1951

Lap requirements of corrugated aluminum roofing as affected by roof slopes

Teddy Omar Hodges
Iowa State College

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LAP REQUIREMENTS OF CORRUGATED ALUMINUM
ROOFING AS AFFECTED BY ROOF SLOPES

by
Teddy Omar Hodges

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Agricultural Engineering
(Farm Structures)

Signatures have been redacted for privacy

Iowa State College
1951
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INTRODUCTION

The Project

History

Project 1011, entitled "The Utilization of Aluminum and Aluminum Products in Farm Buildings and Equipment", was originated at the Iowa Agricultural Experiment Station on March 1, 1947. The initiation of the project came as a result of a grant-in-aid by the Aluminum Company of America.

Purpose

The title of the project suggests the purpose of the study. The main use of aluminum on the farm at the time the project was originated was its use as roofing sheet. During the period immediately succeeding World War II building materials of all kinds were extremely scarce and aluminum sheeting was stocked by some lumber dealers primarily because of the scarcity of proven roofing materials, such as galvanized steel.

Although aluminum sheeting first came on the market as a substitute material, the question naturally arose as to whether or not it had suitable qualities which would merit its use even when steel became plentiful.
Proper application is essential with any roofing material and this is especially true of a relatively new material which has not been proven and is on trial. Could aluminum sheeting be applied in the same way as steel, or were special precautions necessary? This lack of knowledge of the proper methods of application led to the beginning of one part of the investigations to determine the suitability of aluminum for use in farm structures.

The proper method of application of aluminum roofing involved study of nailing girts and roof deck requirements, and nail requirements.

Other features of aluminum sheets which needed study were the effects of aluminum on the temperatures in a building and the effects of temperature change on aluminum sheet roofing.

Of these needed studies, much research has been done by Dale (5) on temperatures under roofs, by Robison (23) and by Boyd (4) on nail performance, and by Pandya (22) on the effects of temperature changes on aluminum sheet roofing. Their work will be covered in the review of literature.

It seems that very little research has been carried out on deck requirements for aluminum sheet roofing and on side lap and end lap requirements. Therefore, this study was set up in an effort to find the lap requirements for various roof slopes.
Objectives of the Study

Until this investigation little work has been done on side and end lap requirements of aluminum sheets. This is especially true as far as the effects of roof slope on lap requirements are concerned. Therefore, this study was initiated with the following objectives:

1. To evaluate the factors causing water to move through the side laps and end laps of corrugated aluminum sheets
2. To determine side lap requirements of corrugated aluminum sheets for various slopes of roofs
3. To determine end lap requirements of corrugated aluminum sheets for various slopes of roofs
4. To determine the probability of leakage occurring through the nail hole of the underlapped sheet at the lapped joints.

Justification

Iowa, with an investment of approximately 800 million dollars, leads all other states in farm building investment (25). To express it in another way, approximately one out of every twelve dollars invested in farm buildings in the United States has been spent in Iowa.
The purpose of a farm building is to provide protection for livestock or to provide storage or processing space for farm products. It might be said that a building is no better than its roof. A roof is generally accepted as being satisfactory if it keeps out the rain, wind, and snow and has a long life. Proper application of a roofing material is an important factor in providing a roof that will satisfy these minimum requirements of a satisfactory roofing material.

Dale (7), in a study of the relation of costs of various components that go to make a roof, showed that, for fifty-three roofs, the cost of the roofing material was 54.2 percent of the total cost for the lowest cost roof while it was 40.6 percent for the most expensive roof. It can be seen that roughly 50 percent of a roof cost is for the materials. Proper application of the materials adds very little, if any, to the overall cost of a roof. Also, proper application of a sheet metal, such as aluminum, will insure a roof that meets the minimum standards of a good roof.

Inspections of roofs on farm buildings in Iowa show that leakage problems do exist on sheet metal roofs. These problems would not be encountered if the laps were sufficient to prevent water from passing through and if all nail holes were properly sealed.

Again, very little, if any, correlation between roof
slopes and required laps can be found on the existing sheet metal roofs on Iowa farm buildings. In view of these facts, the study described in the following pages was initiated in an effort to find answers to some of these unknown factors.

Review of Literature

History of aluminum

Aluminum, the most abundant of all the metallic elements found in the earth's crust, was at one time more precious and rare than silver and gold.

For years the metal remained locked so tightly in the compounds in which it occurs in nature that it resisted all attempts at isolation until a little more than one hundred years ago.

In 1825, the Danish physicist and chemist, Hans Christian Oersted, announced to the Royal Danish Academy of Sciences that he had obtained aluminum by gently heating aluminum chloride and potassium amalgam.

Two years later, Frederick Wohler recaptured the metal by the use of metallic potassium in place of the amalgam, and by 1845, he had sufficient aluminum to determine that it was a light, malleable metal.

The advancement in the recovery of aluminum continued with such scientists as Henri Sainte-Claire Deville, a
French chemist contributing greatly to the goal of producing the metal cheaply.

A few years later, two young chemists, Charles Martin Hall, an American, and Paul Louis Toussaint Heroult, a Frenchman, developed simultaneously in the two countries the electrolytic process for producing aluminum.

The effect of the discovery of Hall and Heroult on the aluminum industry can best be told in terms of the amount of the metal used today and at the time of their discovery. In 1886, the world production of aluminum was approximately 35,300 pounds; in 1943, more than 1,820,000,000 pounds were produced in the United States alone. The United States production of aluminum is shown in Figure 1 and the world production is shown in Figure 2 (17).

One of the first uses of aluminum was in the production of cooking utensils, and from its start in the kitchen it has spread to almost every room in the modern home.

Since the development of the electrolytic progress for the production of aluminum a great variety of industrial uses of aluminum have been brought into existence. The use of aluminum conductors for transmission of electricity has been known for the last forty years. The metal has acquired an important place in the transportation industry, which is the largest single user of aluminum.

During World War II, the expansion of the aluminum industry was very rapid. This fact is shown in Figures 1
Fig. 1. Production of aluminum in the United States.
* Estimate by U.S. Bureau of Mines.

Fig. 2. Production of aluminum in the world.
and 2. Aluminum was one of the most important materials in the production of aircraft and other vehicles in which the light weight was a major factor in determining the construction metal.

After the war ended, aluminum was released for a number of peacetime products, one of which was aluminum corrugated sheet roofing, to which this study pertains.

