in Figure 10. The building, shown at the right of Figure 9a, housed the automatic electrical controls for the test rigs and was also used as a small laboratory where the exposed coupons were cleaned and analyzed.

Figure 10. Views of traffic simulators in winter.

The arrangement of the corrosion test coupons within the fenders is shown in Figure 11. The door at the rear of the fender is shown in the open position to display the arrangement of the coupons in 8 racks with 5 coupon pairs to each rack. All wheels of the test rigs were equipped with 7.60 snow tires. Figure 11 was taken at the start of the test before any corrosion had occurred on the coupons.

To simulate ordinary driving conditions, where a car is used and parked several times a day, the test rigs were run and stopped at time intervals. The operation was automatic and was controlled by an electric timer. Four runs of 15-min duration each, were made every working day (5 days per week).

Weather Records

Monthly meteorological summaries were obtained from the Meteorological Branch of the Department of Transport, Canada, for each of the eight areas. These summaries showed all weather data on a daily basis and allowed the correlation of weather conditions with corrosion. In addition to these summaries, which were records of measurements usually taken at an airport in the area, the actual weather conditions existing at the site of the test rigs were measured and recorded. These measurements included continuous records of temperature and humidity made with a thermohygrograph, and a record of precipitation made with a standard rain gage.

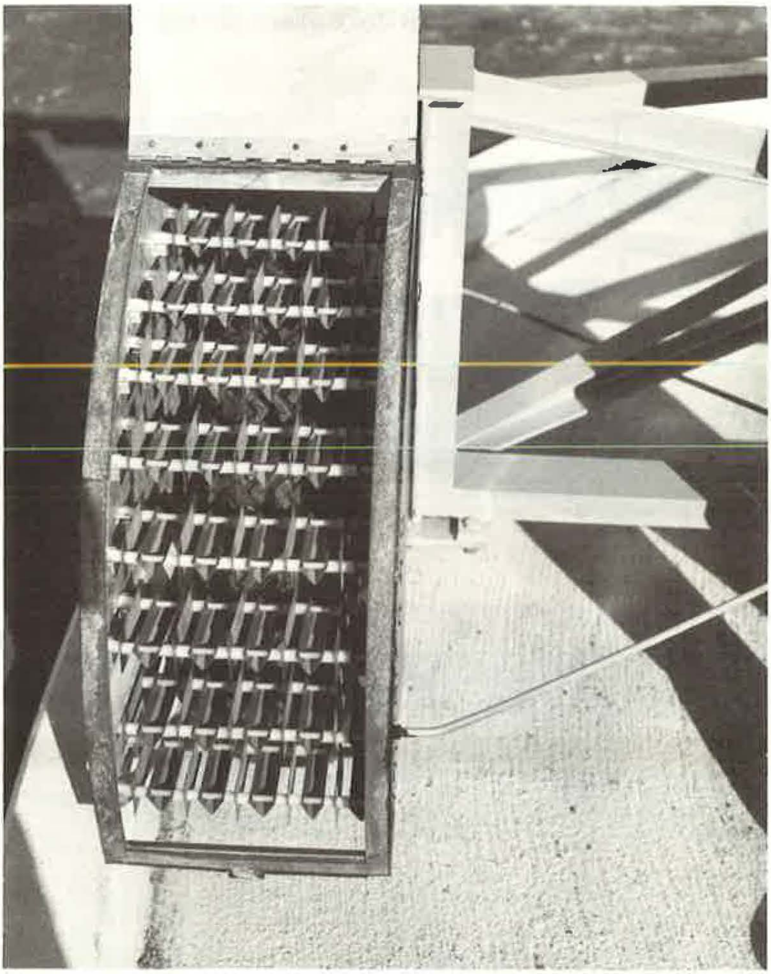

Figure 11. Test coupon arrangement inside the fender.

Deicing Salt and Corrosion Inhibitors

The deicing salt used was commercial rock salt (NaCl), all pieces passing the ¼-in. screen and retained on the No. 10 screen. All material passing the No. 10 screen was removed to insure easy distribution of the salt over the test track surface. The salt was spread evenly over the tracks by hand.

The corrosion inhibitors considered for use in the tests were required to fulfill the following criteria:

1. The proposed inhibitor had to be reasonably competitive in price with sodium hexametaphosphate $(NaPO_3)_X$. This product was chosen as a guide since it had been used by Adair (1).
2. The inhibitor had to be available in Ontario for blending with Ontario-produced rock salt.
3. The composition of the inhibitor had to be revealed to the Department of Highways. This was to prevent the testing of two products having the same composition.
4. Proof of the inhibitor's effectiveness under at least laboratory conditions, by an exhaustive series of tests, had to be established.
5. The inhibitor had to be nontoxic under the conditions of use. Here the word toxic is used in its broadest sense to mean any compound which is injurious to health; it was not only restricted to compounds which can cause death or serious injury when ingested, but it included compounds which could cause injury or discomfort by simply coming into contact with the skin. For this reason any inhibitors containing hexavalent chromium compounds were rejected as unsuitable for use (3, 6).

The three inhibitors selected for testing were as follows:

Inhibitor A—An impure hexametaphosphate. This compound is removed at an intermediate stage in the process of making pure, food grade, hexametaphosphate. It contains some metal impurities such as iron. To this compound 10 percent by weight of calcium chloride was added. The latter compound was added to assist the formation of the cathodic inhibiting film.

Inhibitor B—A finely divided metal powder, electropositive to iron, and treated with a surfactant to render it readily dispersible in water.

Inhibitor C—A proprietory product reputed to have both anodic and cathodic inhibiting properties. This product was also reputed to be effective as an antifreeze for salt piles stored outdoors in very cold weather.

The corrosion inhibitors were all finely divided and were readily coated on the exterior of the salt granules. This was accomplished by weighing the required quantity of salt into a clear plastic bag, then weighing-in the inhibitor. The top of the bag was then closed by twisting to trap as much air as possible inside the bag, which was then shaken to distribute the inhibitor over the surface of the salt. All inhibited deicing salts were prepared as required.

The inhibitors were used in the concentrations recommended by their manufacturers. The following are the concentrations, expressed as a percent by weight of the deicing salt: inhibitor A, polyphosphate—1 percent; inhibitor B, metal powder—0.5 percent; and inhibitor C—0.5 percent.

Plowing and Salting Procedures

After each snowfall the snow was removed to a depth of ½ to 1 in. by shoveling. Then salt (or inhibited salt), as applicable, was added in the tracks of the test rigs to thaw out the remainder. The tracks were of such an area that the addition of 1-lb salt to a track was equivalent to the addition on the highway of 500-lb/mi of two-lane road. However, although 500 lb/mi or less will leave a road "center-bare," 1-lb of salt per track was not sufficient to clear the snow completely out of the track. Consequently, 2 lb of salt was placed in each of the tracks (except Test Rig No. 1). This amount usually turned the snow to slush, which was then splashed out by the action of the wheels. Occasionally when ice formed in the tracks larger quantities of salt (4 to 6 lb per track) were required to clear them. The unsalted test rig (No. 1) tended to build up a layer of hard-packed snow and ice. This sometimes had to be removed by shoveling when the temperature was just above the freezing point, because bumps formed which caused the wheels to bounce and there was a possibility that the coupons would become dislodged.

During the first fall and winter of the test, road dirt was added to the test tracks in an attempt to build up dirt poultices on the coupons. This was done because it is this material which collects in crevices and holds moisture, thus speeding up the corrosion process of automobile bodies.

Several types of dirt were used, including crushed-rock screenings and sandy clay. Some of the material was splashed into the recess of the creviced coupons but never in large quantities. As soon as it rained all of this material washed out, and because of this the attempt was abandoned after the first winter.

EXPERIMENTAL RESULTS AND DISCUSSION

General Observations

Weather Records—The weather conditions in each of the eight areas during this test are shown in Figures 12 through 19. Each graph shows the daily temperature range and the amount of precipitation. The weather was abnormal in two aspects. The first winter, especially in the Toronto area where the test rigs were running, was below normal in the amount of snow and the number of snowfalls requiring plowing and salting. The Toronto area also suffered a 6-week drought from mid-June to the end of July. This had a marked effect on the corrosion, reducing it to a low level.

Snowfalls and Salt Usage—The weather conditions in Toronto during the two winter seasons (salted period) are given in Table 3 (see Fig. 16). The number of rainfalls and snowfalls per month are given with the total precipitation. The number of times the tracks were salted per month and the total monthly salt usage, in pounds per test rig, are also given. During the second winter more snow fell, and salt had to be added on 24 days, compared to 17 days for the first winter. This explains, in part, the higher amount of corrosion encountered during the second winter.

Several times during the two winters the brine concentration in the test rigs was measured. When the snow or ice had been just liquified the salt concentration ranged between 2.5 to 3.5 percent.

Remarks on the Observed Corrosion of Test Coupons

During this investigation, an unexpected type of corrosion was encountered which complicated the interpretation of the results from the latter half of the investigation—corrosion under the lacquered ends of the coupons.

The corrosion test coupons were lacquered to protect them from corrosion where the polyethylene spacers touched the coupons. These places would tend to retain moisture and cause excessive corrosion. Another purpose was to keep the identifying number, stamped into the coupons, from being obliterated. After 8 months' exposure the coupons

TABLE 3

WEATHER CONDITIONS AND SALT ADDITIONS

(Test Rigs Toronto)

Item	Winter 1965—1966					Winter 1966—1967				
	Dec.	Jan.	Feb.	Mar.	Total	Dec.	Jan.	Feb.	Mar.	Total
Operating days	21	19	20	22	82	20	14	16	22	72
Total runs	84	74	79	80	317	79	47	54	85	265
Days salt added	3	6	5	3	17	6	5	8	5	24
Times salt added	4	13	6	5	28	7	6	8	7	28
Amount of salt, lb.	7	25	12	9	53	11	30	28	16	85
Days rain	16	9	11	14	50	11	18	15	7	51
Total precipitation, in.	2.51	2.39	1.20	2.19	8.29	3.34	2.18	1.67	0.83	8.02
Days snow	8	8	8	5	29	4	9	7	5	25
Total snow, in.	4.10	27.1	6.3	4.6	42.1	6.0	21.7	16.3	9.1	53.1

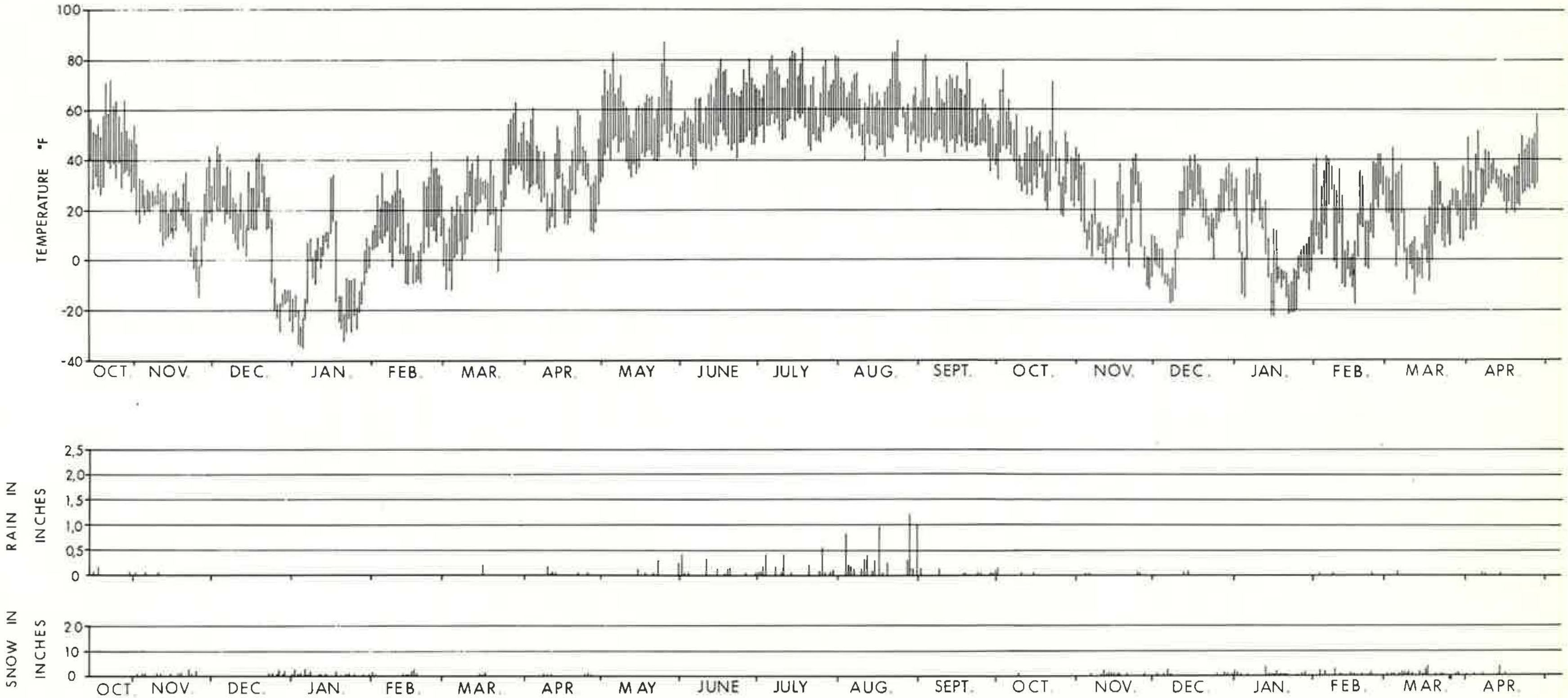

Figure 12. Weather records—Edmonton.

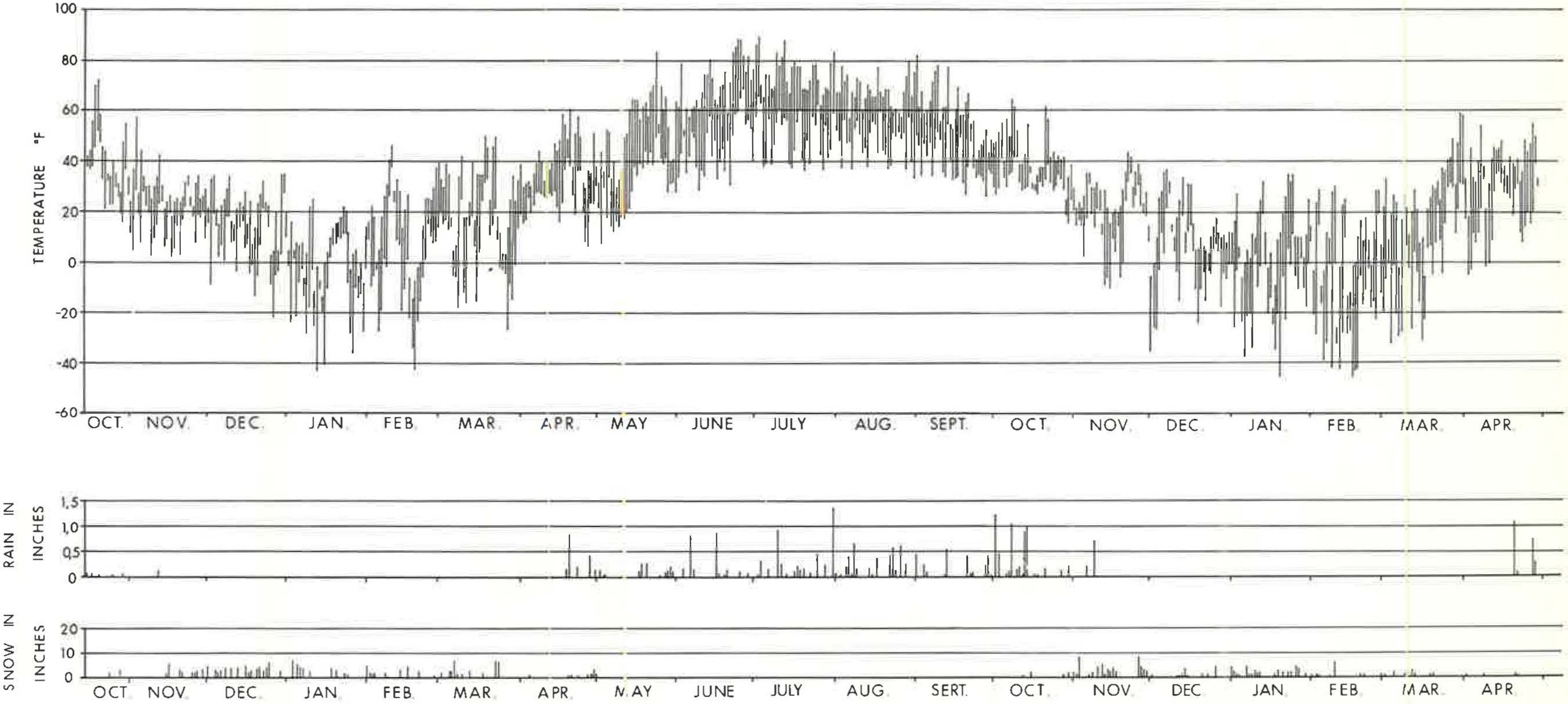

Figure 13. Weather records—Cochrane.

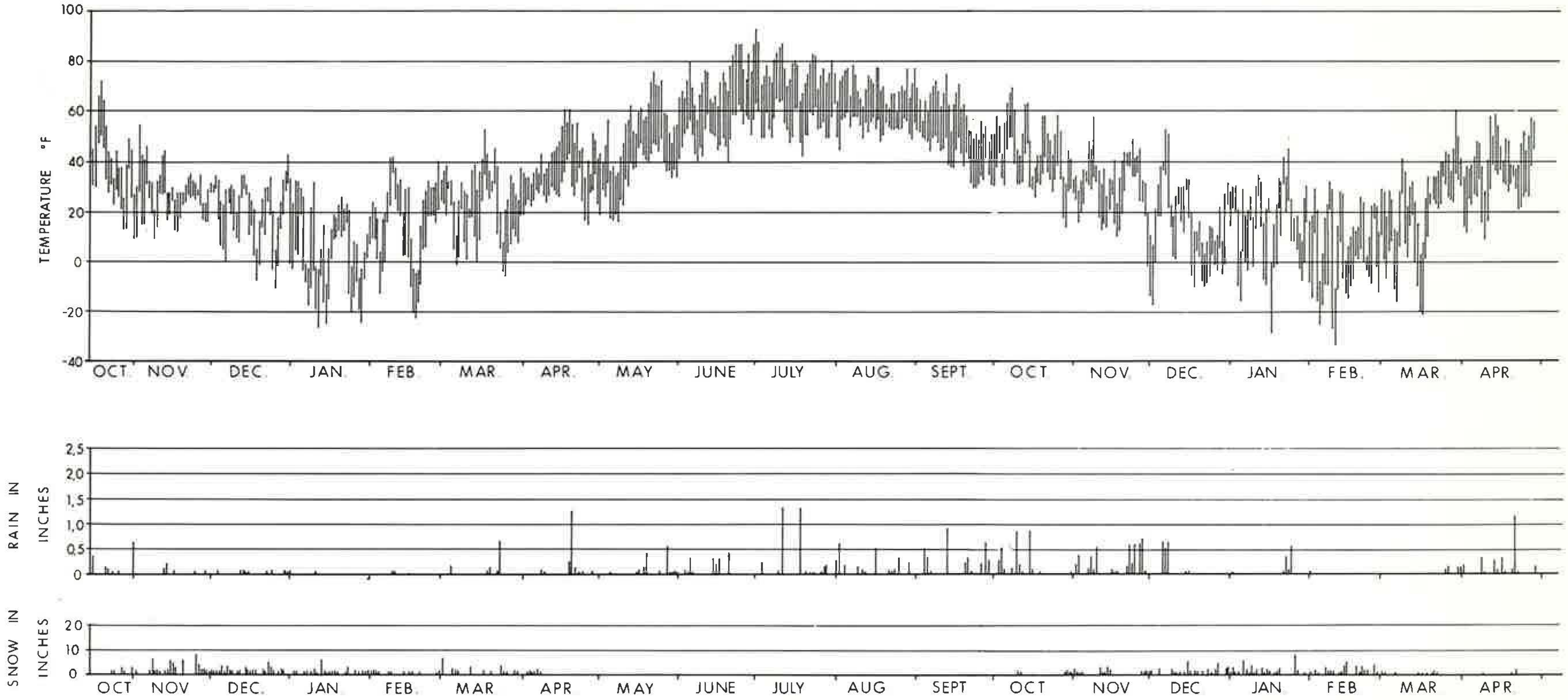

Figure 14. Weather records—North Bay.

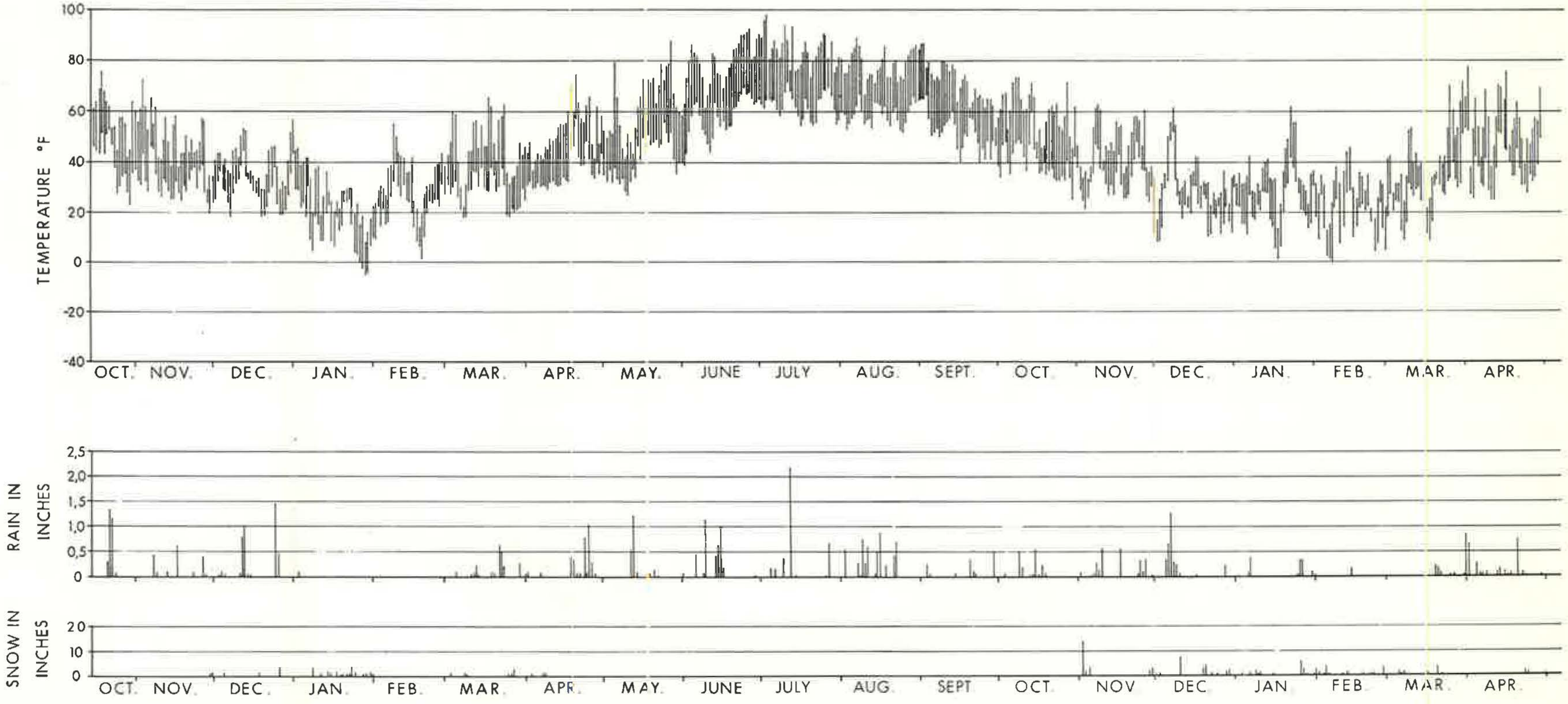

Figure 15. Weather records—Chatham.

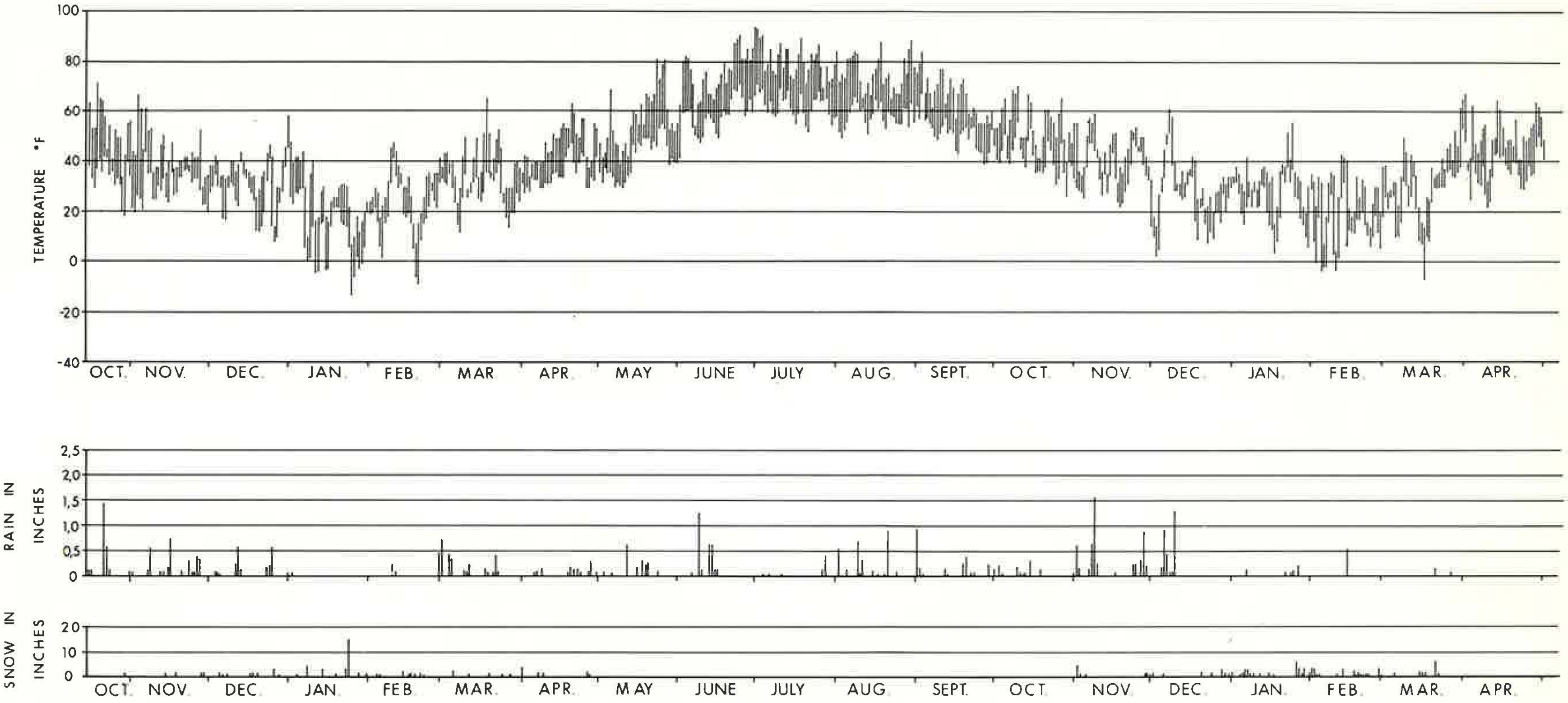

Figure 16. Weather records—Toronto.

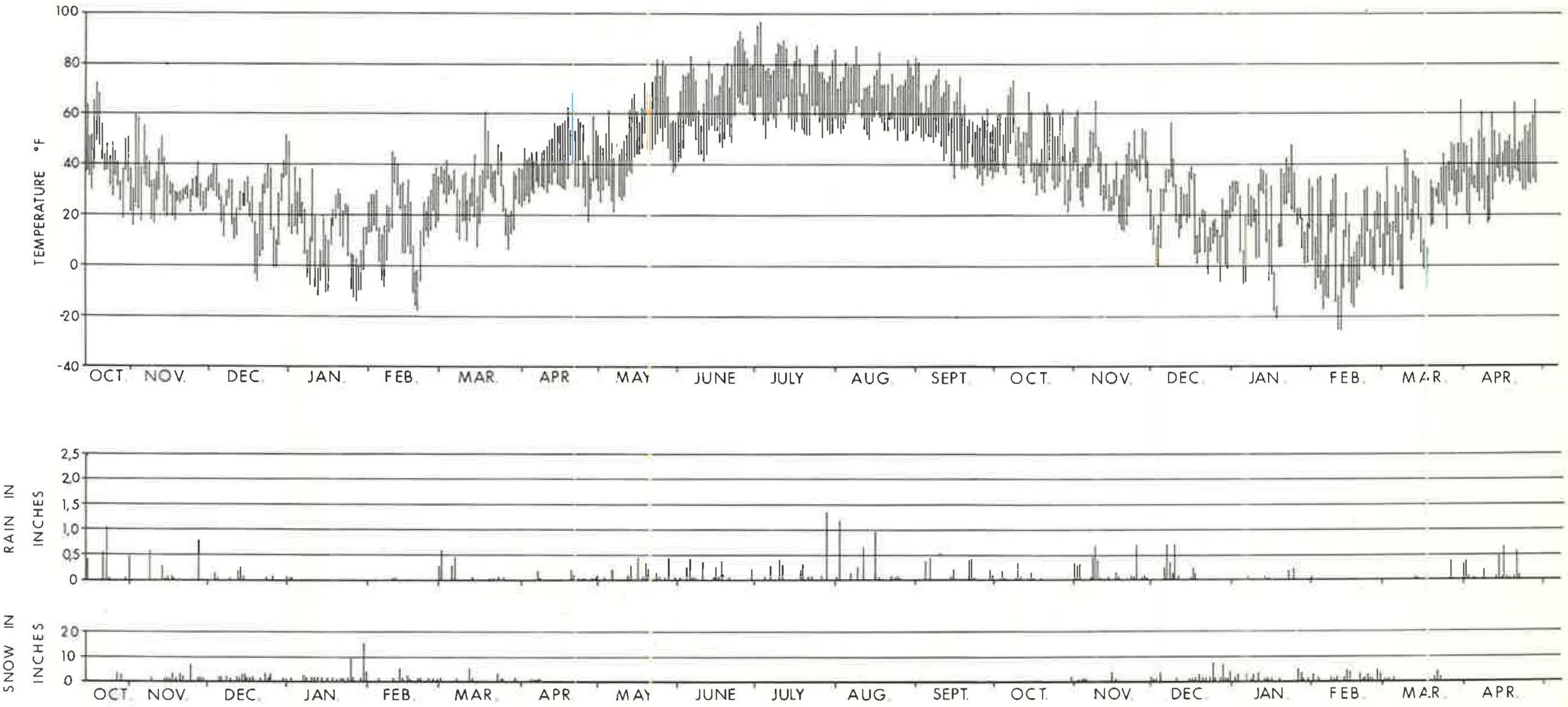

Figure 17. Weather records—Ottawa.

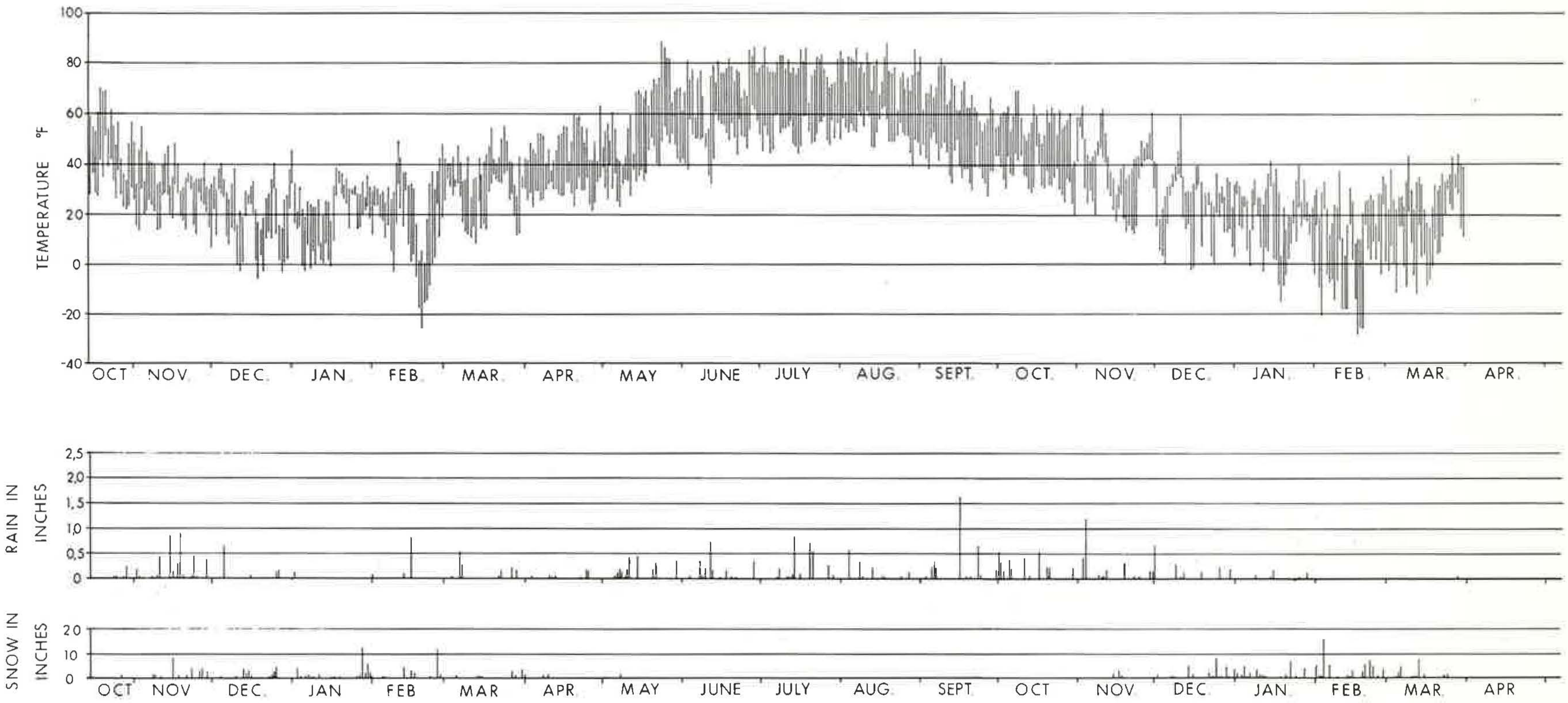

Figure 18. Weather records—Fredericton.

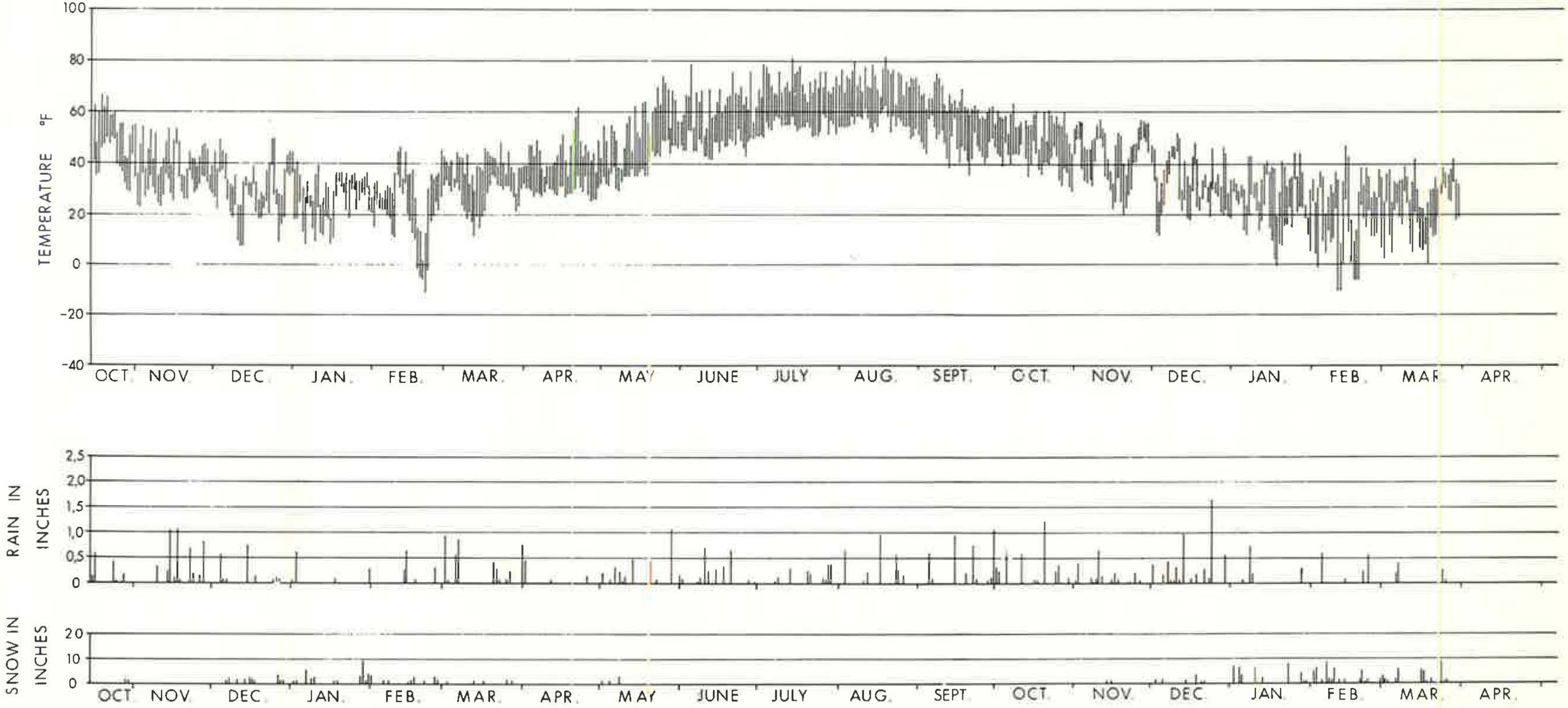

Figure 19. Weather records—Halifax.

were beginning to show corrosion under the lacquered ends. This began at the edge of the film, where the exposed metal ended and the lacquer began, and worked its way slowly under the film. In time, this deposit increased in size, until at the coupon withdrawal after 12 months' exposure, large areas of attack were visible (Fig. 20). This attack was apparently due to an oxygen concentration cell being set up. The areas under the lacquer became anodic with respect to the exposed metal, and the iron went into solution as ferrous ion, resulting in the formation of deeply pitted areas. The corrosion deposit formed under the lacquer was black and very hard; it dissolved slowly in the pickling acid.

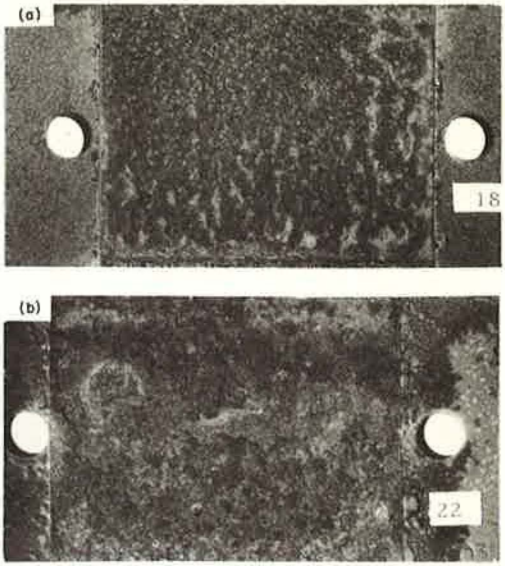

Figure 20. Different degrees of corrosion beneath protective lacquer on vehicle test coupons: (a) after 8 months' exposure and (b) after 12 months.

Once the attack of the metal under the lacquer film became measurable it made exact calculations of metal loss per unit area impossible since the size of the area attacked could not be measured accurately. Therefore, the metal loss per-unit-area calculations were made using the original exposed area. Thus, the graphs and tables where corrosion loss is reported in terms of milligrams per square decimeter are actually accurate only for the first 8 months. Afterwards, the reported corrosion loss per unit area is too high since it includes the pitting loss under the lacquer. This does not invalidate the results, however, since the prime objective of the study was to determine a relative comparison of corrosion in the different areas and under the different conditions in the test rigs.

The coupons from the vehicle tests were very badly attacked under the lacquer; in several cases the lacquer was peeling off. Thus, the metal loss is reported only as "relative metal loss."

It is recognized that the fresh sand-blasted surface of the test coupons would corrode more rapidly at the beginning than part of an auto-body with its covering of oil, dirt, etc. This type of surface was specifically used since it was reproducible, and for this type of investigation, it was the only type of surface that could be considered.

The creviced coupons were purposely constructed to simulate the crevices on the underside of a vehicle where road dirt and moisture collect. This was obviously successful in the vehicle tests where the creviced coupons showed more corrosion than the flat coupons. In the test rigs, however, it was not successful. Dirt in the form of sand and clay was added to the test tracks during rain and snow storms, to build up a dirt poultice in the crevices. Some build up did occur but most of it washed out during the next rainfall.

At the start of the investigation, the corrosion rate for the flat coupons was higher than for the creviced coupons. By the end of the investigation, the amount of corrosion was approximately the same for both types. As a result, the final analysis was performed on both types of coupons combined.

Previous investigators informed the author that a definite splash pattern exists inside the fender, due in part to the centrifugal force which tends to throw the spray to the outside of the fender. Careful observation during light rain or snowfalls substantiated this pattern. Three areas were noted: a light, a medium, and a heavy splash area. As a result, the corrosion results from coupons from each of these areas were separated and analyzed by the computer. Virtually no difference was found between the corrosion occurring in the different areas. Special attention was given to the heavy splash area since it was reasoned that this area would receive the greatest concentration of salt and inhibitor, and if any inhibition resulted, it should be recognizable where heavy splashing occurred. This area did not, however, show any difference in corrosion from the medium or light splash areas.