At the present time, aluminum is again being channeled into war production and the production of aluminum roofing, for farm use is very limited or non-existent. However, this gives the researchers an excellent opportunity to solve some of the problems connected with aluminum roofing, so that when the war emergency is over, the metal will be ready to take its place as a farm building material.

**Performance of aluminum sheets as affected by nail fasteners**

Aluminum sheets are impervious to water or water vapor. However, when the sheets are fastened to the roof deck with nails, the punched holes become potential leakage points. Various devices, such as lead heads and different kinds of washers, have been used to seal the holes on the top sheets. However, the hole in the underlapped sheet remains a point of potential leakage.

Even when washers are used to seal the holes, a point of leakage is presented when nail creep takes place. In
view of this fact, it becomes advisable to use the nail which is least likely to creep.

Boyd (4, p. 119) has the following to say concerning nail creep.

Due to the slight variation of withdrawal resistance of ring shank nails with moisture changes, it appears that they would be relatively unaffected by creep. This is also true of the aluminum combination shank with sharp serrations.

Concerning creep, Giese and Henderson (13, p. 528) present the following:

The tendency of nails to "creep" or move outward without any apparent cause, thus necessitating re-nailing, has been a troublesome problem. No definite conclusions have been reached regarding the causes of this phenomenon, but some suggestions are offered for its remedy. Forces exerted by the wind and by the expansion and contraction of the metal due to changes in temperature may have some influence in loosening the nail. Creeping of nails from asphalt roofing and from boxes, however, shows that internal forces are probably of major importance. These may be the minute changes in dimension and character of the wood as it absorbs or gives up moisture. Screw shank nails probably creep less than plain shank nails, and it appears that ring shank nails will not creep. Many failures have been the result of using poor nailing girts or of carelessness on the part of the workman in failing to hit the girt.

They (13, p. 529) add this comment.

The authors believe that a serrated screw shank nail will not creep, because the serrations engage the ends of the wood fibers displaced when the nail is driven.

Any loosening of the nails affects the laps in that
when the fits become loose, leakage is more likely when rains, accompanied by winds, occur. Therefore, the problem includes using the nail with the greatest withdrawal resistance so that the lap fit stays tight over a long period of time.

Robison (23, p. 128) says:

The ring shank nail gives better withdrawal results than nails of other shank types. Best performance is attained with 20 rings per inch.

From his studies, Boyd (4, p. 113) arrived at the following conclusion:

Ring Shank nails are significantly superior to all plain and barb shank nails. Little variation in withdrawal resistance can be associated with changes in moisture content, but the tendency is for the greatest withdrawal resistance to occur at the lower moisture contents. The monel ring shank nail exhibits superior performance, but is rather expensive. Clean cut rings provide the greatest withdrawal resistance.

It is the writer's opinion that any of the commonly used roofing nails would suffice as far as the tests of this study are concerned. The tests will be run with close-fitting laps and the results will not be applicable to poor-fitting laps. Since ring shank nails seem to offer more chances for long lasting good fits, these nails will be used for nailing on the test sheets.

This opinion is in agreement with Giese and Henderson (13, p. 523) who say the following:
All nails are probably satisfactory when first driven. The chief advantage of the processed nails lies in their ability to retain or improve their withdrawal resistance under changes in the moisture content of the wood.

Slant driving of nails, while perhaps increasing their holding power, probably adds to the leakage problem. Robison (23, p. 7) agrees with this fact. He said the following:

When slant driving is used with roofing, especially corrugated metal, the chances of damage to the roofing are very high. . . . Trouble is usually encountered in starting the nail as well as in sealing the hole. Considering these disadvantages, it would seem that, in spite of increased withdrawal resistance, slant driving is unsatisfactory in the application of roofing.

The importance of the nail head should not be overlooked in a leakage study. One of the main functions of a nail head or washer is to seal the nail hole. Maze (16) expresses concern over the fact that lead-encased heads become loose due to hammer blows and do not seal the hole effectively. Deniston (9) recommends the washer type of lead head in which the lead does not take the hammer blows.

Giese and Henderson (13, p. 568) conclude from a study of lead head types:

1. Nails with lead washers are to be preferred to those with lead caps, because they do not loosen during driving but do provide effective use of the lead as a seal.
2. Rotation of screw shank nails during withdrawal can probably be prevented by the use of a head or seal which maintains extended contact with the corrugation.

Several types of washers have been developed using impregnated tapes and various resilient compounds. One such washer, known as neoprene, is described in Sheet Metal Worker (20) as being the greatest single recent boost to aluminum roofing.

The foregoing conclusions indicate that the seal is very important in giving a satisfactory roof.

Effects of temperature changes on sheet aluminum

Wrought aluminum alloys have an average coefficient of thermal expansion of 0.0000125, varying from 0.0000114 to 0.0000128 inches per degree Fahrenheit. (1, p. 12). This coefficient is about two times that for steel.

Aluminum sheets are put on a roof deck and fastened with nails at some temperature. The roofing sheet tries to expand in summer and to contract in winter. There is the possibility that this contracting and expanding might cause elongation of nail holes and permit leakage at these points. Also, buckling of the sheets due to restrained expansion could cause poor fitting side laps which would allow leakage during rain storms.

Pandya (22) made a study of the effects of temperature change on aluminum sheets. His tests were made by nailing
aluminum sheets on wooden frames at 24° F. and then heating the panels to a temperature of 130° F. From his studies Pandya (22, p. 67) concluded:

1. If the aluminum corrugated sheets are properly applied to a sound roof deck, sheets will not tear around the nail holes if the temperature differential is within 100° F.

2. The bearing stresses developed in the sheet around the nails are not large enough to enlarge the nail holes to cause leaks in roofs.

3. There will not be appreciable buckling so as to be undesirable from standpoint of structural stability if the sheets are properly applied.

These studies should be repeated, except the sheets should be applied in the hot room and then cooled through the 100° F. differential. No buckling would occur because the metal would contract rather than expand, and the possibility of nail hole elongation would be greater.

Laps for aluminum corrugated sheet roofing

Very little research has been done to determine the needed side and end laps for aluminum roofing. Dale (6, p. 159) makes the following recommendations for corrugated sheets.

1. Minimum slope for the roofing is 4" per foot. 6" or more per foot is better.

2. End lap should be 8" for any slope less than 6" per foot and 6" for any slope 6" or more per foot.
3. Side lap should be 2-1/2 corrugations for slopes less than 6" per foot; 1-1/2 corrugations for slopes 6" per foot up to 12" per foot; 2-1/2 corrugations for slopes greater than 12" per foot.

A good lap at the sides and ends is necessary in order to get a tight, leak-proof roof. Dale and Giese (8) say that side laps should be at least 1-1/2 corrugations on the 1-1/4-inch roofing. With 2-1/2-inch corrugated material, they say overlap one corrugation for roofing but overlap 2 corrugations on siding. They add that contrary to general belief, the steeper the roof slope the more likely one is to get sidelpap leakage.
INVESTIGATION

General

This study consists of a field trip through northwestern Iowa, theoretical analysis of the various factors considered by the writer to affect the movement of water through the laps of metal sheets, and experimental studies involving capillarity and lap requirements. These factors will be discussed separately as they appear under their subheadings.

Field Observations

During the second week in September, 1950, a field trip was taken through northwestern Iowa to observe how the farmers were applying sheet metal to their buildings and to ascertain as nearly as possible if they were experiencing any leakage problems, and if so, to see what was causing the leakage. Buildings covered with aluminum were given special attention, but, since similar problems probably exist on aluminum and steel, sheet steel roofs were examined also. It was also desirable to find if the farmers were receiving any instructions such as the proper end and side laps which should be allowed for various roof slopes, and
if the instructions, if any, were being followed.

Figure 3 shows the general area covered on the trip and Table I gives the exact locations of the farms on which buildings were examined. In the following discussion of some of the buildings which were inspected the buildings will be designated by farm number and building number. Table I should be consulted for the locations of the farms. The characteristics of each roof are given in the Appendix.

The discussion of the various buildings is presented to show both the conditions found in the field and the opinions of farmers as to why they like or dislike aluminum sheet roofing.

**Building 1, Farm 1**

This building, a corn crib, was covered with 1.26" corrugated galvanized steel. The steel was applied over old wood shingles on a roof with a slope of 4° per foot of run. Plain shank 8 penny nails were used for fastening the metal on the roof. Whether or not leakage had occurred on this roof was not ascertained. However, poor side and end lap fits because of excessive nail creep could easily have caused leakage. The end lap was only about 3", while the side lap, which opened toward the east, was 1-1/2 corrugations. It is very doubtful if 3" of end lap is sufficient on a slope such as is used here.
Fig. 3. General area covered in field study in northwest Iowa.
Table I
Locations of Barns in Iowa on which Roofs Were Examined

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<th>Township</th>
<th>Section</th>
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<td>Maple River</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Carroll</td>
<td>Maple River</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Carroll</td>
<td>Maple River</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Sac</td>
<td>Viola</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Sac</td>
<td>Clinton</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>Sac</td>
<td>Clinton</td>
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<td>Booth</td>
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<td>17</td>
<td>Buena Vista</td>
<td>Newell</td>
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</table>

Building 1, Farm 2

The general purpose barn shown in Figure 4 was covered with 2.66" corrugated steel which was still in fairly good condition after 45 years of use. The slope of the roof was 8" rise per foot of run which might possibly give a velocity of runoff fast enough to warrant only 5 inches of end lap and 1 corrugation of side lap used.

The main axis of the barn was east and west. The
farmer indicated that leakage was excessive when a rain was accompanied by a southeast wind. As shown in Fig. 5, some of the sheets had been applied incorrectly by placing the overlap with the last curve of the corrugation up rather than down.

The sheets were nailed approximately every 2 feet with from 5 to 7 3" plain shank nails with common flat heads. Some creep was evident causing the sheets to be loose. However, the farmer believed that his major leaks were through the incorrectly applied sheets causing the poor side lap fits.

On this and two other barns of similar age and construction some leakage was believed to be through nail holes where the nails had creeped, causing the holes not to be sealed. Fig. 4 shows some of the nail creep and some damage because of machines striking the metal sheets.

Building 4, Farm 2

The inspection in this case was of an aluminum-covered machine shed which was attached to a corn crib. The slope of the roof was only 4" per foot of run, but no leakage had occurred, so the farmer said. Approximately 2 feet of end lap and 1-1/2 corrugations of side lap were used on this shed. The excessive end lap was used only because shorter sheets were not available and it was not considered advisable to cut the sheets. The sheets were of 1.25"
Fig. 4. Nail creep permitting sheets to become loose

Fig. 5. Roofing improperly applied

Fig. 6. General purpose barn covered with corrugated aluminum sheets
corrugation size. The sheets were well applied to 1-1/2" nailing girts spaced 18" on center. Five screw shank lead head nails were used at each 18"-on-center nailing girt. This caused the sheets to be held firmly and gave a good tight fit at all joints. All nails which came through the girts were clinched. Generally speaking, the farmer was pleased with the aluminum, but he did think that the sheets should be made stronger.

Building 1, Farm 6

This implement storage building was a frame structure covered on sides and roof with 1.26" corrugated aluminum sheets .019" thick. On the roof the sheets were well applied with one sheet reaching over the roof so that no end laps were required. One and a half corrugations of side lap were used. The side sheets were nailed to 2"x4" headers placed between the studs. These headers were 4' on center and were placed edgewise such that the nails were driven into the edges of the 2"x4" material.

The owner was not at home and could not be questioned about the building. However, the structure appeared to be in good condition except for damage at one door where apparently a machine had struck the side of the door frame causing some of the aluminum to strip over the nail heads.
Building 1, Farm 10

This general purpose barn was a frame structure covered on the roof and sides with 1.26" corrugated aluminum 0.019" thick. In general, the large number of buildings on this farm seemed to be in excellent repair, and the first impression obtained was that the aluminum-covered barn was a soundly constructed building. This fact is brought out by Fig. 6. However, on talking with the owner, it was learned that the building was not entirely satisfactory in that leakage was excessive when it rains. Since the building was only about one year old, the farmer was certainly dissatisfied because of the leakage. However, he recognized the insulation qualities of the aluminum and he appreciated the fact that the building was usually fairly cool.