Atmospheric Corrosion Tests

The cumulative atmospheric corrosion curves obtained for the eight districts are shown in Figures 21 through 28. Each of these curves is accompanied by a bar graph showing the 2-month corrosion rate as obtained from the coupons of Sample Group 1 (Fig. 3). If these bimonthly corrosions are summed, period by period, the total is greater than that indicated by the cumulative corrosion curve. This is caused by the passivation of the surface of the coupons by the buildup of the corrosion deposits. The rate of passivation can be calculated from these graphs.

The lowest cumulative atmospheric corrosion for the nineteen month period was found in Edmonton where it was 1225 mg/dm^{-2}. This northern region is subject to very cold winters and very dry air at all seasons of the year. It is largely devoted to farming

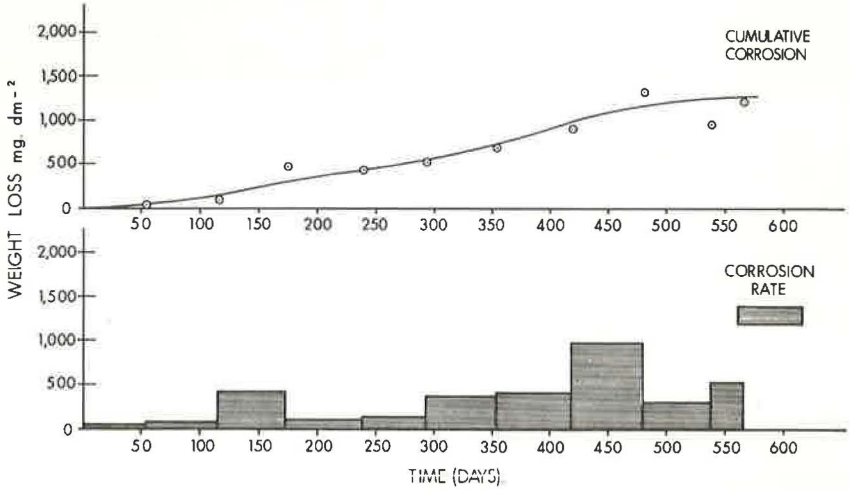

Figure 21. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Edmonton.

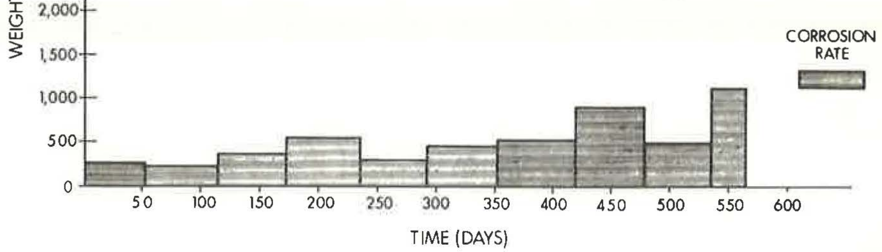

Figure 22. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Cochrane.

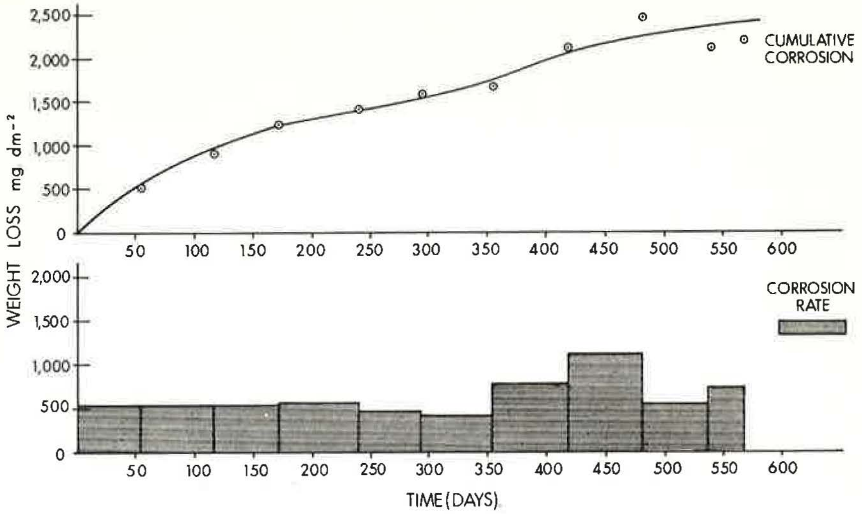

Figure 23. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—North Bay.

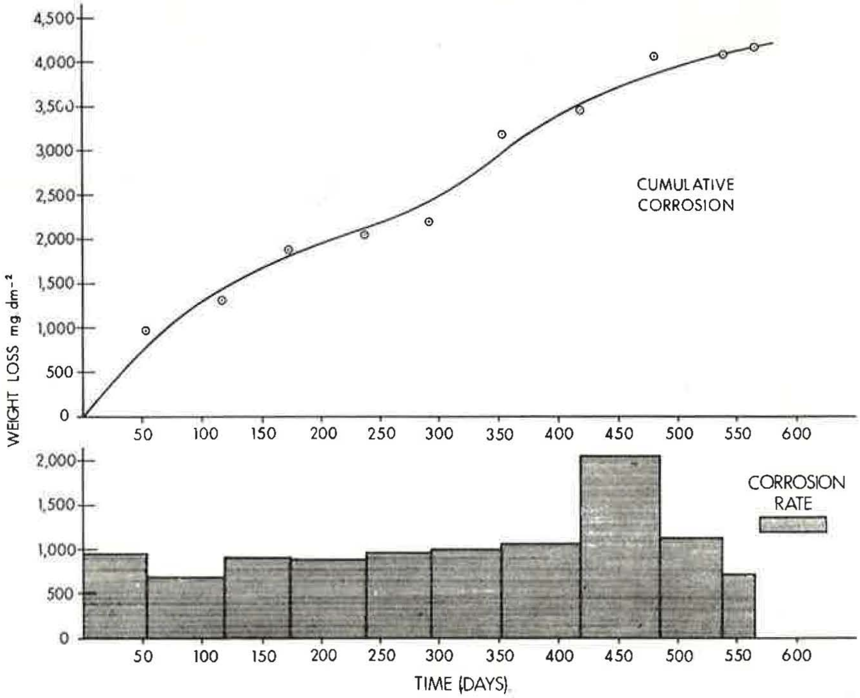

Figure 24. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Chatham.

and crude oil production, both of which have very little effect on atmospheric corrosion.

Next to Edmonton, in the low corrosion category, were North Bay and Cochrane. These again are northern areas but the air in Ontario is more humid than northern Alberta, and as a result, the final atmospheric corrosion obtained in these two localities was almost 1000 mg higher.

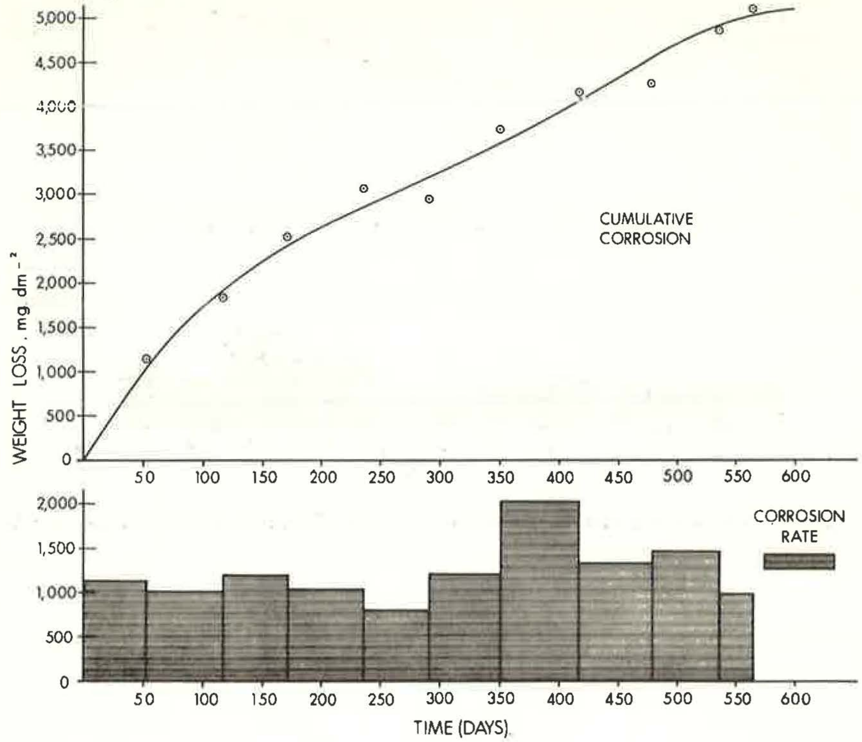

Figure 25. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Toronto.

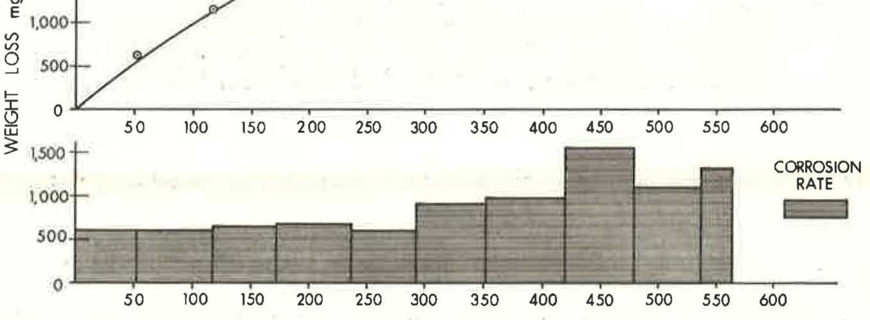

Figure 26. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Ottawa.

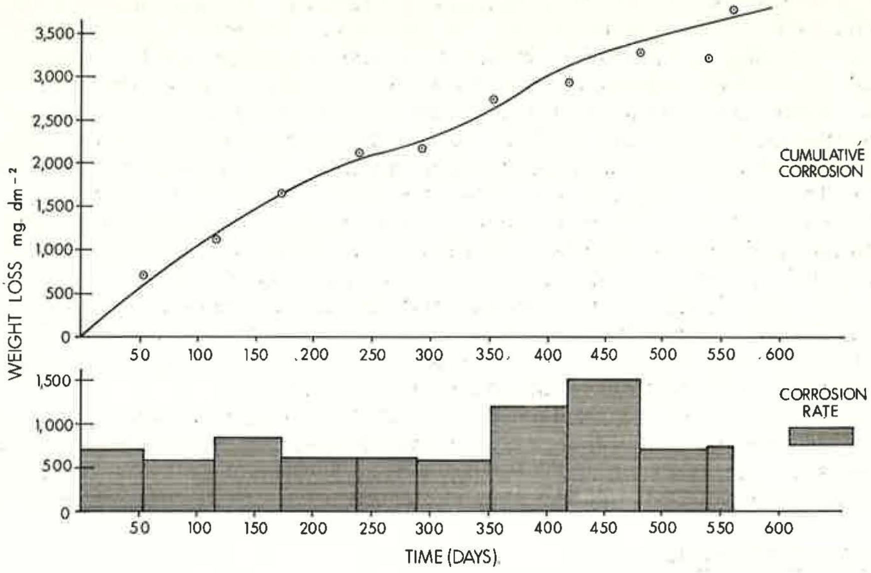

Figure 27. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Fredericton.

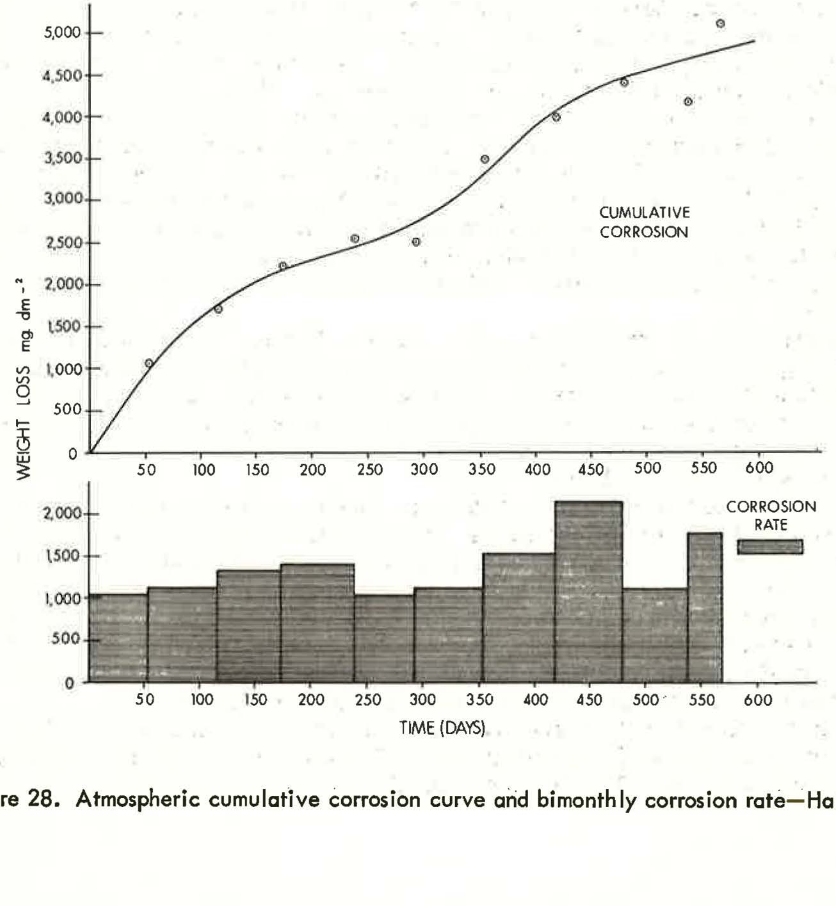

Figure 28. Atmospheric cumulative corrosion curve and bimonthly corrosion rate—Halifax.

Next in rank were Fredericton, Ottawa and Chatham. Fredericton is an urban center of moderate climate and industrial concentration. Ottawa has a cold climate in the winter but is higher in industrial concentration and population density. Chatham is a moderate-sized urban community with milder winter temperatures and humid conditions; it is down-wind from the high industrial concentration in the Detroit-Sarnia area. The total nineteen month corrosion in these areas amounted to approximately 4000 mg/dm^{-2}.

The highest atmospheric corrosions were registered in Toronto and Halifax where the 19-month corrosion figures were 5108 and 5087 mg/dm^{-2}, respectively. The Toronto area has both a very high population and industrial density; its climate is moderate and humid during the summer. Halifax has a much lower population and industrial density, and its climate is even more moderate than that of Toronto. The major difference, however, is the Atlantic Ocean. Halifax has very humid conditions, and fogs and salt spray blow inland for considerable distances. The latter is believed to cause a marked increase in corrosion. This can be seen when comparing the coastal Halifax area's corrosion with that of the inland Fredericton area.

The atmospheric corrosion data indicate that the lowest atmospheric corrosion rates occur in cold, dry areas and increase as temperature, industrial and population densities increase. The presence of a large body of salt water close by and conditions such that the salt spray can drift into the area can cause a considerable increase in corrosion.

Vehicle Corrosion Tests

It was mentioned previously that the vehicle coupons exhibited such serious corrosion beneath the protective lacquer that the actual coupon corrosion has been reported only as a relative figure. The first three coupon withdrawals (Fig. 2) were made as scheduled. The fourth withdrawal, scheduled for the middle of the second winter, was omitted due to corrosion occurring on the support brackets. At the end of the test, the fourth and fifth coupons, along with the replacement coupons, were all withdrawn together.

Indoor and outdoor storage facilities for the test vehicles were used in nearly all areas, and in most cases, the relative corrosion reported is an average of the two types of storage. One exception is the Toronto area, where the trucks were the emergency service vehicles on the MacDonald-Cartier Freeway. Some of these were in service for 24 hours a day, at times, and all were subjected to mostly outdoor storage when not in use. The other exceptions were the Cochrane area where all of the vehicles were stored outdoors, and the Halifax area where all but one were stored indoors.

At the start of the test, all areas had six vehicles carrying coupons in service. Some areas lost one or more coupon brackets and a few trucks were taken out of service during the test. At the conclusion, Edmonton, Fredericton, Cochrane, North Bay and Chatham still had six of the test vehicles in operation; Halifax and Ottawa, five; and Toronto, four.

The relative amounts of corrosion are shown in Figures 29 and 30. The first four bars in each group form the cumulative corrosion graph and represent the relative corrosion metal loss at 4, 6, 12, and 18 months, respectively. The last two bars represent the corrosion loss of two of the replacement coupons, which were exposed for the second winter only, November 1966 to April 1967, inclusive, and for the entire year, May 1966 to April 1967, inclusive.

The corrosion losses of these replacement coupons were the exact reverse of what had been expected. In all but two cases, the corrosion losses for the replacement coupons were greater for the winter period than the losses exhibited by cumulative corrosion coupons for the entire year. A possible explanation for this anomaly could be that the summer corrosion deposits formed from May to October passivated the metal surface to such an extent that the winter saline solutions were much less corrosive than when they acted on an unprotected surface. In general, Figure 30 shows that the creviced coupons were more severely corroded than the flat coupons.

In this test, the order of severity of corrosion by area is somewhat different from the order in the atmospheric corrosion test. The Edmonton area again showed the lowest corrosion losses. The Toronto area showed the second highest corrosion loss,

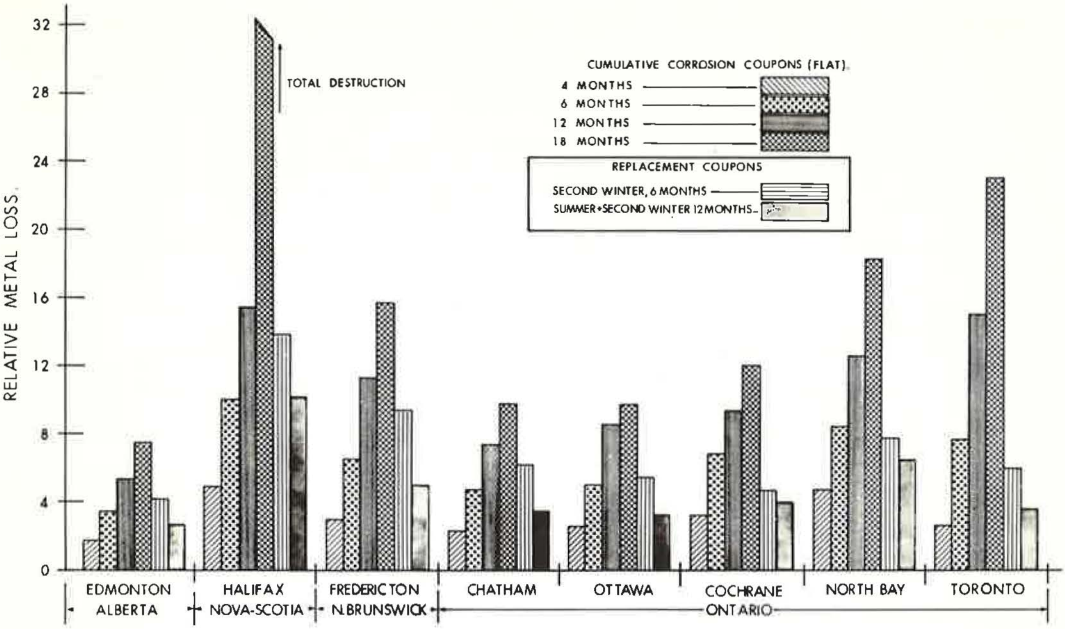

Figure 29. Relative metal loss due to corrosion—flat coupons.

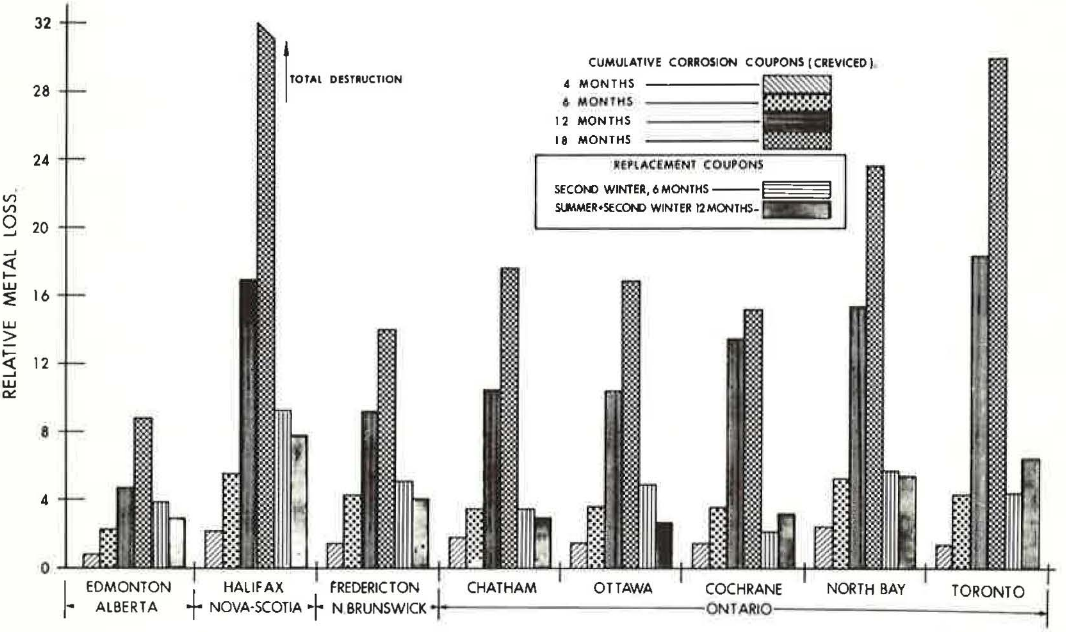

Figure 30. Relative metal loss due to corrosion—creviced coupons.

whereas Halifax displayed by far the highest vehicle corrosion losses. Most of the 18-month coupons received from the Halifax area were reduced to a mass of iron oxide and broke into pieces when flexed. These results showed, without any doubt, that conditions such as those prevailing at Halifax are very destructive to auto-body steel at all seasons of the year, and the use of corrosion inhibitors in deicing salt would be of little use even if proved effective elsewhere.