The barn was 60 feet by 30 feet in size and had a roof slope of only 2-1/3" per foot of run. The gable roof was as shown in Fig. 6. The rafters were of 2" material placed flat as shown in Fig. 8. These rafters consisted of a 2"x6" board followed by two 2"x3" boards with 4-1/2" clear space between. This series was repeated for the length of the building. The farmer said that he used this method of construction so that he could nail into a 2-inch board without having to use regular nailing strips as normally used.
A close inspection of the barn revealed the following things which could have contributed to this farmer's leakage problems.

1. The rafters, supported at 8' spans, had warped causing the roof to sag. This sag would not have been so severe had the rafters been placed on edge rather than flat.

2. The average end lap was only about 5" and some end laps were measured to be only 3-1/2". This lap is less than the minimum recommended by Dale on page 159 of his 1948-49 Progress Reports to be used only on slopes of 4" or more per foot of run.

3. The side lap varied from 1 to 2 corrugations. In some places it was easy to see light between the sheets, indicating very poor side laps.

4. Numerous holes were found where the nails had missed the nailing strips, leaving a hole when the nail was removed.

5. In almost all cases, the nails were driven approximately 3/4 of the way up the corrugations. Some nail creep was evident which left the holes unsealed after the nail creep had occurred. This presented a possible point of leakage since the nail holes were only 3/4 of the distance up the corrugation. The velocity of runoff is
slower on this pitch of roof than on a steeper roof, causing the water to pond and become deeper in the corrugations and ultimately causing leaks because of the many faults cited on the building.

6. Water stains can be seen on the rafters and plates shown in Fig. 7.

7. The owner stated that the leakage did not occur immediately with the first few rains but began after several rains had occurred. Although the exact reasons for this are not known, it is believed that the sheets were probably held down very tightly at first and that the leakage due to improper side and end lap was not prevalent at first. As nail creep occurred, it is likely that the fits were not as well and the nail holes were no longer sealed. The sagging of the roof could also have contributed to the later leakage by causing the sheets to buckle.

By using proper construction methods, all of the preceding faults, other than nail creep, could have been prevented.

Building 2, Farm 11

This building was of the circular type with laminated
Fig. 7. Water marks on rafters and purlins

Fig. 8. Rafters placed flat

Fig. 9. Points of leakage caused by nails missing nailing girts

Fig. 10. A poor roof frame
rafters. One side of the building, used for implement storage, was covered with 1.26" corrugated aluminum and the other side was covered with 1.26" corrugated galvanized steel. The tenant on this farm indicated that he was well satisfied with the building and that no leakage had occurred. The appearance showed that the material had been well applied with screw shank, along with a few plain shank, nails. The sheets were given 2 corrugations of side lap and 3 inches of end lap.

**Building 1, Farm 12**

This building, also an implement storage construction, was covered on the roof and the sides with 0.019" aluminum of 1.26" corrugation type of sheets. The roof slope was 3-1/3" per foot of run, and this building was another example of extremely poor construction. The first thing noticed was that only 2 inches of end lap were allowed. Generally, the side lap was 1-1/2 corrugations. The big trouble on this building seemed to be that the aluminum sheets were applied on an inadequate frame. The studs and rafters were placed 2 feet on center so that the edges of the aluminum sheets could be nailed to them. The nailing strips consisted of 1"x4" and 2"x4" headers as shown in Fig. 10. These strips were approximately 3 feet on center. In Fig. 10, the light colored area above the upper left
header is light coming through a very poor end lap. Fig. 9 shows a damaged place in an aluminum sheet and places where nails had missed the narrow nailing strips.

The farmer on this place said that leakage was severe on the building. Numerous holes were visible in the sheets where nails had missed the narrow nailing strips and much buckling of the sheets, caused by a warped roof deck, was noticeable. Some of the sheets were loose due to nail creep. Ring shank lead head nails were used in this case. Also, there was no ridge roll on the top of the gable roof.

Obviously, this farmer was not satisfied with the implement storage shed. He thought that the aluminum sheets were too weak and too expensive, and he complained that he could not nail the sheets down as tightly as he would like to because the corrugations caved in before the nail was driven far enough down. It was his idea that a 4" strip at either end of the sheet should be left flat so that tight nailing could be accomplished. Of course, the same effect could be obtained by nailing in the valleys. However, valley nailing will present more leakage hazards if the nails creep and leave the holes unsealed.

Building 1, Farm 13

This building was an implement storage structure with a gambrel roof. The roof slopes were 5" and 8" per foot of run. The farmer, the owner of the place, was well
satisfied with the building. He reported that his only leaks were at the break in the roof slope and that these leaks occurred only when the rain was accompanied by a strong wind. The sheets on the upper roof extended about 3 inches over those of the lower roof and no other precautions were taken to prevent leakage at this point. One and a half corrugations of side lap were used here.

**Building 1, Farm 15**

This building was a general purpose barn 56 feet by 64 feet with a gable type of roof. More than one-half of the north aluminum roof had blown off during the May 5, 1950 wind storm. The slope of the roof was 10" rise per foot of run. The sheets had 1.26" corrugations and were 0.019" thick. They had been nailed on with smooth shank aluminum nails before the storm. However, ungalvanized ring shank lead head nails were used to replace the roof. In all cases, the nails had pulled out of the sheathing—the aluminum was put on over old wood shingles—and none of the nail heads had been pulled through the sheets. The trouble was due to the poor holding power of the smooth shank nails or to an improper base for holding the nails. Evidently the nails were not held very securely in the sheathing because a large number of nails were found near the barn where they had fallen when the sheets blew off and these nails were in very good condition. Very few of
the heads were deformed and no bent nails were found. These factors indicate that the nails were pulled out fairly easily.

The farmer on this place had applied the aluminum himself and he said that the nails just didn't feel like they were "sticking" when he drove them. He was of the firm opinion that the ring shank nails used in reroofing would hold. However, these ungalvanized nails will probably rust.

On the roof where the sheets had not blown off, considerable nail creep was noticed. The farmer thought that frost, or freezing and thawing, caused the nails to creep.

No leakage was reported, even though the end lap was only 4 inches. The side lap was 1-1/2 corrugations.

The farmer thought that aluminum should be used only on steep slopes so that the snow would slide off when it begins to thaw. If the snow begins to thaw and does not slide off, a head of water will be built up causing leakage through the laps. However, it is believed that this would be just as true on any roof.