The intermediate areas varied in order of severity depending on whether the creviced or the flat coupons were considered. The only real difference was the surprisingly high corrosion loss shown by the Cochrane and North Bay samples. In the atmospheric corrosion test these areas ranked at the bottom, just above Edmonton. In this vehicle corrosion test, they ranked just below Halifax and Toronto.

The reason for North Bay's elevated position is attributed to severe weather during November and early December 1965. The North Bay area had an unusually large number of small snowfalls and freezing rain storms, requiring almost daily use of salt or sand. This caused the 4-month (mid-winter) corrosion to be higher than anywhere else tested.

The difference between the Halifax and Fredericton areas can be seen clearly—corrosion in the Halifax area is at least double that in the Fredericton area.

The vehicle corrosion data show that as population and industrial densities increase, vehicle corrosion increases. If, however, the area is a cold dry one as in western Canada or the northern midwestern United States corrosion should be of a lesser degree. This has been demonstrated by Craik (2, 3). Vehicle corrosion can, however, be quite severe in a moderately cold area of moderate industrial and population density if road salt is used very frequently during the winter period (North Bay). In maritime areas where the area is subjected to salt spray drift and to the use of deicing salts during the winter, the vehicle corrosion can be expected to reach a very high level.

Traffic Simulator Corrosion Tests

General—During the course of this investigation (a total time lapse of 565 days) the traffic simulators operated on 372 days. The total number of 15-min runs was 1445. Since the mean peripheral speed of the test rigs was 12.5 mph, the total distance traveled was 4515 miles.

Only one major shutdown (3 days) occurred. This was during the first spring and resulted from the seizing of several wheel bearings due to the entry of dirt. A few shutdowns (one or two runs in length) occurred for minor maintenance or snow removal.

Proof of Traffic Simulators—The five simulators (test rigs) used in this investigation were made by the same company from the same materials using the same set of plans. Similarly, the test tracks were all cast one after the other by the same contractor. Despite all of these precautions, it was still felt that some differences might exist among the test rigs which would cause differences in the amounts of corrosion to the test coupons. The experimental design adopted was such that a test for this effect was "built-in" and the results were available after two months' operation.

When the coupons were withdrawn from Group 2 after two months' operation, the coupons were also removed from Groups 17, 18, 19, and 20, to make way for the new winter coupons. Up to this time, all of the test rigs had been operating under the same conditions—no deicing salt had been used. Thus, these coupons afforded an opportunity to compare the test rigs to see if any significant differences existed between them. It was not necessary to test all of the coupons which were removed. The coupons from Groups 18 and 20 were selected by random choice to be tested along with the coupons from Group 2.

The results of the corrosion analyses were then tested by the analysis of variance, using four variables. The first variable was the five traffic simulators. The second variable was the three sample groups, which was included to test the success of the randomized coupon withdrawal plan. If this randomization was successful there should be no significant difference in the corrosion shown by any of the three groups tested. The third variable was wheel type. There were two types of wheels on each test rig—drive wheels and idler wheels. Wheels 2 and 4 with the electric motors mounted on them (Fig. 9) were drive wheels, wheels 1 and 3 were idler wheels. This variable was included, since the program could accommodate it and also some skidding action, which would create extra spray, was expected where the drive wheels were concerned. The fourth variable was replication. Eight coupon pairs were withdrawn from each test rig for each sample group. Since these were now divided between two types of wheels, the replication level was four. The two types of coupons were analyzed separately. It was

TABLE 4

ANALYSIS OF VARIANCE: FIRST TEST OF TRAFFIC SIMULATORS—FLAT COUPONS

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic simulators, i	72,816.8	4	18,204.2	2.2626	N. S.	$\sigma^2 + 8\sigma^2_{ik} + 24\sigma^2_i$
Wheel type, j	172,992.3	1	172,992.3	21.502	***	$\sigma^2 + 20\sigma^2_{jk} + 60\sigma^2_j$
Interaction, i × j	16,335.5	4	4,083.9	—	N. S.	$\sigma^2 + 4\sigma^2_{ijk} + 12\sigma^2_{ij}$
Sample groups, k	29,051.0	2	14,525.5	1.805	N. S.	$\sigma^2 + 40\sigma^2_k$
Interaction, i × k	12,858.3	8	1,607.3	—	N. S.	$\sigma^2 + 8\sigma^2_{ik}$
Interaction, j × k	4,916.3	2	2,458.1	—	N. S.	$\sigma^2 + 20\sigma^2_{jk}$
Interaction, i × j × k	7,235.5	8	904.4	—	N. S.	$\sigma^2 + 4\sigma^2_{ijk}$
Error α (ijk)	724,096.5	90	8,045.5			
Total	1,040,302.2	119				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_k + \gamma_{ik} + \delta_{jk} + \lambda_{ijk} + \epsilon_{\alpha(ijk)}$
$S_{(error)} = 89.7\ \text{mg/dm}^{-2}$

TABLE 5

ANALYSIS OF VARIANCE: SECOND TEST OF TRAFFIC SIMULATORS—FLAT COUPONS

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic simulators, i	156,312.0	3	52,104.0	1.9639	N. S.	$\sigma^2 + 8\sigma^2_{ik} + 16\sigma^2_i$
Wheel type, j	10,522.5	1	10,522.5	—	N. S.	$\sigma^2 + 16\sigma^2_{jk} + 32\sigma^2_j$
Interaction, i × j	11,134.5	3	3,711.5	—	N. S.	$\sigma^2 + 4\sigma^2_{ijk} + 8\sigma^2_{ij}$
Sample groups, k	33,846.5	1	33,846.5	1.2757	N. S.	$\sigma^2 + 32\sigma^2_k$
Interaction, i × k	98,019.5	3	32,673.2	1.2315	N. S.	$\sigma^2 + 8\sigma^2_{ik}$
Interaction, j × k	12,167.0	1	12,167.0	—	N. S.	$\sigma^2 + 16\sigma^2_{jk}$
Interaction, i × j × k	28,214.0	3	9,404.7	—	N. S.	$\sigma^2 + 4\sigma^2_{ijk}$
Error, α (ijk)	1,273,505.0	48	26,531.4	—	N. S.	σ^2
Total	1,623,721.0	63				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_k + \gamma_{ik} + \delta_{jk} + \lambda_{ijk} + \epsilon_{\alpha(ijk)}$
$S_{(error)} = 163\ \text{mg/dm}^{-2}$

TABLE 6

MONTHLY CUMULATIVE CORROSION METAL LOSS—MEAN VALUE OF FLAT AND CREVICED COUPONS

(mg/dm^{-2})

Days From Start of Test	Test Rig No. 1 Unsalted	Test Rig No. 2 Salt Only	Test Rig No. 3 Salt + Inhibitor A	Test Rig No. 4 Salt + Inhibitor B	Test Rig No. 5 Salt + Inhibitor C
32	170	160	164	166	155
53	429	428	447	426	398
88	584	1112	1152	1139	1082
116	705	1410	1311	1312	1365
144	887	2020	1920	1932	2104
172	1001	2737	2501	2678	2511
200	1084	2996	2671	2799	2677
235	1436	3675	3484	3152	3111
294	1488	3724	3425	3482	3284
354	1567	4537	4082	3888	4231
412	1977	4809	4568	4309	4355
448	2235	5637	5416	5434	5127
483	2029	5609	4990	5070	4986
509	2127	6027	5948	5486	5682
536	2526	6712	6425	6626	6080
565	2844	6592	7277	6384	6905

felt that the precision of the measurements on the flat coupons might quite possibly be different from that on the creviced coupons, leading to nonhomogeneity of variance.

The results of the analysis of variance for the flat coupons is given in Table 4 (results for the creviced coupons were the same). The only significant variable was wheel type. A detailed examination of the data showed that the difference was due to a higher amount of corrosion occurring on the coupons in the idler wheels—not in the drive wheels as expected. The only explanation that can be offered is that wheel 3, the outermost wheel, traveled the fastest and therefore threw up more spray than the others; this was more than sufficient to counteract the effect of wheel 1, the innermost wheel, which traveled the slowest.

The most important factor, however, is that there was no significant difference between the five test rigs at the 0.05 probability level. This was confirmed in another test, run one year later. The standard deviation of the test method for 2-month exposed coupons was 89.7 mg/dm^{-2}. This gives a 95 percent confidence limit of ±0.180 mg/dm^{-2} (Table 4).

Unexpected results started to materialize during the summer period. To determine if differences were beginning to show up between the test rigs, a further proofing test was applied. New coupons were placed in Groups 4 and 9, at the beginning of October, in Test Rigs Nos. 2, 3, 4, and 5. These coupons were withdrawn and processed at the beginning of December after two months' exposure. The same analysis of variance was again applied; the only difference was that there were only four test rigs and two sample groups involved (Table 5). There was even less difference between the test rigs than before; in fact, no significant difference was evident even between the wheel types.

When the analysis of variance was applied to the creviced coupons the result was the same, except the difference between wheel types was again significant. The mean corrosion loss per coupon for the flat coupons in this analysis was 910 mg/dm^{-2}. In the previous analysis run a year earlier, the mean corrosion loss per coupon was 438 mg/dm^{-2}. This difference can be attributed to a somewhat longer exposure period for the second test (58 days against 53), a greater number of rain periods in the second set, and different temperature conditions. The standard deviation for the 2-month period of the second test also increased to 163 mg/dm^{-2}. This suggests that the precision of the corrosion analysis is best expressed by a coefficient of variation rather than a standard deviation.

Salted Conditions—The cumulative corrosion data obtained from the test rigs (Table 6) were obtained from the coupons taken from Sample Groups 1 to 16. Here the metal loss of the flat and creviced coupons has been averaged and each value is the average of 16 individual coupons. These data are shown graphically in Figures 31 through 34. Each curve (with the exception of that for Test Rig No. 1 in Fig. 31) can be considered as being composed of four sections. The first represents the first two months of operation. The second represents the first winter (when salt was used) and has a much steeper slope. The third represents the spring-summer-fall period when again no road

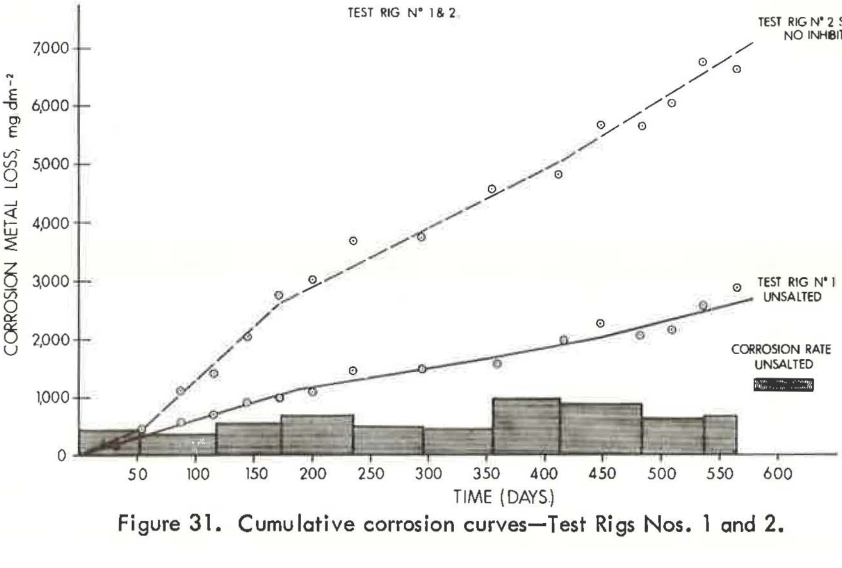

Figure 31. Cumulative corrosion curves—Test Rigs Nos. 1 and 2.

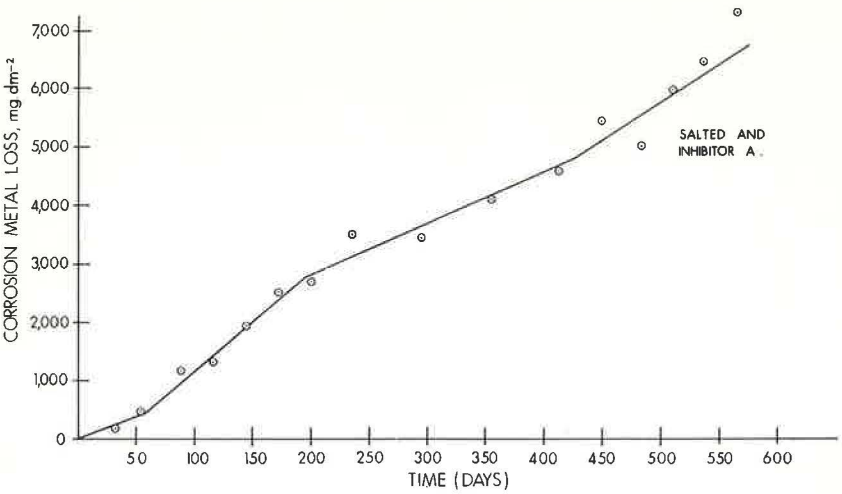

Figure 32. Cumulative corrosion curves—Test Rig No. 3.

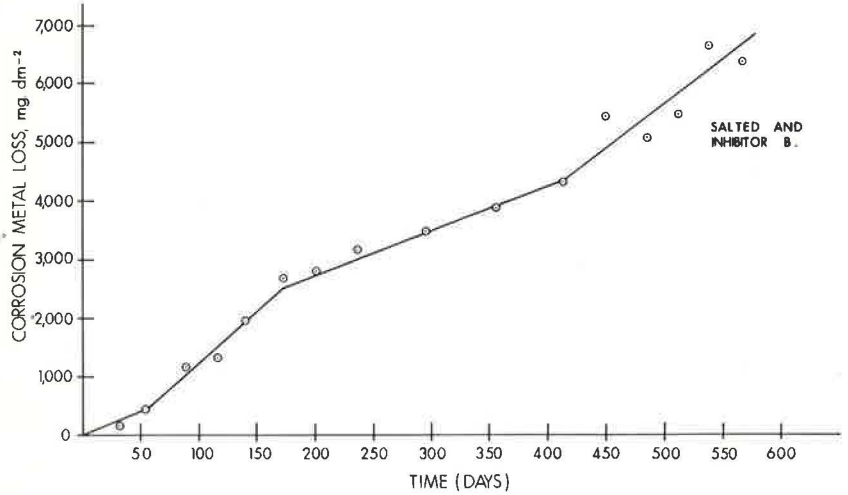

Figure 33. Cumulative corrosion curves—Test Rig No. 4.

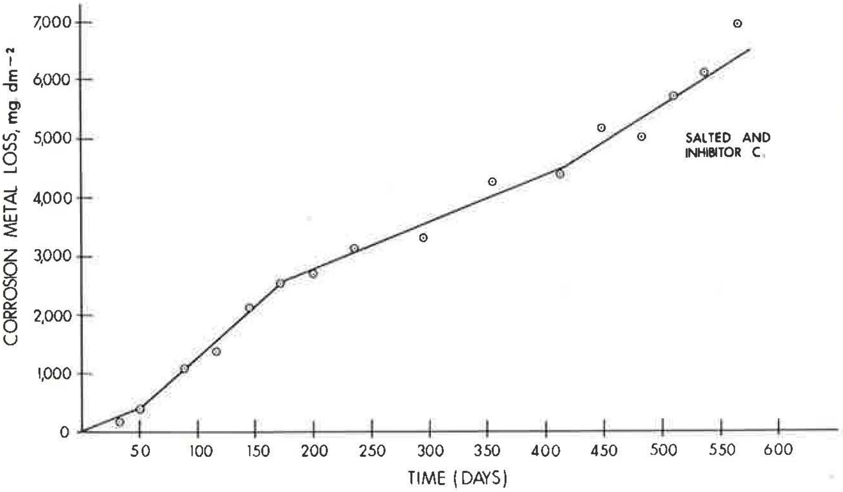

Figure 34. Cumulative corrosion curves—Test Rig No. 5.

TABLE 7

BEST ESTIMATE OF METAL LOSS FROM REGRESSION LINES

(mg/dm^{-2})

Number of Days Exposure	Test Rig No. 2 Uninhibited	Test Rig No. 3 Inhibitor A	Test Rig No. 4 Inhibitor B	Test Rig No. 5 Inhibitor C
53 (End of Fall)	428	447	426	398
172 (End 1st Winter)	2604	2418	2518	2514
412 (End of Fall)	4989	4628	4355	4451
536 (End 2nd Winter)	6510	6206	6272	5980

salt was used and has a lower slope than the previous section. The fourth and final section represents the second winter when salt was again used and the curve has a steeper slope.

To compare these curves the regression line for each section was calculated and then the analysis of covariance was used to compare the slopes of the lines. In order that corresponding sections of all curves would all join at the same point on the time axis, the following technique was used: the time in days and the mean corrosion value found for the end of the fall (two months' exposure) were subtracted from each of the four values of each curve representing the winter period; this simply translated the origin to the beginning of the winter period. The regression line for the four winter values was then determined using a formula which forced the regression line through the origin (0, 0). From this line the best estimate of the corrosion at the end of the winter period was calculated. This estimate and its associated time in days were used to transform the spring-summer-fall data and the regression line for these data was calculated in the same manner as the previous section. Finally, the best estimate of the corrosion at the end of the fall was calculated, the second winter data transformed, the regression line through the transformed origin was calculated and the best estimate of the corrosion at the end of the test was calculated.

These best estimates of corrosion metal loss at the end of the first fall, the end of the first winter, the end of the second fall and the end of the second winter are given in Table 7. For all periods (except the end of the first fall), the coupons from the inhibited test rigs showed less corrosion than those from the uninhibited test rig. The reduction, however, was not great, being less than 10 percent in all cases. The individual coupons analyzed at each withdrawal showed considerable variation, and in view of this, it was considered possible that the apparent reduction was a chance effect. The data were then analyzed by covariance techniques to determine if the reduction was significant or just due to random variations.

It can be readily shown (5) that the slope of the regression line which passes through the origin

$$Y = mX_i$$

where the ordinate intercept equals 0, is given by

$$m = \frac{\Sigma X_i Y_i}{\Sigma X_i^2}$$

The regression coefficient has a standard error of

$$S_m = \frac{S_{y.x}^2}{\Sigma X_i^2}$$

where the residual error of regression is

$$S_{y.x} = \sqrt{\frac{\Sigma Y_i^2 - m^2 \Sigma X_i^2}{n - 1}}$$

If a corrosion inhibitor was effective in reducing the corrosion attributable to deicing salt, then the regression coefficient for the winter section of its cumulative corrosion curve should be lower in value than the comparable regression coefficient of the cumulative corrosion curve of the uninhibited test rig.

The values of the regression coefficients of the winter cumulative corrosion curves for the three inhibited test rigs were compared individually with that of the uninhibited test rig, using covariance techniques. The null hypothesis that there was no difference between the uninhibited and inhibited data populations was adopted. Then the populations could be combined and the residual error of regression written as

$$S_{y_{1,2}.x} = \sqrt{\frac{\Sigma Y_{1i}^2 + \Sigma Y_{2i}^2 - m_1 \Sigma X_{1i}^2 - m_2 \Sigma X_{2i}^2}{n_1 + n_2 - 2}}$$

The estimates of the two slopes m_1 and m_2 are normally distributed and have variances

$$\frac{S^2_{y_1.x}}{\Sigma X_1^2} \quad \text{and} \quad \frac{S^2_{y_2.x}}{\Sigma X_2^2}$$

The hypothesis that the true regression coefficient is the same in each class, $m_1 = m_2$ can be tested since

$$S^2_{m_1 - m_2} = \frac{S^2_{y_1.x}}{\Sigma X_1^2} + \frac{S^2_{y_2.x}}{\Sigma X_2^2}$$

then

$$\frac{m_1 - m_2}{S_{y_{1,2}.x} \sqrt{\frac{1}{\Sigma X_1^2} + \frac{1}{\Sigma X_2^2}}}$$

is distributed as student's t with $n_1 + n_2 - 2$ deg of freedom. This method then permitted the comparison of the regression coefficients for the inhibited test rig cumulative curves with those for the uninhibited test rig. The t-values thus developed were compared with a table of percentage points of the t-distribution to see if they were significant.