Even though this particular farmer had had trouble with his roof, he was still well pleased with the aluminum since he thought that the sheets would have stayed on had they been properly nailed. It is his opinion that the ring shank nails will hold the aluminum on satisfactorily. It was noted that at least twice as many nails were used
in putting the sheets back on as had been used initially.

**Building 1, Farm 16 and Building 1, Farm 17**

These two implement buildings had circular-shaped laminated rafters covered with 1.26" corrugated aluminum. No leakage problems were present on these farms other than snow blowing under the ridge roll of the building on farm 17. The farmer had trouble in applying the ridge roll as he could not get the ridge roll to match with the corrugations on both sides of the roof. To alleviate this trouble, Dale has recommended that the ridge roll be applied after one side of the roof has been covered, and then the sheets on the second roof slope can be applied to line up with the ridge roll. Good construction procedure was carried out in both of these buildings.

**Dairy barn in southeast Story County**

On September 23, 1950, a trip was made to a farm in southeast Story County where a new dairy barn had just been completed. The barn, as shown in Fig. 11, was built at a cost of approximately $8,000. The cost is given in this case to emphasize the magnitude of some farm building investments. Structural weaknesses, other than those contributing to a poor roof, were numerous. The roofing material was 1-1/4" corrugated aluminum sheets which were 0.019" thick. The sheets were nailed on with 1-3/4" screw
Fig. 11. Dairy barn covered with corrugated aluminum sheets

Fig. 12. Sunlight showing through poor side lap

Fig. 13. Outside view showing nailing pattern and laps on the dairy barn
shank aluminum roofing. Neoprene washers were used under the nail heads. The side lap was 1-1/2 corrugations and the end lap was approximately 5 inches. Poor side lap fits can be seen in Fig. 12.

Fig. 13 is a close-up view of the outside of the roof showing the nailing pattern used. Some poor side lap fits are shown here also. All of the side laps opened to the east and the owner of the barn reported that he has leakage when rains are accompanied by southeast or northeast winds.

**General discussion of buildings**

As shown in Table XI, no set pattern has been followed in applying the sheets. Side laps vary from 1 to 2 corrugations and end laps vary from 2 to 24 inches. Only in one case did a farmer say that he had received any instructions concerning the end or side lap which he should allow on his roof for a given slope. The farmer, in this case, did not follow the recommendations because he had miscalculated the lengths of sheets needed and did not bother with exchanging them. Only 5 inches of end lap were used on the general purpose barn on farm 10 and the slope was just 2-1/2" per foot of run.

As a whole, the farmers were not too well satisfied with aluminum. However, those farmers who had used good construction methods were generally better satisfied, which indicates that some higher degree of satisfaction could
Table II
Laps and Slopes of Sheet Metal Roofs
Examined in Iowa

<table>
<thead>
<tr>
<th>Farm no.</th>
<th>Bldg. no.</th>
<th>Roof slope</th>
<th>Material &amp; size of corrugation</th>
<th>End lap inches</th>
<th>Side lap corrugations</th>
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<td>8</td>
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<td>1-1/2</td>
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* Gambrel roof

have been attained if the users of aluminum were instructed as to where and how the material should be used. It is believed that 0.019" sheets definitely should have a very good frame to apply them to and that the farmers should be given the limitations in which this thin material may be used satisfactorily.
Conclusions

1. Excessively poor construction procedures on the buildings inspected undoubtedly contributed to the leakage problems.

2. Proper application of the roofing materials would have prevented or reduced the leakage on these roofs.

3. No correlation was found between roof slopes and side laps.

4. No correlation was found between roof slopes and end laps.

5. One and one-half corrugations of side lap on 1-1/4-inch corrugated aluminum appeared to be inadequate on the majority of the roofs inspected.

6. In general, the farmers interviewed had not been given any recommendations as to how to apply aluminum. In most cases, they used the minimum lap which they guessed would be sufficient. The slight saving in materials probably added much to the unsatisfactory service which they were receiving from their buildings.

7. Nail creep, causing the nail holes to be unsealed and thereby presenting points of leakage, was very noticeable on a number of roofs. Creep was less evident where ring shank or screw shank nails had been used.
Preliminary Tests

As was pointed out in the discussion of the field trip through northwestern Iowa, leakage problems exist on many of our farm buildings. In view of this fact, it was thought advisable to run a few preliminary tests in an effort to obtain some idea of the factors which contribute to the leakage on corrugated aluminum roofing. Some farmers thought that aluminum roofing presented more leakage problems than did galvanized steel. If this were true, it seemed logical to assume that a property of the aluminum material must contribute to the problem. This assumption would probably be true if comparable laps could be obtained for both galvanized steel and aluminum roofing, and at this point in the study, this assumption seems to be in order. Capillarity might possibly be the factor which causes aluminum to give more leakage problems than does galvanized steel. The following tests were run to observe how water was carried through the lapped joints.

The roof section used for both of these preliminary tests and for other tests which follow is shown in Fig. 14. This apparatus was built in 1948 by Dale (7) for his proposed side and end lap tests. The roof section is approximately 8.5 feet long and 6.5 feet wide. The roof frame is mounted with two bolts at the lower end so that it can be pivoted to give any desired roof slope from horizontal
to vertical. When the section was taken out of storage, it was covered with 1.26" corrugated aluminum sheets which were 0.019" thick. The end lap of the sheets varied from 4 inches to 8 inches and the side lap was 1-1/2 corrugations. The condition of the roof section was probably better than could be found on the average farm building. However, a little nail creep was evident. Where nail creep was present, the nail holes had become unsealed. The condition of the roof was not altered for the following tests.

The first test was one of simply spraying water on the roof with a hose and nozzle. As might be expected, leakage occurred at the nail holes where creep had taken place. Nail creep is evident on many of the roofs inspected by this writer, and this source of leakage probably can be stopped only by devising a means of keeping the holes sealed. Previous studies have been made along these lines by other researchers, and it is not the purpose of this study to carry further the problem of nail creep. However, it is seen that an unsealing of a nail hole presents definite probabilities of leakage.

The roof was set at a slope of 3" per foot of run, and water was run down corrugation number 1, shown in Fig. 15, at a rate just fast enough to maintain a water depth of from 1/2 to 2/3 of the total depth of the valley. The valleys of these sheets are 3/8" deep.

The slope of the roof was kept low, as stated above,
Fig. 14. Variable-pitch roof section.