The values of the regression coefficients and standard errors for all of the regression lines are given in Table 8; the computed values of t, in Table 9. All values were obtained by regressing the mean values and not the individual coupon metal losses. Thus there were 4 - 1 = 3 deg of freedom associated with the m-values for curve sections 2 and 4, while the m's for curve section 3 had 5 - 1 = 4 deg of freedom.

TABLE 8

VALUES OF THE REGRESSION COEFFICIENT AND STANDARD ERROR FOR THREE SECTIONS OF CUMULATIVE CORROSION CURVES

Curve Section		Test Rig No. 2	Test Rig No. 3	Test Rig No. 4	Test Rig No. 5
2	m	18.28	16.55	17.58	17.78
	S_m	0.1078	0.1122	0.1875	0.0698
	$S_{y \cdot x}$	17.9	18.65	31.2	11.6
3	m	9.937	9.208	7.654	8.070
	S_m	0.2009	0.1905	0.0235	0.0970
	$S_{y \cdot x}$	66.7	63.32	7.837	32.25
4	m	12.27	12.73	15.46	12.33
	S_m	0.3199	9.8503	1.283	0.3421
	$S_{y \cdot x}$	56.4	150.0	226.3	60.4

TABLE 9

ANALYSIS OF COVARIANCE—VALUES OF STUDENT'S t FOR COMPARISON OF TEST RIG NO. 2 WITH INHIBITED TEST RIGS

Curve Section	Test Rig No. 2 vs Test Rig No. 3	Test Rig No. 2 vs Test Rig No. 4	Test Rig No. 2 vs Test Rig No. 5	Degrees of Freedom $n_1 + n_2 - 2$
2	1.2244	0.4284	0.3449	6
3	0.5807	2.3973	1.7027	8

In normal regression procedures where an ordinate intercept is involved, the number of degrees of freedom for the regression coefficient is n - 2. Here, since the regression is through the origin and there is no ordinate intercept, the number of degrees of freedom is n - 1.

When the values of t (Table 9) for curve section 2, were examined, none was found to be significant at the 0.05 probability level.

The regression coefficients (Table 8) for curve section 2 indicate that the corrosion rates from the inhibited test rigs were lower than from the uninhibited test rig. When these data were analyzed by covariance techniques the results in the first line of Table 9 were obtained. None of these three t-values was significant at the 0.05 probability level. Thus, it can be stated with 95 percent confidence that no significant differences were due to the effect of the inhibitors, and the position that the difference is due to random variation must be adopted.

The regression coefficients (Table 8) for curve section 4 were surprising in that a very low slope was indicated for the summer cumulative corrosion in Test Rig No. 4. This could indicate that a residual inhibitor effect carried over from the winter period. The t-value for this slope when compared to that of Test Rig No. 2 was significant as given in Table 9 ($t_{\alpha(0.05),\,8} = 2.306$). This significant value was, however, most probably due to random variations as shown by the behavior of curve section 4. Here (Table 8), the slope was suddenly much greater than that of the other three curves and the best estimate of corrosion at the end of the second winter (Table 7) was slightly higher than that for Test Rigs Nos. 3 or 5. The values of the regression coefficient for curve section 4 (Table 8) were not tested by covariance since there was obviously no difference between them except for Test Rig No. 4. Thus, in the second winter there was no inhibition of corrosion due to the use of the inhibitors as shown by the cumulative corrosion curve.

These analyses were performed by regressing the average corrosion values. It seemed possible that the greater number of degrees of freedom obtained if the individual coupons were regressed might make a difference. To test this, the computer was used to repeat all of the above analyses using data from the individual coupons. The results

TABLE 10

WINTER ONLY CUMULATIVE CORROSION METAL LOSS—MEAN VALUE FOR FLAT AND CREVICED COUPONS

(mg/dm^{-2})

Days From Start of Winter	Test Rig No. 1 No Salt	Test Rig No. 2 Salt Only	Test Rig No. 3 Salt + Inhibitor A	Test Rig No. 4 Salt + Inhibitor B	Test Rig No. 5 Salt + Inhibitor C
First winter:					
35	193	802	746	778	793
63	371	1142	1094	1144	1170
91	636	1764	1686	1742	1757
119	661	2283	2147	2190	2326
Second winter:					
36	590	1168	1202	1211	1211
71	854	1665	1669	1661	1713
97	1052	2386	2292	2332	2437
124	1236	3268	3234	3135	3182

obtained were almost the same as those given and lead to exactly the same conclusions.

In a further attempt to detect a difference due to the use of inhibitors, the computer was used to perform an analysis of variance on the corrosion data obtained in the first six months of operation. Two analyses were performed, one for the flat and one for the creviced coupons. The variables used were the same as those used in the proof of traffic simulators test—Test Rigs Nos. 2, 3, 4, and 5; Sample Groups 1 to 6 inclusive; and Type of Wheels, 2. The results showed again that there was no significant difference between the test rigs for either the flat or the creviced coupons.

Thus the three types of statistical analyses performed on the cumulative corrosion curves showed no significant effect due to the use of corrosion inhibitors. Even if the small reductions in the amount of corrosion (Table 7) had been significant statistically, they were of little practical use. A reduction of less than 10 percent in the winter corrosion only would have had little or no effect on the overall picture.

These analyses showed that corrosion inhibitors had little or no effect in reducing the amount of salt-induced corrosion on prerusted coupons. The special coupons in Sample Groups 17 to 20, where a fresh metal surface was exposed to salted conditions, were next examined. The mean cumulative corrosion metal loss values for the four months of each of the two winters are given in Table 10. The difference between the effect of natural conditions and the use of salt during the winter period was a definite increase in corrosion.

TABLE 11

ANALYSIS OF VARIANCE—COMPARISON OF TWO WINTERS

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic simulators, i	309,480.0	3	103,160.0	0.9315	N. S.	$\sigma^2 + 16\sigma^2_{ik} + 64\sigma^2_{i}$
Winters, j	37,253,464.0	1	37,253,464.0	21.55	*	$\sigma^2 + 40\sigma^2_{jk} + 160\sigma^2_{j}$
Sample groups, k	113,824,536.0	3	37,941,512.0	342.59	***	$\sigma^2 + 8\sigma^2_{ijk} + 32\sigma^2_{ij}$
Interaction, i × j	127,816.0	3	42,605.3	0.3847	N. S.	$\sigma^2 + 80\sigma^2_{k}$
Interaction, i × k	209,424.0	9	23,269.3	0.2101	N. S.	$\sigma^2 + 16\sigma^2_{ik}$
Interaction, j × k	5,185,136.0	3	1,728,378.7	15.6063	***	$\sigma^2 + 40\sigma^2_{jk}$
Interaction, i × j × k	191,728.0	9	21,303.1	0.1923	N. S.	$\sigma^2 + 8\sigma^2_{ijk}$
Error, α (ijk)	24,807,816.0	224	110,749.2			σ^2
Total	181,909,400.0	255				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_k + \gamma_{ik} + \delta_{jk} + \lambda_{ijk} + \epsilon_{\alpha(ijk)}$

The effect of the use of inhibitors here was less than that shown for the prerusted coupons. The data were analyzed by the computer using the analysis of variance program. The variables used were Test Rigs Nos. 2, 3, 4, and 5; Winters 1 and 2; and Sample Groups 17, 18, 19, and 20.

The data for the individual coupons were used and two analyses were performed, one for the flat and one for the creviced coupons. The results of the analysis for the flat coupons (Table 11) showed no significant difference for the test rigs meaning that no significant effect attributable to the inhibitors was in evidence. The significant interaction "winter × sample groups" simply means that the relative intensity of corrosion (Winter 1 over Winter 2) varied from sample group to sample group. The significant difference for the winters means that the second winter was significantly different and caused a greater amount of corrosion than the first winter.

It was observed that the coupons from Sample Group 6 of the salted test rigs and the coupons from Sample Group 20, end of first winter, differed in appearance when the corrosion deposits had been removed. Those from Sample Group 6 (which had been prerusted before exposure to salt) had an even, lightly pitted and eroded appearance. Those from Sample Group 20, in addition to the pitted appearance, seemed to have an etched appearance. When the loss of metal due to corrosion for the two groups was compared there was virtually no difference between the two. The prerusting of the coupons in Sample Group 6 did not afford any protection from the winter saline solutions.

The final analysis performed on the data from the test rigs involved an analysis of the terminal coupons from sample groups 1, 2, and 16. The coupons in Sample Group 16 had been exposed at the start of the test and remained in the test rigs until the end, 565 days later. The coupons in Sample Groups 1 and 2 were replacement coupons having been placed there 32 days and 53 days, respectively, after the start and remained there until the end of the test. The mean corrosion metal loss for the coupons from these groups is given in Table 12. The data for the individual coupons were analyzed by the computer, using the analysis of variance program. The variables used were: Test Rigs Nos. 2, 3, 4, and 5; Wheel Types 1 and 2; Sample Groups 1, 2, and 16. Two analyses were run; one for the flat and one for the creviced coupons. The results are given in Table 13. There was no significant difference between the test rigs which again meant that no effect attributable to the inhibitors could be detected.

Natural Conditions—The corrosion values obtained on Test Rig No. 1 (unsalted) represent the corrosion occurring under natural conditions. These values are shown in column 2 of Tables 6 and 10. These values are much lower than those obtained on Test Rig No. 2. The latter test rig was salted but uninhibited. The two cumulative corrosion curves plotted from these data for the 19 months of the investigation are shown in Figure 31. The corrosion losses shown by the upper curve are a little more than double those of the lower curve. This suggests that the use of deicing salt in the Toronto area caused a doubling of the amount of corrosion that would have occurred had no deicing salt been used.

The bar graph below the lower curve (Fig. 31) represents the amount of corrosion occurring in each 2-month period as measured on new coupons. These data were obtained from the coupons which were inserted every two months in Sample Group 18 of Test Rig 1. The latter data, if added period by period, produce a higher total amount of corrosion than that indicated by the cumulative corrosion curve for Test Rig No. 1

TABLE 12

MEAN CORROSION METAL LOSS—FLAT AND CREVICED TERMINAL COUPONS

(mg/dm^{-2})

Sample Group	Test Rig No. 1	Test Rig No. 2	Test Rig No. 3	Test Rig No. 4	Test Rig No. 5
1	2,262	7,048	5,969	7,065	6,728
2	2,146	6,925	6,935	6,949	7,778
16	2,585	6,976	8,341	6,493	7,738
Total	6,992	20,949	21,245	20,507	22,253

TABLE 13

ANALYSIS OF VARIANCE—TERMINAL COUPONS

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic simulators, i	937,184.0	3	312,394.7	1.0602	N. S.	$\sigma^2 + 16\sigma^2_{ik} + 64\sigma^2_{i}$
Wheel type, j	813,664.0	1	813,664.0	2.7615	N. S.	$\sigma^2 + 40\sigma^2_{jk} + 160\sigma^2_{j}$
Sample groups, k	1,236,480.0	2	618,240.0	2.0982	N. S.	$\sigma^2 + 8\sigma^2_{ijk} + 32\sigma^2_{ij}$
Interaction, i × j	1,107,680.0	3	369,226.7	1.2531	N. S.	$\sigma^2 + 80\sigma^2_{k}$
Interaction, i × k	421,088.0	6	70,181.3	0.2382	N. S.	$\sigma^2 + 16\sigma^2_{ik}$
Interaction, j × k	2,292,736.0	2	1,146,368.0	3.8906	*	$\sigma^2 + 40\sigma^2_{jk}$
Interaction, i × j × k	946,144.0	6	157,690.7	0.5352	N. S.	$\sigma^2 + 8\sigma^2_{ijk}$
Error, α (ijk)	21,214,816.0	72	294,650.2			σ^2
Total	28,969,792.0	95				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_k + \gamma_{ik} + \delta_{jk} + \lambda_{ijk} + \epsilon_{\alpha(ijk)}$

shown above the bar graph. This reduction in corrosion was due to the passivating effect of the corrosion deposits on the metal surface.

The corrosion occurring only during the unsalted period was measured by the coupons which were put in Test Rig No. 1 at the beginning of April in Sample Groups 3-6 and 17-20. The mean cumulative corrosion for the flat plus creviced coupons, month by month, is shown in Figure 35. The flattening in the center of this curve is due to the very dry period during June and July. Had this drought not occurred, the corrosion loss by the end of November (240 days) could easily have been 1500 mg.

Comparison of Test Methods

It is interesting to compare the amounts of corrosion obtained in the vehicle corrosion test, the atmospheric corrosion test and the traffic simulator test at Toronto. Figure 36 is a composite graph on which cumulative corrosion loss curves are shown

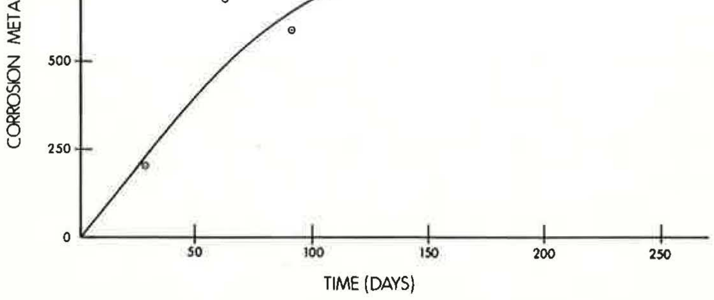

Figure 35. Cumulative corrosion curves—Test Rig No. 1, Apr. to Nov. 1966.

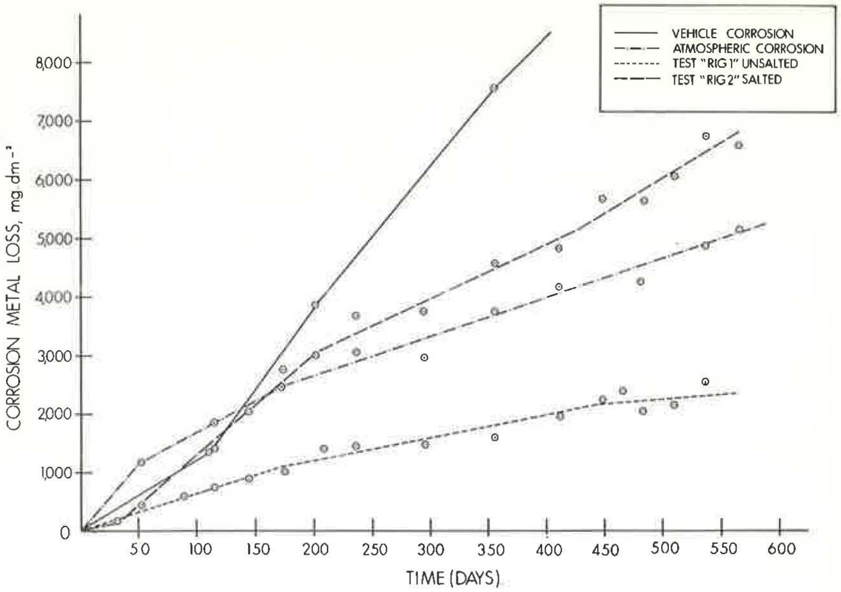

Figure 36. Comparison cumulative corrosion curves—Toronto.

for Test Rig No. 1 (natural conditions), Test Rig No. 2 (salted but uninhibited conditions), atmospheric corrosion, and finally, vehicle corrosion in the Toronto area.

The first comparison is between the curve for Test Rig No. 1 and the atmospheric corrosion curve. The cumulative corrosion curve for Test Rig No. 1 represents less than half the corrosion shown by the cumulative atmospheric corrosion curve. This is caused, in part, by the shielding action of the fender which protected the coupons from the dew at night and, in part, by the fact that the test rigs did not run on weekends, whereas the atmospheric coupons were exposed at all times.

The second comparison involves the atmospheric curve and the curve for Test Rig No. 2. The curve for Test Rig No. 2 lies somewhat above that for the cumulative atmospheric corrosion, but there is not too much difference between the corrosion caused on auto-body steel by the natural and salted conditions and that caused on a fully exposed piece of steel by natural atmospheric conditions in the Toronto area.

The third comparison involves the curve for Test Rig No. 2 and the vehicle corrosion curve. For the first 7 months the two curves were close together and Test Rig No. 2 seemed to be matching the corrosion obtained on the road. As time progressed the two curves diverged. It is possible that the severe corrosion under the lacquer of the vehicle coupons was responsible for at least part of this divergence. The salted test rig did, however, simulate reasonably well the conditions existing on the road in the Toronto area.

Pitting Corrosion

Pitting corrosion was noticed early in this investigation. The Toronto atmospheric corrosion coupons were showing light pitting after two months' exposure. The corrosion occurring under the protective lacquer of the coupons resulted in the formation of deep pits. An example of light pitting is shown in Figure 37, which is the exposed surface after chemical cleaning of a coupon. The pits are evenly distributed over the surface and have an average depth of about 8.5 mils. All pit depths reported here were measured with a Starrett depth micrometer, No. 643-131.

One of the deep pits which occurred under the lacquer in the vehicle corrosion test coupons is shown in Figure 38, taken after the coupon had been chemically cleaned. The pitted area is in the upper left-hand portion. The actual size of the pit diameters

Figure 37. Example of light pitting in exposed portion of coupon—coupon exposed for 12 months in Test Rig No. 2.

Figure 38. Example of deep pitting beneath protective lacquer—coupon exposed for 12 months on a test vehicle.

can be obtained by comparing them with the number shown in the photograph. The number is twelve-point type and is $\frac{1}{6}$ in. high. The pit had a depth, at the center, of 23 mils. There was very little metal left at this point when the corrosion on the other side of the coupon was considered; the original thickness of these cleaned and sand-blasted coupons was 35 mils.

Another deeply pitted area occurring under the lacquer is shown in Figure 39. This coupon has been cleaned and has three pinhole perforations in the pitted area. The photograph was taken on a light table so that the largest pinhole, which is designated by an arrow, would be made visible. The left side shows the exposed coupon surface and the right side, the surface which was protected by lacquer. This large pit has all but obliterated the 1 and 0 of the coupon number 1077.

Pitting was evident in the coupons in all test rigs, including the one running under natural conditions but, in this latter case, it was less than in the salted rigs. This, offered another chance to test the inhibitors to see if they had any effect on the depths of the pits on either the exposed surface or on those occurring under the lacquer. Two sample groups were selected. These were Sample Group 1, replacement coupons, 18 months' exposure, and Sample Group 16, original coupons, 19 months' exposure. Test Rigs Nos. 2, 3, 4, and 5 were selected, Test Rig No. 1 was omitted because of the much lower corrosion. Five chemically cleaned flat coupons were selected at random from each sample group, from each test rig for the pit analysis. Two separate analyses were run. The first was an analysis of the pit depths in the exposed coupon surface, and the second, an analysis of the pit depths in the area under the lacquer.

For each analysis six points were chosen at random at which the pit depth was measured; six points in the exposed area for the first analysis and six points in the lacquered area for the second analysis.

The large tables of results obtained are not reproduced in this report since little difference existed between the test rigs or between the sample groups. The results were, however, subjected to the analysis of variance (Tables 14 and 15).

Figure 39. Example of deeply pitted area beneath protective lacquer, showing actual perforation—coupon exposed for 19 months in Test Rig No. 5.

TABLE 14

ANALYSIS OF VARIANCE: PITTING CORROSION—EXPOSED COUPON SURFACE

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic simulators, i	0.00002470	3	0.000008233	3.0951	*	$\sigma^2 + 6\sigma^2_{k(ij)} + 30\sigma^2_{ij} + 60\sigma^2_{i}$
Sample groups, j	0.00000542	1	0.00000542	2.398	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)} + 120\sigma^2_{j}$
Interaction, i x j	0.00000507	3	0.00000169	0.748	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)} + 30\sigma^2_{ij}$
Coupons within traffic simulators and sample groups, k(ij)	0.00008708	32	0.00000272	1.204	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)}$
Error, α(ijk)	0.00053194	200	0.000002660		N. S.	σ^2
Total	0.00065421	239				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_{k(ij)} + \epsilon_{\alpha(ijk)}$

TABLE 15

ANALYSIS OF VARIANCE: PITTING CORROSION—AREA UNDER THE LACQUER

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Ratio	Significance	Avg. Value of Mean Square
Traffic Simulators, i	0.00009379	3	0.00003126	1.045	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)} + 30\sigma^2_{ij} + 60\sigma^2_{i}$
Sample Groups, j	0.00002946	1	0.00002946	0.985	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)} + 120\sigma^2_{j}$
Interaction, i x j	0.00022932	3	0.00007644	2.556	N. S.	$\sigma^2 + 6\sigma^2_{k(ij)} + 30\sigma^2_{ij}$
Coupons within traffic simulators and sample groups, k(ij)	0.00095664	32	0.000029895	2.771	**	$\sigma^2 + 6\sigma^2_{k(ij)}$
Error, α(ijk)	0.00214956	200	0.0000107478			σ^2
Total	0.00345877	239				

Model III $X_{ijk\alpha} = \mu + \xi_i + \eta_j + \beta_{ij} + \zeta_{k(ij)} + \epsilon_{\alpha(ijk)}$

The analysis of the pits in the exposed surface (Table 14) shows that only the test rigs were significantly different. The application of Tukey's test to the results showed:

1. Test Rig No. 4 was significantly different from Test Rigs Nos. 5, 3, and 2.
2. Test Rig No. 5 was significantly different from Test Rigs Nos. 3 and 2.
3. There was no significant difference between Test Rigs Nos. 3 and 2. Although these significant differences did exist between the test rigs with reference to pit depth, this difference was of no practical advantage. The average pit depths were as follows: Test Rig No. 4, 8.10 mils; Test Rig No. 5, 8.41 mils; Test Rig No. 2, 8.86 mils; and Test Rig No. 3, 8.90 mils.