Fig. 15. Cross section of corrugated aluminum sheet.

Fig. 16. Forces caused by falling raindrops.
so that water would maintain a fairly uniform depth all of the way down the roof. A steep slope will increase the velocity of run-off to such an extent that the depth will be much lower near the bottom of the roof. Since the purpose here was to see if water would be carried over the corrugations, it was desirable to keep the depth fairly uniform all of the way down the corrugation.

When water was run down corrugation 1 of Fig. 15 at the depth shown above, leakage occurred at two places on the roof. The leaks were intense enough to cause dripping at a fairly high rate. An inspection revealed that the water was not coming over the lap at point B, but was coming through two nail holes such as at point A. Since the water definitely was not going into the holes on the top sheet, because the water was not that deep, it can be assumed that the water was carrying up between the sheets and entering the holes in the bottom sheet. Also, some water came from between the sheets at point C. Since no water was put in this corrugation, it must have gone over the corrugation at A and into the adjacent valley.

Next, the slope of the roof was changed and the amount of water running down valley 1 was held the same as used previously. With this greater slope, 4" per foot of run, and the same amount of water as before, the leakage ceased. The velocity of the water had increased to a point where the depth was considerably less than that previously described.
The force which had been forcing the water over the corruga-
tion was not strong enough, evidently, to raise the water
over this greater height.

The amount of water was then increased to a volume which
again gave a depth equivalent to that used on the lesser
slope. The leakage again occurred as described for the 1/3
pitch.

These preliminary tests indicated that some force,
possibly capillary attraction, causes water to carry over
the corrugations of aluminum roofing. If such a force ex-
isted, it was feasible that capillarity could be a critical
factor in the study of side and end lap requirements and of
the leakage problem in general. A theoretical analysis of
capillary phenomenon and experimental tests were performed
to aid in answering the question of whether or not capil-
arity causes leakage on corrugated aluminum roofing.

Theoretical Analysis of Capillary Action

In order to make an analytical study of possible leak-
age because of capillary action, it is necessary to tie in
molecular action and surface tension with the attraction of
liquids by solids.

Action between molecules

There is evidence to show that as two molecules
approach each other, a separation is reached where their combined potential energy is a minimum. In this condition, work is needed to move them either nearer together or further apart, because of forces which are probably electrical. When the molecules are very close together, these forces produce a tremendous repulsive effect, keeping the centers of the molecules at slight distances from each other. When the molecules are further apart, the force becomes one of attraction; such forces are known to be very great (14).

The attraction between molecules of the same substance is called "cohesion", and the attraction between molecules of unlike substances is called "adhesion". These two forces are very important in a study of capillarity, as will be shown. The theory of molecular attraction explains the behavior of a liquid surface, which necessarily becomes a critical factor in the study of side and end lap leakage.

In Fig. 17, line XY represents a free liquid surface, and A, B, and C represent molecules of the liquid. The molecule A, which is well within the body of the liquid, will be attracted equally on the average in all directions by other molecules, and will be as likely to move in one direction as another. The molecule B, which is near the surface, will experience a downward force since there are more molecules in the lower half of its sphere of action than in the upper half. Similarly, the molecule C will
be acted upon by a considerable downward force. Hence, a molecule which in its motion tends to rise above the surface is pulled downward. The surface acts like a stretched membrane, tending to shorten itself as much as possible, and assumes at each point a direction at right angles to the resultant forces acting on the surface molecules.

There is experimental evidence to show that the molecules of a body are in a state of eternal motion, this motion being entirely erratic and irregular, and depending only upon the temperature of the substance.

The attraction between molecules is responsible for a number of effects which are usually referred to as surface phenomena, since they occur at the surfaces of liquids.

**Contact of liquid and solid**

The surface of a liquid where it meets the side of a vessel seldom remains level. An exception to this is when water meets silver as in Fig. 20. In most cases, the edges of a free water surface curve up as shown in Fig. 18. Mercury falls more like Fig. 19. The angle of contact depends upon the relation between the molecular forces in the liquid, which determine its surface tension, and the adhesive forces of liquid to solid. This relation may be seen by an analysis of the figures. Consider a molecule at the point of contact 0. The resultant force on a
Fig. 17. Surface tension of water.

Figs. 18-21. Angles of contact at edge of liquid surface.
particle at the surface of any liquid is perpendicular to
that surface, since the shear modulus of a liquid is zero
(18).

The force of adhesion $A$ exerted by the wall is per-
pendicular to the wall surface; the force of cohesion $C$,
which is due to the surrounding molecules of liquid, acts
on the molecule at point 0 in a direction which bisects
the angle. As previously stated, $R$, the resultant is at
right angles to the liquid surface. The shape shown in
Fig. 18 is characteristic of those cases where the liquid
wets the solid, the adhesion between the liquid and solid
being greater than the cohesion of the liquid. Here, any
liquid molecules near the wall which happen to rise above
the free liquid surface are pulled toward the wall by the
force of adhesion, causing the liquid to pile up along the
edge. When the liquid does not wet the wall, as in the
case of mercury and glass, the adhesion is less than the
cohesion, and the liquid surface curves downward as in
Fig. 19. The angle of contact at the edge of the liquid
surface varies with the substances used, being 0° between
water and glass, 90° between water and silver, and 132°
between mercury and glass, when pure liquids and clean
surfaces are used. A simple test of holding two small
sheets of aluminum together and pushing them vertically
into a pan of water indicates that water curves up on
aluminum and that the angle of contact lies somewhere
between those of water and glass and water and silver, or between 0 and 90 degrees. The relationship between the cohesion of water and the adhesion of aluminum and water becomes an important factor in studying the possibility of leakage on aluminum roofs due to capillary action.