Whether the inhibitors were responsible for this difference in pit depth or not is not known, but the difference is so small as to be of no practical advantage.

The results of the second analysis are given in Table 15; there was no significant difference between the test rigs with regard to pit depth. The only significant difference shown here was for "coupons within test rigs and sample groups." This simply meant that the coupons, within each group of five, differed among themselves with regard to pit depth under the lacquer, but there was no significant difference between test rigs or sample groups. When both analyses are viewed together, it would appear that the use of corrosion inhibitors did not materially affect the development of pitting corrosion.

LABORATORY EVALUATION OF CORROSION INHIBITORS

The best method of evaluating any deicing salt corrosion inhibitor is to test it in actual use on the road. This procedure is, unfortunately, time consuming and expensive. A laboratory test, duplicating to some extent the conditions existing on the road, would be more efficient and practicable. With this in mind several test methods were reviewed. The Corrodkote test (7) had been used to test these types of inhibitors by Palmer, at the Ontario Research Foundation and by Jacoby, International Salt Company. Jacoby had also used the Dip-Dry test. Palmer had developed an apparatus to simulate the action of a car wheel spraying road salt solutions over test coupons, in a closed system with controlled temperature conditions (8). It seemed that the Corrodkote test did not really simulate the field conditions while Palmer's apparatus was complex and expensive. Thus the Dip-Dry test appeared to offer the best possibilities for laboratory evaluation.

An apparatus was developed which would immerse and remove the coupons from the test solutions for any desired number of cycles over a 24-hr period. It was controlled by an electric timer (on which the desired cycles were set) and driven by a slow-speed (72 rpm) synchronous motor which had an electronic latching device to prevent any further rotation after the limit switches turned off the current.

The cycle used was 1-hr immersion and 3 hr drying. The length of the test period was 7 days, a total of 42 dip-dry cycles. Testing was done at room temperature, 70 F, in an air-conditioned laboratory and at 32 F in a cold room.

The results of the first test are shown in Figure 40. This test was run at 70 F and used salt concentrations ranging from 1 to 10 percent, with the percentage of inhibitor based on the salt as recommended by the manufacturer. A set of solutions of uninhibited salt was included along with a set of solutions of salt inhibited with 1 percent potassium dichromate based on the salt and buffered to render it alkaline so that the hexovalent chromium was present at the chromate ion. The uninhibited salt solutions were present as a control, so that the degree of inhibition for the other inhibitors could be measured, and the dichromate inhibitor was included so that the 3 deicing salt inhibitors could be compared to a well-known and proven laboratory corrosion inhibitor.

The usual brine concentration found in the test rigs during the winter was 2.5 to 3.5 percent. The results (Fig. 40) at a salt concentration of 3 percent indicate no inhibition under the conditions of the test for Inhibitor B, less than 10 percent inhibition for Inhibitor C and about 30 percent inhibition for Inhibitor A. Thus at room temperature, at the recommended concentrations, Inhibitor A was the only one to show any promise. The dichromate as expected proved very efficient. Its efficiency increased with increasing salt concentrations because, as a result of the increasing salt, the dichromate

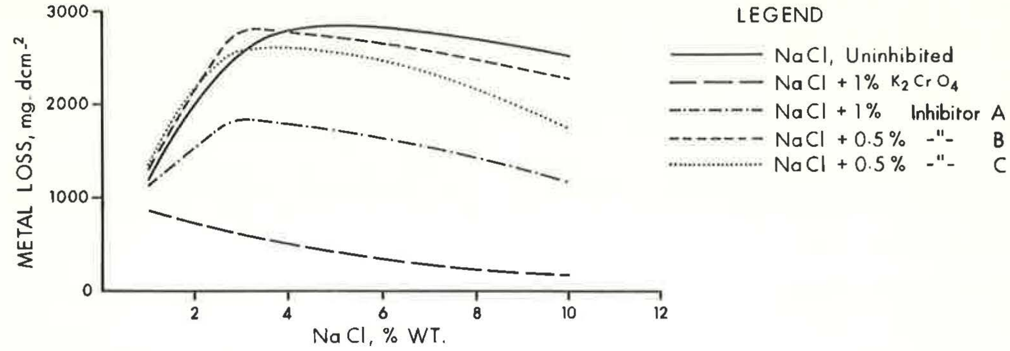

Figure 40. Results of first Dip-Dry test (7 Days at 70 F).

concentration in the solution increased. The amount of corrosion due to the uninhibited salt solutions rises rapidly with increasing salt concentration, reaching a maximum at about 5 percent salt, and then slowly decreases. This is in accord with the findings of other researchers (6).

The inhibitors were next tested in the same apparatus at 32 F (Fig. 41). The three inhibitors, A, B, and C produced very little or no inhibition at the recommended concentrations. The dichromate inhibitor was still highly effective at 32 F. This and lower temperatures are the region where these inhibitors are expected to produce results. This test shows little can be expected from these inhibitors at the recommended concentration. These results confirm the earlier results and show that the Dip-Dry test, run under these conditions, offers a possibility of screening proposed inhibitors. Inhibitor A seemed to be becoming more efficient as the salt concentration increased and seemed to produce about 40 percent inhibition at a 10 percent salt concentration. This suggested that if the inhibitor concentration based on the salt were increased a better performance might be expected.

The next Dip-Dry test involved testing the same inhibitors again (dichromate omitted) at double the previous concentrations and also omitting the 10 percent salt concentration. Before this test was run, a new corrosion inhibitor was proposed. This material was crude calcium hydroxide extracted from residues obtained in the manufacture of acetylene. This material was proposed for use at a very high concentration which would have proved uneconomical. Technical grade calcium hydroxide was included in the test at two concentrations (2 and 5 percent) to represent this material. The results are shown in Figure 42 for 70 F and in Figure 43 for 32 F.

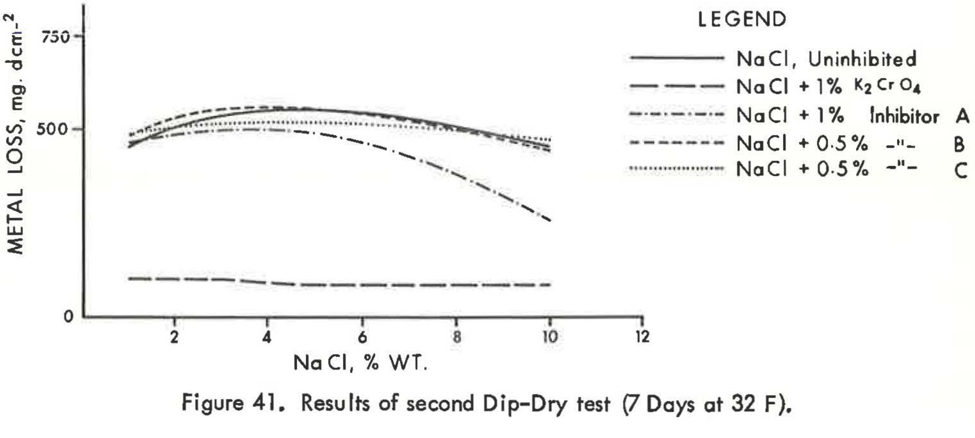

Figure 41. Results of second Dip-Dry test (7 Days at 32 F).

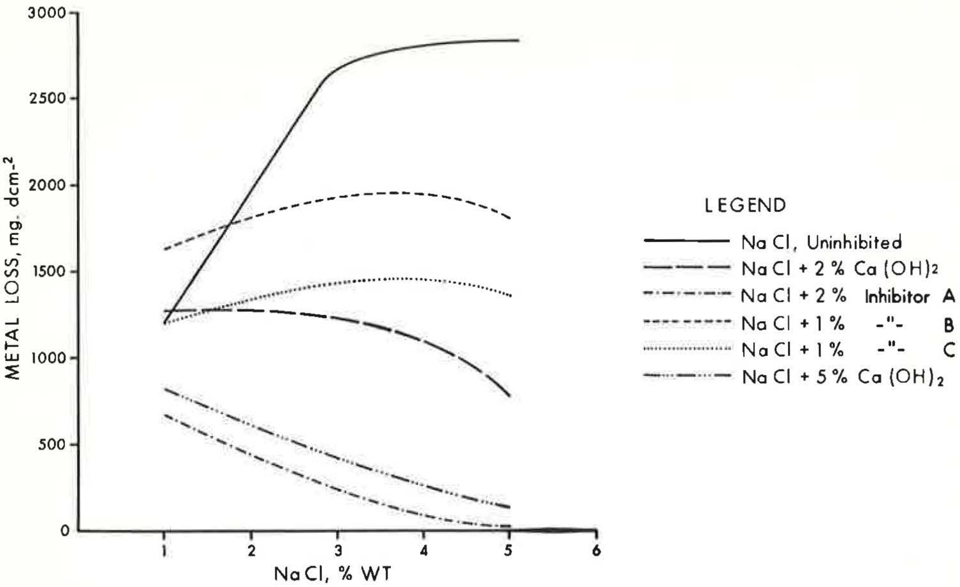

Figure 42. Results of third Dip-Dry test (7 Days at 70 F).

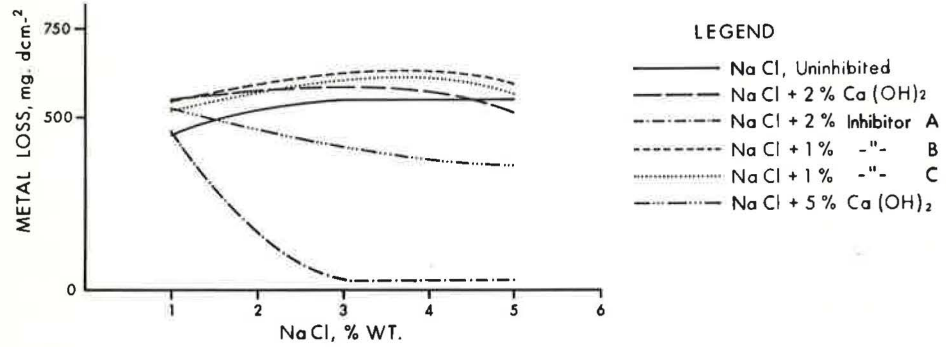

Figure 43. Results of fourth Dip-Dry test (7 Days at 32 F).

Figure 43 shows that doubling the inhibitor concentration did not increase the efficiency of Inhibitors B or C at all. Inhibitor A, however, increased markedly in efficiency and at 3.0 percent salt concentration reduced the corrosion to a low level. The calcium hydroxide, 5 percent concentration, produced about a 25 percent reduction in corrosion at 32 F for a 3 percent salt solution.

This Dip-Dry test is an accelerated test and was an attempt to obtain some idea of what might be expected from an inhibitor under field conditions. The data obtained from the test at 70 F (Fig. 40) indicate a corrosion loss of about 2700 mg/dm^{-2} for the 3 to 4 percent salt solutions. This is equivalent to the corrosion loss shown by the salted test rig (Fig. 31) at the end of the first winter. The results (Fig. 40), however, for the solutions containing 1 percent of the polyphosphate inhibitor do not match what occurred in Test Rig No. 3 where this same inhibitor was tested outdoors under natural conditions and no significant reduction in corrosion was found. The Drip-Dry results at 32 F (Fig. 41) indicate little or no inhibition occurred for salt solutions of concentrations varying

TABLE 16

EFFECT OF INHIBITOR C ON MOBILITY OF SALT PILES AT LOW TEMPERATURES

Amount of Inhibitor C	Moisture Concentration (%)	Temp. + 15 F	Temp. + 7 F	Temp. 0 F	Temp. -10 F
No inhibitor	1	Mobile	Mobile	Mobile	Mobile
	3	Frozen	Frozen	Frozen	Frozen
	5	Frozen	Frozen	Frozen	Frozen
0.5% Inhibitor C	1	Mobile	Mobile	Mobile	Mobile
	3	Mobile	Mobile	Mobile	Mobile
	5	Mobile	Mobile	Mobile	Mobile

from 3 to 4 percent. The amount of corrosion, however, obtained in the test was only 500 mg/dm^{-2}. This was equivalent to 27 days' exposure to salted conditions of the first winter and to 20 days' exposure to salted conditions of the more severe second winter. These figures, 27 and 20 days, were calculated from regression data for the new coupons exposed in Test Rig No. 2 in Sample Groups 17 to 20. These data lead to the tentative conclusion that the Drip-Dry test when run at 32 F and under the conditions described, has an acceleration factor of from 3 to 4.

It was thought that the inhibitor coating the outside of the salt granules might have an effect on the penetration rate of the salt through ice. This was tested by forming a film of ice, 1 mm thick, in a petri dish and placing several granules of the deicing salt on its surface and measuring the time taken for the granules to penetrate the film. The moment at which the film was completely penetrated could be seen by observing the dish from the bottom. These tests were carried out in a cold room at 20 F. Single-sized $^1/_8$-in. salt particles were used and four inhibited salts along with the uninhibited salt were tested.

The salt granules were coated with the recommended amounts of inhibitor and the inhibitors and their concentrations used were as follows: Inhibitor A, 1.0 percent; Inhibitor B, 0.5 percent; Inhibitor C, 0.5 percent; and Dichromate, 1.0 percent.

The latter was included since it is a well-known laboratory corrosion inhibitor and it does form a major part of a commercial product which is currently being marketed as a deicing salt corrosion inhibitor.

When the tests were run, considerable variation in the penetration time was noted. This, no doubt, was due to the geometry of the salt granules. The averages of the penetration times were taken for each salt and compared. It was found that Inhibitor A (polyphosphate) and Dichromate caused an increase in the penetration time of approximately 50 percent, whereas Inhibitor B (metal powder) seemed to cause a slight increase and Inhibitor C, no increase at all.

The conclusions to be drawn are simply that the use of an inhibitor on the deicing salt can cause a slowing down of its action on the road, but this should prove to be no deterrent to its use since it is doubtful if this effect would be seriously noticeable in actual practice.

When Inhibitor C was developed it was originally intended as an antifreeze for salt piles to keep them mobile even in very cold weather. This property was tested by placing plastic bags containing 1000 g of salt, with and without a coating of 0.5 percent of inhibitor and containing varying percentages of water, in the cold room and observing the bags at a series of descending temperatures.

The results obtained are given in Table 16. This inhibitor kept salt containing up to 5 percent moisture free and mobile down to 0 F. It must be remembered, however, in actual use, where outdoor storage is concerned, some leaching of the material would occur and this temperature might not be reached.

CONCLUSIONS

1. The atmospheric corrosion rate varies from area to area within a country. It varies with weather conditions and is highest in areas where moderate to warm temperatures and high humidities predominate. It also varies with population concentration

and industrial densities; being lower in rural communities and higher in the more industrialized and populated centers. Proximity to a large body of salt water causes a marked increase in the corrosion rate.

2. The motor vehicle corrosion rate follows much the same pattern as the atmospheric corrosion rate; however, the use of the regular types of deicing salts causes an increase in the rate which varies directly with the amount of salt used.
3. Test coupons installed in traffic simulators corroded at a rate which was very close to that obtained from similar coupons mounted on test vehicles.
4. When tested in traffic simulators under natural conditions (no deicing salts used) the corrosion rate of unprotected auto-body steel is approximately one-half of the atmospheric corrosion rate.
5. The corrosion rate of auto-body steel under the conditions prevailing in the Toronto area (deicing salt used during winter) is little greater than the atmospheric corrosion rate.
6. The corrosion of a bare, unprotected piece of auto-body steel is not as severe or as damaging as the pitting corrosion which can occur under a protective lacquer film. This type of corrosion can occur wherever a break occurs in the film and an oxygen concentration cell is set up. Perforation of 20-gage steel was observed from this type of corrosion in a 19-month period.
7. From an economic point of view, none of the corrosion inhibitors tested produced a worthwhile reduction in the amount of corrosion.

ACKNOWLEDGMENTS

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REFERENCES

1. Adair, H. T. Effect of an Inhibitor on the Corrosion of Auto-Body Steel by Deicing Salt. Rpt. to the Dept. of Metropolitan Roads, Toronto, Ontario Research Foundation, Investigation No. M-60110, 1961.
2. Craik, D. W., and Yuill, G. K. Deicing Chemicals Corrosion Investigation: Part 1, Automobile Body Steel Investigation; Part 2, Pavement Materials Damage and Ice Melting Mechanisms. Rpt. to Metropolital Corp. of Greater Winnipeg by the Univ. of Manitoba, Mech. Eng. Dept.
3. Bregman, J. J. Corrosion Inhibitors. 1st Ed., Macmillan Co., New York, 1963.
4. Boies, D. B., and Bortz, S. Economical and Effective Deicing Agents for Use on Highway Structures. NCHRP Report 19, 28 pp., HRB, 1965.
5. Bennett, C. A., and Franklin, N. L. Statistical Analysis in Chemistry and the Chemical Industry. John Wiley and Sons, New York, 1954.
6. Uhlig, H. H. The Corrosion Handbook. John Wiley and Sons, New York, 1948.
7. Campion, F. A. Corrosion Testing Procedures. 2nd Ed., John Wiley and Sons, New York, 1965.
8. Palmer, J. D. Effect of an Inhibitor on the Corrosion of Auto-Body Steel by Deicing Salts. Ontario Research Foundation, Report No. M-6440, 1965.

Snow and Ice Control—
A Critical Look at Its Critics

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ABRIDGMENT

•MUCH is written and said in the public media each winter about the effects on autos and roadside environment of the chemicals used to provide safe driving surfaces. Little is reported of their benefits to the snow-belt economy and to individual motorists.

Salt is the principal tool in a highly essential operation financed with tax funds. A recent survey of 1, 250 city public works agencies showed that all use salt for deicing.

Tremendous growth in deicing salt use—now over 6 million tons annually in the United States and nearly 1. 5 million tons in Canada—is the result of public demand for safe, bare pavements for winter driving.

Most commonly voiced criticisms of deicing chemicals are outlined in the following paragraphs.

Salt causes auto corrosion. The fact is that salt does not corrode, but may attract moisture to an auto metal and thus speed corrosion. But if motorists take adequate care of vehicles there is no need for serious rust damage to modern autos. One automobile manufacturer has announced that its products will withstand rusting for ten years. Other automakers have made similar strides. Corrosion is caused by many factors, including atmospheric pollutants and ordinary moisture from whatever source.

Salt kills trees, grass and shrubs. The fact is that deicing chemicals rarely cause permanent harm to vegetation. Deicing chemicals have been used by the hundreds of thousands of tons for decades, and there are no barren, brown roadsides, devoid of plant life. Public safety is more important than sustaining plantings very near the pavement edge, which are themselves a safety hazard. The Bureau of Public Roads says the "desired roadside" should be clear of all nonessential obstacles—including trees—at least 20 feet beyond the road shoulder. This would solve the problem of effects of deicing chemicals on trees that in some cases actually touch the pavement.

Salt pollutes water supplies. Records of the U. S. Geologic Survey and the Public Health Service show little or no change in chloride concentrations in major drainage areas of the northeast United States, hence no effects on these drainage basins from salts used for deicing. Water flow is so large that the dilution factor decreases chloride levels to an acceptable point.

Deicing salts can pollute local wells, ponds, small aquifers and streams where the dilution factor is not enough to lower the chloride level sufficiently. Most pollution problems result from improper storage of deicing salt. This is a local problem, and can usually be solved by proper placement of storage piles, covering stockpiled materials, and ditching to discharge runoff to suitable drainage points. Chemical producers stand ready to assist public works officials in planning storage facilities to avoid problems of local pollution.

In design and construction of new highways, plans should take into account future maintenance needs, and location of small watersheds and acquifers.

It is easy to overlook the positive aspects of deicing salt use. Here are a few facts about the benefits of current deicing programs to motorists.

In Massachusetts between 1930 and 1936, before straight chemicals were used, there was an annual average of 21 fatalities and 1, 635 injuries due to skidding accidents. Be-

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tween 1940 and 1950, after officials began using straight chemicals, there was an average of only 9 deaths and 736 injuries annually because of skids.

A study by Ohio Department of Highways showed that 35.4 percent of all rural traffic accidents occurred while roads were covered with snow and ice. With no plowing or chemical application, it was estimated there would have been another 22,735 accidents, costing over $14 million. The Ohio researchers said that, conservatively, every dollar spent for snow and ice removal saved road users over two dollars.