Capillarity

The rise of liquids in fine-bore tubes is a result of surface tension and is called capillarity. When a tube of small radius \( r \) is dipped into a liquid which wets it, a concave miniscus is formed, and the adhesion of the glass, being equal and opposite to the surface tension \( T \) of the liquid, has a vertical component \( T \cos \theta \) which pulls directly upward on the liquid. As a result, the liquid rises in the tube as shown in Fig. 21. Its elevation \( h \) will be such that the total upward force, which is \( T \cos \theta \times 2\pi r \), just balances the weight of the column of liquid, which is \( \pi r^2 dh \), \( T \) being the surface tension of the liquid per unit length of contact, \( d \) being the density of the liquid. Equating these forces and solving, the height of the column is found to be

\[
h = \frac{2T \cos \theta}{\pi rd}
\]

This analysis, with some modification, can be applied equally as well for water rising between aluminum sheets because of capillary action. The difficulties arising here
are that the angle \( \theta \) is very difficult to measure and that, for given lengths of sheets, the downward force due to the weight of water will increase as the space between the sheets decreases. This indicates that leakage because of capillary action is more likely on roofs with tight-fitting joints. The formula shown above can be modified to cover this situation. For any length of sheets, \( T \cos \theta \times 2l = \) the upward force, and \( l \times d \times h = \) the downward force, where \( l \) is the length of the sheets, \( n \) is distance between the sheets, \( d \) is the density of the water, and \( h \) is the height the water rises between the sheets. Equating these forces and solving the height of water column is found to be

\[
h = \frac{2T \cos \theta}{nd}
\]

The surface tension of pure water is 75 dynes/cm (14, p. 193), which was 5.14 x 10^{-3} lbs/ft when the units were changed.

To figure theoretically how high water will rise between two aluminum sheets, two assumptions must be made. The angle of contact \( \theta \) is not known, but will be estimated to be 30°, since it is 0° for glass and it is not believed that aluminum will wet as readily as glass. On the other hand, aluminum is wetted fairly easily, so 30° will be assumed. The other unknown is the space \( n \) between the sheets. However, the space between two sheets on a
side lap on the experimental roof, described in previous reports, was measured at a point where the fit was good and was found to be 0.092 inch. This measurement was made by slipping papers between the aluminum sheets and then measuring the thickness of the sheets with a micrometer.

**Calculations for rise of water between aluminum sheets**

Using the formula shown above, the calculations, based on one foot of lap length, for the water column height follows:

\[
h = \frac{2 T \cos \theta}{nd}
\]

\[
h = \frac{2 \left(5.14 \times 10^{-3} \text{ lbs} \right) \cos 30^\circ}{(0.092 \text{ in.})(12 \text{ in})\left(3.61 \times 10^{-2} \text{ lbs} \right) \text{ in}^3} = 0.223 \text{ in.}
\]

With the assumptions used here, it is seen that capillary action alone would raise water a little less than \(\frac{2}{3}\) the depth of a 3/8" corrugation, which would become critical if the valley were flowing at a depth of 0.152 inches. Also, if the adhesion between aluminum and water approaches that between glass and water giving a contact angle near 0 degrees, and if the space between the sheets should be half that used above, or 0.0046 inch, the following height \(h\) would be theoretically possible:
\[ h = \frac{2T \cos \theta}{nd} \]

\[ h = \frac{(2) (5.14 \times 10^{-3})(\cos \theta)}{(.0046)(3.61 \times 10^{-3})} = 0.516 \text{ in.} \]

It is seen from these calculations that these extreme conditions do not have to exist to give a head of water which might be critical in causing leakage with aluminum sheets which have corrugations only 3/8 inch deep. These calculations show further that capillarity could be critical at any time the valleys are flowing about 1/3 full or deeper. Also, the closeness of the lap fits is a factor in how high the water will rise due to capillary action. Water is more likely to rise to a critical height where the sheets fit closely. The close fit will ordinarily be at the point of nailing, which is also the point at which leakage is likely to occur. These factors led to the experimental studies which follow.

Experimental Study of Capillarity

An accurate measurement of the rise of a liquid between two opaque sheets of material, such as aluminum, is very difficult to obtain. In fact, the rise of water in a capillary tube is quite variable under near exact conditions. Even a speck of dirt or other foreign material can cause a variation in capillary rise. However, for this
study it is not necessary to determine with a high degree of accuracy the height to which capillarity will cause water to rise between aluminum sheets. The scale of the magnitude is the important thing in this case.

As mentioned previously, the rise between aluminum sheets is difficult to measure because the sheets are opaque. The method used to determine the rise was to measure the rise of water between two glass sheets, where the water could be seen, to then measure the rise between one glass sheet and one aluminum sheet, and to then predict what the rise would be between two aluminum sheets.

Factors affecting capillary rise

To determine whether the method suggested above is sound and reasonably accurate, it is necessary to consider those things which cause capillary rise and how this rise is calculated. The theory involved and the mathematical formula for calculating the rise were discussed under the theoretical analysis. The formula is as follows:

\[ h = \frac{2T \cos \Theta}{nd} \]

\( h \) is the rise, \( T \) is the surface tension, \( n \) is the space between the sheets, and \( d \) is the density of the water. \( T \cos \Theta \) represents the upward force per unit of length because of one sheet. Now, to obtain the total upward force, \( T \cos \Theta \) is simply multiplied by 2 when two like sheets, such
as two sheets of glass are used. The angle of contact $\theta$ is approximately 0° between glass and water. However, the angle is different when aluminum sheets are used, and the formula is modified as shown below for calculating the rise between one glass sheet and one aluminum sheet.

$$h = \frac{T\cos \theta + T\cos \theta_2}{nd}$$

where $\theta$ is the angle of contact for glass and $\theta_2$ is the angle of contact for aluminum.

Now, if $T$, $d$, and $n$ are held constant, it is seen that $h$ varies with the change in $\cos \theta$. It is seen further that, since only the one variable is involved, $h$ would vary the same amount, when two aluminum sheets are used instead of one glass and one aluminum, as it had varied when one glass sheet and one aluminum sheet were used instead of two glass sheets.

**Test no. 1**

The tests to determine the rise of water between glass sheets were run with the spacings shown in Table III. Similar tests were run with one glass sheet and one aluminum sheet and these results are also shown in Table III.