In a 1965 study, the Citizens Traffic Safety Board of Chicago found that rain and snow caused 33,000 accidents in that city each year. In 6,000 of these accidents, someone was injured. In 45 of them, someone was killed. A snowfall of less than one-half inch can bring an accident rate ten times that for the same hours when pavements are dry. Streets that got low-priority salting in Chicago had nearly half of all accidents caused by snow, although they carried only about 20 percent of the traffic. Local streets had 8,934 accidents, nearly half the 18,251 that occurred on the more heavily traveled major routes that were quickly salted by street crews. The Traffic Safety Board concluded that Chicago's snow removal program—including use of salt—prevented 15,250 accidents that would have cost $3.71 million. Chicago has now adopted a policy of salting all streets.

Ten years ago, New York's director of engineering said a one-hour disruption of normal traffic flow from an average of eight winter storms would cause an economic loss of over $30 million. That figure would be much higher today.

Detroit's commissioner of public works once put that city's potential losses from winter storms at over $103 million per winter.

Motor fuel tax revenue figures show that fuel consumption has increased just as rapidly in the snow-belt states as in all others; drivers in northern states have not been handicapped by icy pavements in their year-around dependence on motor vehicles, thanks to modern winter maintenance practices that include heavy chemical applications to provide bare pavement conditions in all weather.

The Effectiveness of Antiskid Materials

R. R. HEGMON and W. E. MEYER, The Pennsylvania State University

The effectiveness of four commonly used antiskid materials was tested on a circular track apparatus on ice and packed snow. The tests were conducted with a full-sized automotive wheel which was made to slip until the maximum coefficient of friction was obtained. Initial friction values were quite high and deceptive. To sustain relatively high coefficients of friction after some traffic has passed, increased rates of application are required. The difference in the performance of the four materials was found to be small. The particle size has a pronounced effect on the performance of antiskid materials and especially the contribution of the very fine particles (passing a No. 50 sieve) is minor and their elimination is recommended. The physical properties of the materials that affect their usefulness as antiskid materials were determined and are reported.

•IT is a widely accepted practice to spread ice or snow-covered roads with sand, stone, or cinders to improve the driving conditions if only until the simultaneously applied melting agent has done its duty. Materials used for this purpose are called antiskid materials or abrasives. We shall use the first term, since it describes the desired effect of the material.

Despite the enormous amounts spent yearly for antiskid materials (the Pennsylvania Department of Highways has spent \$15½ million in 1965-1966 for the purchase and application of antiskid materials), the selection is usually made on the basis of local experience and convenience. Accepted practices are reviewed by Mellor (1).

There is no objective criterion, however, on the effectiveness of different antiskid materials—on the effect of size, shape, etc. Only two intensive investigations have been made, one by Matern and Kullberg (2) in Sweden, the other by Wehner (3) in Germany. Both conducted field tests with a slip and skid tester, respectively, and supplied valuable information on the improvement in road friction by spreading antiskid materials. The test methods, however, were not sensitive enough to discriminate between different antiskid materials and other factors.

We are aware that the final selection of antiskid materials will not be made on the effectiveness rating alone, but will be determined by other factors such as availability, cost, ease of storage and application, effect on the pavement, and dust and its effect on the surroundings. There is no doubt, however, of the importance of establishing an objective set of data on the relative effectiveness of antiskid materials.

Several states have issued specifications for antiskid materials; these usually contain some general requirements plus mandatory gradations. The gradation requirements of the Pennsylvania Department of Highways are given in Table 1. The findings in this paper might be profitably applied to review and possible rewriting of such specifications.

MATERIALS INVESTIGATED

Four materials widely used in Pennsylvania were investigated: boilerhouse and coke cinders, sand and stone. The cinders were of the quality as purchased by the Pennsyl-

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Paper sponsored by Committee on Snow and Ice Control and presented at the 47th Annual Meeting.

TABLE 1

PENNSYLVANIA SPECIFICATIONS FOR GRADATION OF ANTISKID MATERIALS

Sieve Size	Maximum Permissible Percentage Passing			
	Cinders[a]	Crushed Stone[b]	Sand[c]	Boiler Slag
No. 100	—	10	10	5
No. 50	18	—	—	5
No. 8	17	30	85	80
3/8 In.	—	70-100	100	100
1/2 In.	—	100		
1 1/4 In.	100			

[a] Boilerhouse or coke cinders, or combinations thereof.
[b] Crushed stone, gravel or slag.
[c] Sand, natural or manufactured.

vania Highway Department. The sand was of a grade which is used as antiskid material. The stone was crushed limestone, which is also used extensively as antiskid material. The results of sieve analyses of the materials as received are given in Table 2. When the fines passing the No. 50 sieve and the large chunks retained on 3/4-in. mesh are removed, the total weight for the four samples would be up to 11 percent less than in the as-received condition.

Typical values for specific weights and volumes are given in Table 3 after these materials had been sieved through a 3/4-in. mesh sieve and fines had been removed by a No. 50 sieve. The specific volumes of boilerhouse and coke cinders are roughly twice those of sand and stone.

The materials were subjected to static and dynamic breakdown tests. The static test measured the reduction in volume under a static load. At 125 psi, the reduction in volume for sand and stone was about 1.75 percent. When the unit loading was increased above 125 psi, the stone tended to compact still more, whereas the sand seemed to have been completely compressed. For cinders the volume reduction under a 125-psi pressure was about 3.25 percent and was slightly higher for boilerhouse cinders than for coke cinders.

Dynamic breakdown strength was measured by subjecting the samples to a sieve analysis before and after an impact test in which a total compactive energy of 8650 ft-lb/ft^2 was applied to all samples. The relative breakdown is given in Table 4 and is about 5 to 6 times greater for cinders than for sand and stone, whereas in the static test the ratio is approximately 2 to 1. The dynamic test reflects the actual conditions on the road because passing wheels impart an impact load to the material. Thus a dynamic test is more representative, although it may be possible that there is a correlation with the simpler static test. In either case, the change in size fractions should be measured by sieving and not by change in volume. However, the breakdown of the largest cinder particles is advantageous, as will be made clear from the experimental results.

Since antiskid materials are almost exclusively used in conjunction with a melting agent, usually calcium chloride, the four materials were tested for their ability to absorb calcium chloride (Table 5).

TABLE 2

GRADATIONS OF MATERIALS AS RECEIVED

Material	Percent Weight Passing Sieve No.							
	100	50	30	16	8	4	3/8 In.	3/4 In.
Boilerhouse cinders	0.9	6.3	19.9	35.2	47.4	63.4	85.4	96.2
Coke cinders	0.4	2.8	17.8	29.4	41.2	52.3	64.1	95.0
Sand	2.6	7.4	43.4	60.7	74.6	93.4	99.8	100.0
Stone	0	5.1			98.1		98.6	100.0

TABLE 3

SPECIFIC WEIGHTS AND VOLUMES OF TESTED MATERIALS[a]

Material	Weight (pcf)	Volume (in.^{3}/lb)
Boilerhouse cinders	48.6	35.5
Coke cinders	60.5	28.6
Sand	117.5	14.7
Stone	103.0	16.8

[a] After removal of fractions passing No. 50 sieve and retained on ¾-in. mesh sieve.

TABLE 4

DYNAMIC BREAKDOWN TEST[a]

Material	Breakdown (%)
Boilerhouse cinders	5.3
Coke cinders	3.9
Sand	0.7
Stone	0.8

[a] Breakdown due to 50 blows of a 10-lb weight falling 1.5 ft onto the 4-in. diameter free surface of the test cylinder (= 8650 ft-lb/ft^2). Breakdown defined as the percent change in the sum of the cumulative percentages retained on each sieve before and after the test.

In the friction tests, the antiskid materials were tested with and without calcium chloride. When treated with calcium chloride the proportion used was 5 percent by weight for all materials. This is within the range recommended by a committee of the Highway Research Board (4). With this percentage, the calcium chloride will be completely absorbed by all materials except the stone.

EXPERIMENTAL TECHNIQUE

Preliminary field tests were made with the Penn State road friction tester which measures skid resistance with an automobile tire. Repeatability, however, was poor due to the difficulty in controlling test conditions. There seemed to be little chance that the desired information could be obtained in this manner. Matern and Kullberg (2) and Wehner (3) had come to similar conclusions; namely, that field tests are not sufficiently sensitive to discriminate between different antiskid materials and determine effects of size, shape, etc.

Therefore, a special test apparatus was built. Figure 1 shows the circular track apparatus as installed in a cold room. It is a self-contained unit with base 1 and frame 11, whose main structure is rotated by an electric motor 7 and reducer 6 (Fig. 2). The test wheel 3 runs on track 2, the prepared test surface. The reference wheel 9 runs on the inner track 10 which has a high friction surface. The test and reference wheels are mechanically coupled through chain drives 4 and 8, gear unit 15, driveshaft 16 and variable speed transmission 20 which can be remotely adjusted via servo-motor 21 to obtain the desired speed of the test wheel relative to that of the reference wheel. The test wheel can therefore be caused to move along the test track with any amount of slip which the drive system components permit. Torque transducer 14 measures the torque due to the tire-test surface interaction.

The wheels and the transmission system are mounted on two half-frames 13 and 22 which are pivoted to center frame 5 and can be lifted or forced downward to apply loads to the wheels by two pneumatic cylinders 18. The turret 17 carries a rotary gland for supplying air to the cylinders and slip rings for connecting the torque transducer, a tachometer generator 12 on the test wheel shaft, and the transmission servo-motor to the control station outside the cold room. The forward speed of the test wheel is obtained by measuring the speed of the main drive motor 7. Thermocouples in the test track permit monitoring the ice temperature.

TABLE 5

CALCIUM CHLORIDE RETENTION[a]

Material	$CaCl_2$ Retained (% by wt.)
Boilerhouse cinders	13.5
Coke cinders	9.9
Sand	6.9
Stone	0.9

[a] Retention determined from the weight increase of oven dried material soaked for 75 min in saturated calcium chloride solution, drained and dried.

For the tests reported here a Firestone 6.00 × 13 tire with standard high-

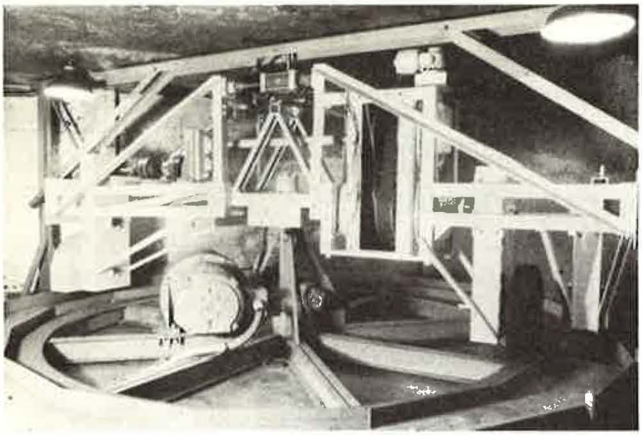

Figure 1. Circular track apparatus.

way tread was used. Inflation pressure was 26 psi and the load 630 lb. The test wheel speed was 7 mph and the wheel passed over a given spot of the track ten times per minute. The speed of 7 mph might be considered excessively low, but all previous experience including our own, had shown that the coefficient of friction on snow and ice, with and without antiskid materials, is practically speed independent. Thus, the choice of the test speed became a matter of convenience. The slip was varied to find the maximum coefficient of friction. The maximum occurs at a slip of 6 to 12 percent. On a vehicle, any slip beyond the friction maximum will cause the wheel to go immediately into the locked condition. This is precisely what we wish to prevent through the use of antiskid materials. Therefore, their performance is evaluated best at the condition which determines whether or not, or when, a skid will develop. Although the friction with wheels locked determines how far the vehicle will slide on ice or snow, disaster will usually occur before the end of the skid. Besides, in a test such as this in which the test wheel moves along a fixed path and repeatedly passes the same spot, locked wheel tests are unrealistic. Track and treatment would get an exposure which differs from that by real traffic.

The preparation of the track, whether of ice or snow, required a certain amount of experimentation. The details of the procedures finally adopted are not thought to be of interest here. Suffice it to say that the ice track was scraped smooth with a scraper attached to the rotating test rig and that the natural snow was packed down for the snow

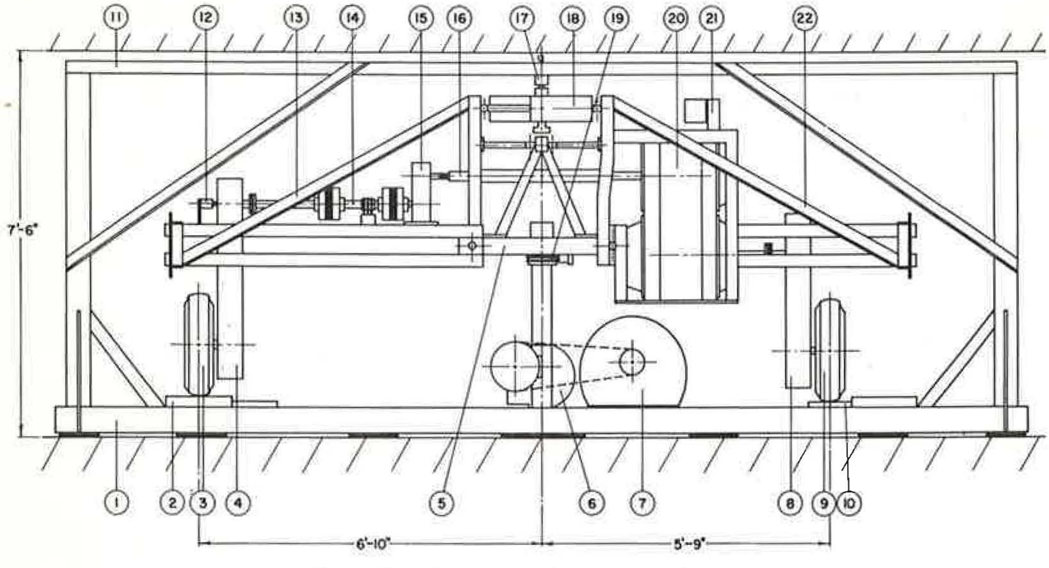

Figure 2. Circular track apparatus layout.

tests. All tests, unless otherwise noted, were made when the temperature of the air in the room and the track had stabilized at 21 F.

The antiskid materials were applied by hand. Various mechanical methods of applying them were considered, but all were discarded as either not good enough or impractical. Since the test wheel torque was recorded continuously, an automatic check was obtained that the application was uniform along the track.

RESULTS AND DISCUSSION

The initial friction obtained after an antiskid material has been spread on an ice or snow-covered road is quite high and gives a false indication of the safety improvement achieved. The effectiveness of antiskid materials must be judged by the friction available after exposure to traffic. Usually the time between application of an antiskid material and the melting of the snow or ice will be a matter of hours. To simulate this condition with the circular track apparatus all test conditions were held constant and the coefficient of friction was measured as a function of the number of wheel passes. The four materials were tested in this manner. The results for two materials with the rate of application as parameter are shown in Figures 3 and 4. All curves represent the averages of the data from at least two tests, with a maximum variance of 15 percent.

The initially high friction value decreases with the number of wheel passes and higher application rates give higher coefficients throughout, even when the coefficient has stabilized. There is probably an upper limit to the rate of application above which no additional benefit will be derived, but in practice the rate will be governed by cost considerations. The performance of all four materials was similar, with only the stone giving somewhat lower friction values, probably because the limestone does not absorb calcium chloride as well as the other materials.

Figure 5 compares results on bare ice and bare packed snow with those obtained with 2 lb of coke (0.6 lb/sq yd) applied to the same ice and snow tracks in treated and untreated condition. Without antiskid materials, friction becomes constant after only eight wheel passes. The initial drop is probably due to smoothing and slight melting by the slipping wheel. With antiskid material applied, the initial friction value is much higher but continued to drop more and longer although at a slower rate. The addition of calcium chloride to the coke cinders gives it initially a better bond to the snow, but after several wheel passes, both the treated and untreated materials embedded equally into the packed snow and give the same coefficient of friction. On ice, there is no measurable difference whether the material is treated or not. Although data are incomplete, we conclude that the added calcium chloride does not significantly increase the obtainable friction. It does, however, facilitate the handling of the antiskid materials and eventually assists in clearing the pavement of the ice and snow.

The four materials were compared on an equal weight basis. The tests were run with 1 to 4 lb of antiskid material spread along the circular wheel track with 1 lb corresponding to 0.3 lb/sq yd. Comparison on an equal volume basis may be of more interest since hauling and spreading are functions of volume rather than weight. Cinders

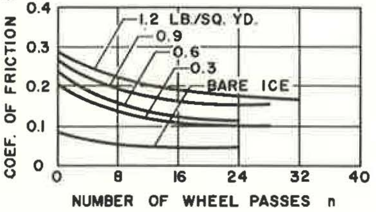

Figure 3. Coefficient of friction f vs number of wheel passes n for treated coke cinders on ice at 21 F for different amounts spread along wheeltrack.

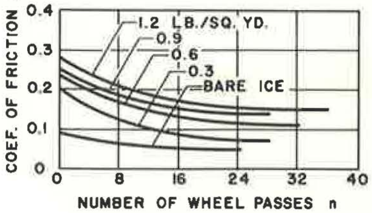

Figure 4. Coefficient of friction f vs number of wheel passes n for treated sand on ice at 21 F for different amounts spread along wheeltrack.

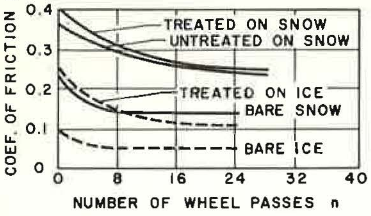

Figure 5. Coefficient of friction f vs number of wheel passes n for 0.6 lb/sq yd of coke cinders, treated with calcium chloride and untreated, spread on ice and packed snow and compared with the same surfaces without any antiskid material.

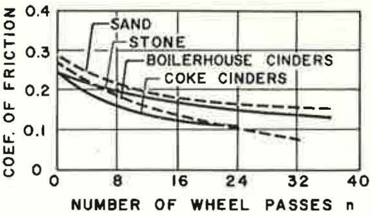

Figure 6. Coefficient of friction f vs number of wheel passes n for four antiskid materials compared on an equal volume basis.

have about twice the specific volume of sand and stone; therefore Figure 6 was plotted to compare 2 lb each of the two cinder types spread along the track with 4 lb each of sand and stone. Compared on this basis sand and stone give a somewhat higher coefficient of friction than cinders.

Whatever way the comparison is made, the effectiveness of all four materials tested is very similar and the friction values obtainable with any can be improved by increasing the rate of application. Using the material which is the least expensive under given circumstances is therefore justified and the criterion should be the maximum rate of application per dollar. No attempt was made here to make a cost comparison, since the prices vary considerably between districts.

The question of how the effectiveness of different size fractions differs is answered by Figure 7. In all cases, the highest coefficients are obtained with sizes between No. 16 and 4. It should be noted that this graph is for effectiveness immediately after spreading except for curve No. 2. Any comminution which may be caused by exposure to traffic is implicitly contained in the earlier graphs which show the change of the coefficient with the number of wheel passes. The conclusion to be drawn is that the fines and large particles are not as effective as the middle sizes. We have not determined how gradation changes with the number of wheel passes but the shift of the peak of curve No. 2 would indicate a breakup of larger particles. Reliable information can be obtained only in the field. Our data do indicate, however, that a modest improvement can be realized by removal of the fines from the original product. Here again, the effectiveness gain must be weighed against the cost increase and other factors.

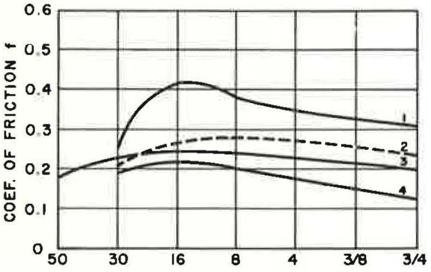

Figure 7. Coefficient of friction for seven size fractions of two antiskid materials: 1—coke cinders on snow, at first wheel pass; 2—coke cinders on snow, after 4 wheel passes; 3—boilerhouse cinders on ice, at first wheel pass; and 4—coke cinders on ice, at first wheel pass.

CONCLUSIONS

In contrast to highway experiments, the experimental conditions of the present investigation could be closely controlled so that the results were reproducible within narrow limits, allowing us to draw the following conclusions, which we believe are applicable to all speed and temperature conditions normally encountered in winter driving throughout the United States.

1. The four materials tested are the most widely used antiskid materials. They were tested untreated and treated with calcium chloride. The performance of all four materials was similar, and therefore factors other than effectiveness will usually decide the choice of material. Delivered price and cost of application, as well as

the ease of handling under below freezing conditions, are the most important considerations.

2. To retain good effectiveness after exposure to traffic, the rate of application should be high.

3. Fine particles, those passing the No. 50 sieve, should be eliminated, since they contribute little to the obtainable friction. The fines constitute less than 10 percent by weight for the currently procured materials.

A more basic study of the mechanism by which antiskid materials perform their intended task may be warranted. A practical benefit of such a study could be the eventual development of antiskid materials of superior performance. No matter how much melting agent is applied, antiskid materials are needed to provide a friction coefficient, which is higher than without them, for the period between a snowfall, plowing or the formation of an ice layer on the roadway and the removal of the ice and snow by the melting agent.

ACKNOWLEDGMENT

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REFERENCES

1. Mellor, M. Snow Removal and Ice Control, Report on DA Project IV025001A130, USAMC Cold Regions Research and Engineering Laboratory, Hanover, N. H., 37 pp., April 1965.
2. Matern, N., and Kullberg, G. Sand and Salt Treatment of Snow-Covered and Icy Roads, Report 28 (in Swedish). Statens Vaeginstitut, Stockholm, 1956.
3. Wehner, B. Griffigkeitsmessungen auf winterglatten Fahrbahnoberflaechen (Friction Measurements on Frozen Pavements). Heft 40 (in German). Forschungsarbeiten aus dem Strassenwesen; Kirschbaum Verlag, Bad Godesberg, 1960.
4. Current Practices for Highway Snow and Ice Control. HRB Current Road Problems 9-4R, 33 pp., 1962.

Electrically Conductive Asphalt for Control of Snow and Ice Accumulation

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An asphaltic concrete made electrically conductive by the addition of graphite was designed and tested in small test plots over two winter seasons. Power dissipation per unit surface area, P/A_S, in watts/ft^2, is $P/A_S = \left(\frac{E}{\ell}\right)^2 \frac{t}{\rho}$, where E = applied potential difference, volts; ℓ = conducting path length; t = thickness of conducting sheet, in.; and ρ = resistivity of material, ohm-in.

From the design requirements of 20 watts/ft^2, ½-in. thickness, 30-volt potential drop between electrodes spaced 5 ft apart, the necessary resistivity was calculated to be 1 ohm-in. Laboratory studies to obtain this value were made, first using simulated asphaltic concrete (paraffin as a binder) and then asphalt-graphite-aggregate briquettes covering a wide range of mixtures. These studies led to the choice of a 25 percent graphite level, and six test sections were constructed at USA CRREL using this mix and three thicknesses and sizes of electrodes. Actual resistivities were 7 to 12 times design value. Mixing, placement and control are critical in achieving satisfactory electrical properties. The test sections performed satisfactorily over a two-winter observation period. The sections were not trafficked and measurements of resistivity showed increases of 21 to 83 percent over an 18-month period. Safety considerations would probably make necessary an overlay, since a steel form placed on one test section and loaded by standing on it resulted in a 40 percent current increase. Cost of a conductive asphalt with electrodes would be competitive with other methods of heating pavement surfaces.

•PRESENT practical methods of control of snow and ice accumulation on paved surfaces can be classified as chemical, mechanical, and thermal. Melting of frozen precipitation by heat can be accomplished by direct application of thermal energy from an exposed flame or an electrically energized radiant source, by pipes carrying hot liquid, or by electrical resistance cables buried in the upper portion of the pavement. The buried electrical cable method has much to recommend it, for it enables the heat to be applied more efficiently to the snow or ice than the other methods. However, there are drawbacks to the use of buried heating cables: either the spacing between the cables must be very small, or temperature of the cables must be very high, to obtain adequate heat input to melt snow or ice in the areas between them. Furthermore, cables must be buried relatively deep in the pavement to obtain the optimum distribution of heat for a given electrical input and cable size—British practice is to bury cables 2 in. below the top surface, with a spacing of 6 in. (1). This requires a major construction job for placement of the cables as well as the undesirable task of breaking the pavement surface in old construction.

A method of applying thermal energy close to the surface, and evenly, is clearly desirable. The 3-P thermo-pavement system developed in Switzerland—now called

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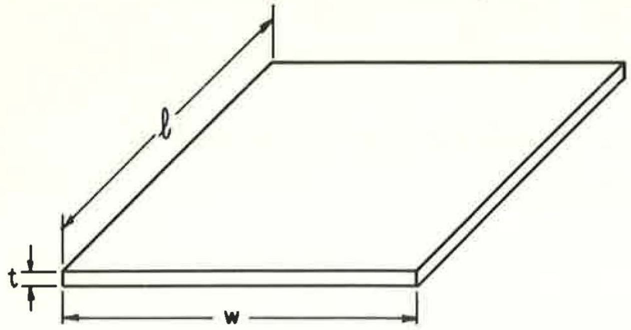

Figure 1. Geometry of the conductive sheet.

Calorway and used in Austria (2)—attempted this; but this system, which required laying insulated heating cables in a prefabricated plastic grid, then covering the whole with a sand-asphalt wear course, is costly in both labor and materials and can be damaged too easily. The latter factor is critical since this system operates at 1000-V potential. Any cable heating system is subject to damage which is both difficult and costly to repair. These considerations led to the investigation of electrically conductive asphalt as a means of heating the pavement surface.

PRINCIPLES

Power dissipation in an isotropic conductive sheet (Fig. 1) is described in the following paragraphs.

Power is consumed when current flows through a purely resistive load under an applied potential according to the relation

$$P = EI = \frac{E^2}{R} \tag{1}$$

where

P = power dissipated, W;
E = applied potential difference, V;
I = current, amp; and
R = resistance, ohm.

Materials exhibit a resistance directly proportional to the length of the conducting path and inversely proportional to the cross-sectional area of the conducting element, A_c, or

$$R = \rho\frac{\ell}{A_c} = \frac{\rho\ell}{tw} \tag{2}$$

where

R = resistance, ohm;
ρ = proportionality constant, resistivity, ohm-in.;
ℓ = conducting path length, ft;
t = thickness of conducting sheet, in.; and
w = width of conducting sheet, ft.

Substituting Eq. 2 in Eq. 1 gives

$$P = E^2\frac{tw}{\rho\ell} \tag{3}$$

Power dissipation per unit surface area, A_s, is

$$P/A_s = \frac{E^2}{w\ell}\cdot\frac{tw}{\rho\ell} = \left(\frac{E}{\ell}\right)^2\frac{t}{\rho} \tag{4}$$

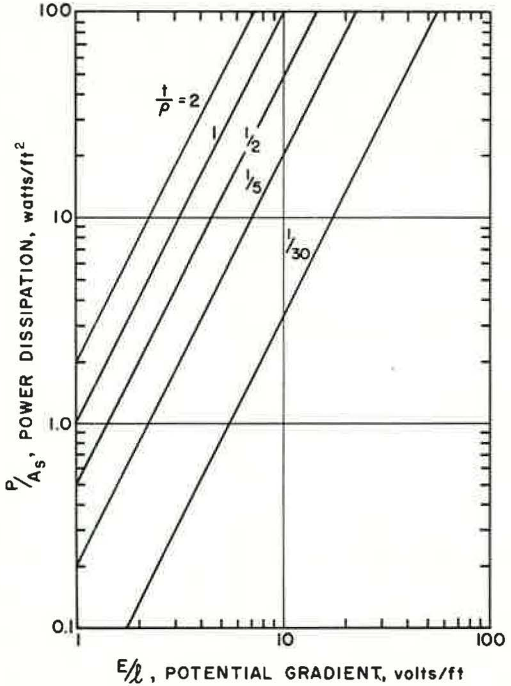

Figure 2. Power dissipation vs potential gradient.

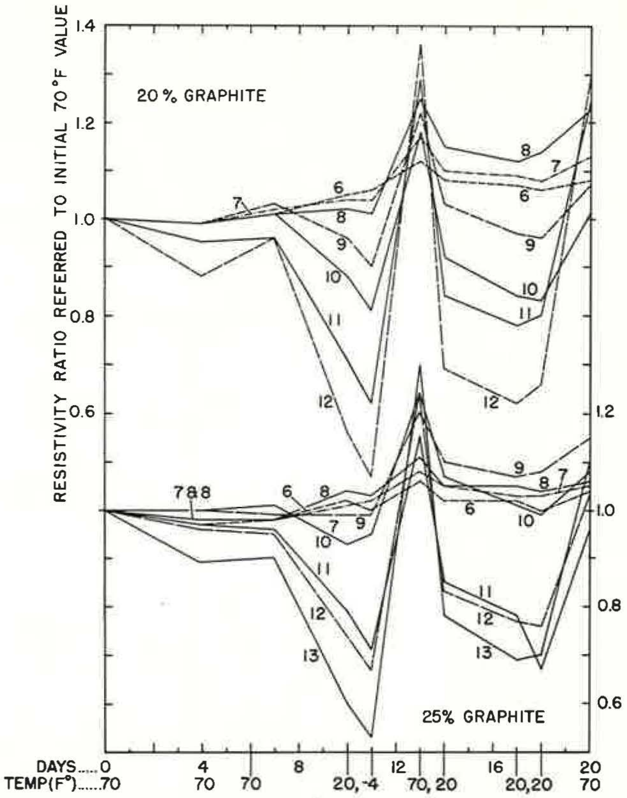

Figure 3. Change in resistivity with temperature for 2 levels of graphite and 7 levels of asphalt (parameter is asphalt content, %).

Figure 4. Test area following a 2⅛-in. snowfall (December 13, 1965); 1 # 2 test section is in) foreground, and reading to right are the 1 # 6, 1 # 2, 1 # 6, # 6, (snow covered) and # 10 sections.

TABLE 1

VOLUME RESISTIVITIES OF ASPHALTIC-CONCRETE INGREDIENTS

Material	Resistivity, ρ		Source
	Ohm-Cm	Ohm-In.	
Asphalt	10^{14}	~4 x 10^{13}	(3)
Graphite (pure)	0.0008-0.0013	0.0003-0.0005	(4)
Limestone	10^4-10^5	4 x 10^3-4 x 10^4	(5)
Granite	10^7-10^9	4 x 10^6-4 x 10^8	(5)
Sand	10^5-10^6	4 x 10^4-4 x 10^5	(5)

TABLE 2

TEST PANEL CHARACTERISTICS

No.	Panel Designation[a]	Resistance Between Outer Conductors (ohm)			
		10/6/65	10/27/65	12/21/66	4/21/67
1	½ # 10	39.6	47.3	54	82
2	½ # 6	116	115	168	141
3	1 # 6	33.0	45.7	79	84
4	1 # 2	26.5	46.6	47	69
5	1½ # 6	17.5	23.5	38	43
6	1½ # 2	12.5	18.0	32	28

[a] First number is the asphalt thickness; second number is the gage of the stranded copper cable used as conductor.

TABLE 3

WEATHER

Date	Temperature	Winds	Sky
10/6/65	48 F	12 kt	Sunny
10/27/65	43 F	Calm	Cloudy
12/21/66	28 F		
4/21/67	46 F	Slight breeze	Clear

This has the form of $y = ax^2$, a parabola, and is most conveniently graphed on log-log scales (Fig. 2); the ratio t/ρ, conductance is the parameter.

DESIGN FACTORS

Maximum power dissipation required for test purposes was established as 20 W/ft² (from work carried out in England and the United States). Maximum potential drop should preferably not exceed 30 V between electrodes for safety reasons.

Desired thickness of conducting material is ½ in., chosen to require the minimum amount of material consistent with ease of placement and minimum disturbance of the electrical field if superficial gouging by traffic action occurs. An approximately 5-ft spacing between electrodes is desired, thereby setting a potential gradient of 6 V/ft. The power dissipation and potential gradient requirements establish the t/ρ ratio as

CONDUCTIVE

Date	New Snow (in.)	Wind Speed (mph)	Air Temp. (° F)	½ # 10			½ # 6		
				P_{tot} (watts)	P/ft² (watts/ft²)	Clear (%)	P_{tot} (watts)	P/ft² (watts/ft²)	Clear (%)
12/20/65	⅞	Calm	7	448	12.5	100	127	3.5	0
1/3/66	¼	Calm	26	505	14.0	Thin covering[a]			
1/7/66	¼	8 mph	30	572	16	100			
1/24/66	16½	8 mph	25	500	13.9	Ctr 100			
12/6/66	½	Calm	30	360[b]	20	50			
12/14/66	2	Calm	27-32	720	20	100			
12/25/66	9½	Calm	27-32	600	17	90	130	3.6	0
12/29/66	2	Calm	23	600	17				
1/13/67	2	Calm	27	600	17	100	240	6.7	95
1/30/67	2-3	15-25 mph	17	600	17	25	180	5.0	10
2/2/67	3-4	Calm	34	600	17	100	180	5.0	Slush
2/8/67	1-2	Calm	16	600	17	50	180	5.0	0
2/21/67	5	Calm	23-28	600	17	100	180	5.0	50
2/24/67	10-12	10-15 mph	20	600	17	0	180	5.0	0
3/6/67	2	Calm	29	600	17	100	180	5.0	0
3/8/67			20-30	600	17	80	180	5.0	0
3/16/67	4	5 mph	26	600	17	100	180	5.0	0 (ice)

[a] Light snow fell during night of Jan. 2-3. Panel 1½ # 6, unheated, did not accumulate; snow adhered to all heated panels, then froze when tem dropped to 20-22 F.

[b] Only half of panel was energized.

approximately 1/2 (Fig. 2). From this, it is seen that a material having a resistivity of $\rho = 2t = 1$ ohm-in. is required. This was the goal in the material tests that were made.

LABORATORY TESTS

Materials

A search of the literature revealed no information on the electrical properties of asphaltic concrete pertinent to this investigation. Therefore, experiments were designed to determine the influence of a conductive additive such as graphite. Published values of volume resistivities of asphaltic-concrete ingredients were found and are given in Table 1. Replacing a portion of the mineral aggregate with a material of higher conductivity such as graphite would offer an approach to obtaining an average resistivity of approximately 1 ohm-in. Just how much aggregate must be replaced is difficult to compute, since neither the particle size distribution of graphite after mixing nor the extent of the carbon-to-carbon chains that may be formed by compaction are known. Sample briquettes were therefore prepared and resistances measured with either a Rubicon Wheatstone bridge or a General Radio type 650-A impedance bridge.

Exploratory tests were made using paraffin as a binder for graphite, graphite-aggregate, and graphite-aggregate-aluminum particle mixes. These were followed by the preparation by the Soils Laboratory, U. S. Army Corps of Engineers, New England, of standard Marshall briquettes for combined stability, flow, and resistivity measurements for a range of conductive asphalt compositions (6). Resistivity was determined by attaching wire electrodes to the briquette faces by brushing on silver conductive paint (Du Pont type 4817) and measuring the resistance on the bridge. A two-level factorial design experiment with three factors (asphalt, graphite, and aluminum) led to the rejection of aluminum as of significant value.

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		1 # 2			1½ # 6			1½ # 2		
²)	Clear (%)	P_{tot} (watts)	P/ft² (watts/ft²)	Clear (%)	P_{tot} (watts)	P/ft² (watts/ft²)	Clear (%)	P_{tot} (watts)	P/ft² (watts/ft²)	Clear (%)
	100	352	9.8	80	565	15.7	90	672	18.7	100
	Thin covering[a]	287	11.7	Thin covering[a]						
	100	316	8.8	100						
	Ctr 100	280	7.8	8 cm deep						
	100	595	16.5	100						
	100	595	16.5	100						
	95	510	14	90						
	100	650	18	100	560	16	100	760	21	100
	20	600	17	95	560	16	50	800	22	40
	100	600	17	100	560	16	100	800	22	100
	50	600	17	95	560	16	100	800	22	95
	100	600	17	100	560	16	100	800	22	100
	0	600	17	0	560	16	0	800	22	10
	100	600	17	100	560	16	100	800	22	100
	100	600	17	100	560	16	100	800	22	100

TABLE 5

TEST PROPERTIES AND RANGES REQUIRED

Test Property	Criteria (roads)	Test Results (at 10.0% A.C.)	Required Range
Stability, lb	500+	1260	1100+
Flow, 0.01 in.	20-	12	10-14
Voids total mix, %	3-5	4.1	3-5
Voids filled with asphalt, %	75-85	83.7	75-85
Density, pcf	—	133.6	—[a]

[a] The density of pavement placed is required to be greater than 98 percent of the density obtained on field-molded specimens of the same mixture using 50 blows per side of the Marshall hammer.

In a new set of briquettes prepared by the Soils Laboratory the asphalt content was increased to improve workability, and the graphite level increased to meet the electrical requirements. The effect of temperature cycling on the resistivity for two levels of graphite (20 and 25 percent) is given in Figure 3. This is presented as the ratio of the resistivity for the data shown on the abscissa to the initial resistivity (measured at 70 F). Increasing the asphalt decreased the deviation of resistivity from the norm (initial 70 F measurement) for both room and low temperatures. The limited data also suggest that the deviation from the initial value decreases with the number of cycles.

FIELD TESTS

A 6 by 8-ft outdoor test section constructed on an existing asphalt parking area of USA CRREL's Hanover laboratory in November 1964 was only partially successful. The mix failed to meet design objectives because of the contractor's unfamiliarity with such an unusual mix; he was forced to add considerably more asphalt than the design called for in order to obtain workability and eliminate lumps caused by adding cold graphite to the mix. Placement was marred by poor thickness control and rapid setting of the mix. Nonetheless, the test section was kept free of ice and snow during the winter, although a high voltage was required for the purpose.

An additional set of outdoor conductive asphalt test sections was constructed in the parking area of USA CRREL in October 1965 and measurements and observations were made over two winter seasons (Fig. 4) 1965-1966 and 1966-1967. These additional sections were designed to investigate the influence of thickness, diameter of embedded conductor, power level, long-term aging characterisitics, durability, and safety. A new mix was designed because of the change in suppliers of the graphite: 10 percent asphalt and 25 percent graphite were used.

Six 6 by 6-ft holes were cut in the existing asphalt parking lot at USA CRREL and backfilled with sand and standard hot mix to give unfilled depths of ½, 1, and 1½-in. (two of each). The graphite balling which occurred during the preparation of the first mix was controlled by dimping warm, preheated bagged graphite through a port in the hopper cover directly into the pugmill after the aggregates had been batched. An insignificant amount of graphite was lost from each bag by leakage.

The test sections were connected to center-tap transformers which were in turn connected to autotransformers for voltage control. The connections were varied during the early part of each season to obtain a spread in power densities (Table 2 and 3).

The resistance of all test sections increased between the time of placement and the final measurement at the end of the second winter season. In some cases, however, the resistance dropped between the middle of the first winter and the end of the second winter, suggesting that the change in resistance may not only be a chemical change (degradation of the asphalt) but may also be a physical change such as voids forming within the mass. This would be particularly critical around the conductors. Since the test sections were not trafficked at any time, there was no compaction other than that at construction and that required to repair the loosened conductors at the beginning of the second season.

Observations of the test sections during periods of precipitation, and their power inputs, are given in Table 4.

Table 5 gives the required Marshall properties of an asphalt pavement and the results that were achieved with the conductive asphalt mix used in the six test sections.

DISCUSSION

Safety

Accidents in which metal conductors fall across the conductive asphalt, or perhaps penetrate the surface, are likely to occur. This aspect of safety was the basis for the design criterion of a 6 V/ft potential gradient. Rudimentary tests to investigate the potential hazard were made on the 1½ #2 panel on a dry, warm day. A steel channel across the panel (energized at 80 V across the outer conductors) caused little change in current flow. However, loading the panel with about 325 lb (two people standing on it, one on each end) caused a 30 percent jump in current. Water alone across the panel resulted in an imperceptible change in current. The current increased less than 10 percent when the unloaded steel channel was placed on the wet panel. A final test was performed by grooving the asphalt about ½ in. deep for a length of 8 in. and placing the steel channel across the dry panel and in the groove. When the channel was loaded by the two people stepping on the ends, the current increase was greater than 40 percent. Thus, the safety hazard is great enough to require a protective surface coating; no studies of such a coating have been undertaken.

Cost

Graphite substitutes for a portion of the sand; therefore, its cost is almost entirely added to the cost of the asphalt mix. The type of graphite used in all the mixes tested costs 7 to 8¢/lb, depending on quantity, FOB plant. For a quick computation, a figure of $200/ton delivered is used. The unit weight of a 10 percent asphalt, 25 percent graphite mix is about 134 lb/ft^3. A 1-ton batch of this mix which contains 450 lb of graphite makes a 1½-in. thick overlay over an area of 120 ft^2 at a cost for graphite of 37½¢/ft^2. In the test arrangement, 0.5 linear feet of cable was used per square foot of heated surface. For No. 10 stranded cable this would involve a cost of about 5¢/ft^2. Thus, the added cost for materials for conductive asphalt pavements totals approximately 45¢/ft^2. Placement costs may be somewhat higher than those for a conventional pavement because of the greater mix and thickness control necessary. However, the total cost exclusive of the electrical distribution system would probably be close to the $1/ft^2 cost of conventional resistance cable or mesh heating installations (7).

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REFERENCES

1. Price, W. I. J. Heated Roads. Jour. of Instit. of Heating and Ventilating Engineers, Dec. 1960.
2. Synthetics Encase Heating System. Engineering News-Record, p. 50-51, April 15, 1965.
3. Pfeiffer, J. P. (ed.). Properties of Asphaltic Bitumen. Elsevier Publishing Co., 1950.
4. Knowlton, A. E. (ed.). Standard Handbook for Electrical Engineers. McGraw-Hill Book Company, Table 4-45, 1949.
5. Chemical Rubber. Handbook of Physics and Chemistry. Chemical Rubber Publishing Company, Cleveland, 1957.
6. Department of the Army. Materials Testing. Technical Manual 5-530, 1957.
7. George, J. D., and Wiffen, C. S. Snow and Ice Removal from Road Surfaces by Electrical Heating. Highway Research Record 94, p. 45-60, 1965.