The test sheets used were 3" x 4-1/2" in size. The size is not significant, just so the sheets are long enough that the water column has a flat top line. At the edges,
<table>
<thead>
<tr>
<th>Space (n) inches</th>
<th>Actual readings</th>
<th>Rise (h) in inches</th>
<th>Readings converted (space)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>0.35</td>
<td>0.135</td>
<td>0.775</td>
</tr>
<tr>
<td>0.012</td>
<td>0.55</td>
<td>0.334</td>
<td>0.66</td>
</tr>
<tr>
<td>0.023</td>
<td>0.50</td>
<td>0.267</td>
<td>0.69</td>
</tr>
<tr>
<td>0.030</td>
<td>0.15</td>
<td>0.095</td>
<td>0.75</td>
</tr>
<tr>
<td>0.007</td>
<td>0.25</td>
<td>0.735</td>
<td>0.755</td>
</tr>
<tr>
<td>0.011</td>
<td>0.98</td>
<td>0.47</td>
<td>0.77</td>
</tr>
<tr>
<td>Average</td>
<td>0.738</td>
<td>0.435</td>
<td>0.132</td>
</tr>
</tbody>
</table>

Table III

Capillary Rise of Water Between Sheets
the water surface is curved down, and measurements must be taken far enough between the sheets to avoid the edge effects. The edge effects seem to be well within the outer inch of the sheets, so 4-1/2 inches is a safe length if the readings are taken near the center, as they were in these tests.

Tap water at room temperature was used. Paper spacers were used and the space between the sheets was measured by the use of a feeler gage.

The spaced sheets were placed vertically in the container of water and the difference between the water level in the container and the water level between the sheets was measured with a divider. The differential was the rise due to capillary action.

For one set of conditions, the rise is inversely proportional to the space between the sheets. Therefore, all of the readings were calculated for a spacing of 0.010 inch so that an average rise could be obtained. These values are also shown in Table III.

It is seen that the rise varies to some extent. This is to be expected since even a speck of dirt will cause a variation. For the purposes of this study where so many variables are present, it is believed that the readings are fairly reliable.

These tests show that water will rise approximately 0.132 inches between aluminum sheets with a spacing of
0.010 inch. If the temperature of the water is increased and the spacing is decreased, the rise will increase. This seems to indicate that capillarity could be a critical factor.

**Test no. 2**

With the fact established that water would rise between aluminum sheets, it was necessary to see if capillarity alone would cause leakage. A few simple tests were run to determine this.

The first test was one in which two aluminum sheets were used, with one sheet being wider than the other. The sheets were placed together with their bottom edges even, and they were then placed at an angle, with the shorter sheet underneath, in the water. Care was taken to see that the sheets were into the water deep enough for capillary action to carry water to the top of the shorter sheet. The water came to the top of this sheet but would not run over the sheet.

Another similar test was run by using corrugated sheets. A hole was drilled through the top corrugations of two sheets so that a nail could be placed through the hole. It was thought that water might travel down the nail after it had been carried to the top of a corrugation by capillarity. However, even though water was seen around the hole, none was detected traveling down the
nail or through the drilled hole. Also, water does not seem to travel down the opposite side of a corrugation, even though it does travel up one side to the top of the corrugation. This seems logical since the capillary pull would be equal on both sides of the ridge, and the force which causes the water to rise would also prevent it from flowing down the opposite side.

Conclusions

1. Capillarity will cause water to rise between aluminum sheets.

2. This capillary water will not cause leakage through nail holes or laps between the sheets, without some force to cause the water to be deposited from the sheets.

3. A force which is stronger than the force of attraction between aluminum and water could cause the water to leave the sheets and give leakage. This force might be a wind, a nail whose attraction for water is greater than that of aluminum, or some unknown force. However, it is doubtful if any of the nails in present use has a stronger attraction for water than does aluminum. Zinc-coated and aluminum nails were used in the tests described and no leakage was noted.
Effects of Roof Slope on Lap Requirements

In applying corrugated aluminum, or other metal roofing materials, if a satisfactory leak-proof roof is to be obtained, it becomes necessary to lap the sheets at the sides and ends sufficiently to prevent water from flowing or being blown through the laps. When the sheets are fastened to the roof deck with nails, a problem of preventing leakage through the nail holes is presented. The slope of a roof affects the required laps, it seems by influencing some of the factors which cause water to flow through the laps.

Theoretical Analysis of Factors Causing Water to Move Through Laps

A number of factors enter into the leakage problem study on metal covered roofs. These factors, as investigated by this writer, are the rate of runoff of water on the roof, the effects of winds on the water running down a roof, capillarity, which has been discussed previously in this paper, the effects of rain falling on the water which is already on the roof, and the pressure differential between the inside and the outside of the roof.
Rate of runoff

The rate of runoff of water on metal roofs is probably a very important unknown factor which enters into a study of leakage problems on sheet metal roofs. No records have been found by this writer of work done on velocity of flow down roof slopes. Further, it is not known how closely the accepted formulas of hydraulics will fit the flow of water down corrugated metal roofs. The conditions of flow down a roof are different from the conditions where the commonly used hydraulic formulas are used in that the slopes are greater on the roofs and the depths of flow are smaller. Surface tension and film coefficients may be large factors in the velocity obtained by water flowing down roofs.

The commonly-used open channel formulas are based on the condition of uniform, steady flow, and therefore do not apply except in those reaches of the channel in which the depth of the fluid is constant, and in which the cross-section and material of the channel remain constant (19). It is doubtful that these conditions would ever exist on a roof, but it is well to consider a few of the more important formulas to obtain some idea of the magnitude of the velocity which water on a roof might attain.

The majority of the formulas consider the roughness of the channel, the slope of the water surface, and the
hydraulic radius of the channel. These factors, except hydraulic radius, are all self-explanatory. The hydraulic radius is defined as the area of the cross-section of the water stream in a channel divided by the wetted perimeter of the cross-section.

The Hazen-Williams formula can be used for either open channel flow or for flow through smooth pipes. This formula is as follows:

\[ V = 1.3126 \cdot R^{0.63} \cdot S^{0.54} \]

in which \( V \) = velocity of flow, \( R \) = hydraulic radius, \( S \) = the slope of the water surface, and \( C \) = a coefficient depending upon the roughness of the surface.

If the 1-1/4-inch corrugations of the aluminum sheets are considered to flow full, the hydraulic radius can be figured from the shape of the corrugations. According to the Alcoa Structural Handbook (1), the corrugation for the nominal corrugated aluminum sheet is 3/8 inches deep with a distance of 1.26 inches from ridge to ridge of the corrugations. The corrugation is made on a 3/8-inch radius which joins an inverted corrugation at the center. This is shown in Fig. 15. When these corrugations are flowing full, the cross-sectional area is 0.236 square inches and the wetted perimeter is 1.57 inches. The hydraulic radius then is 0.236 square inches divided by 1.57 inches, which is 0.151 inches.
For a 1/4 pitch roof, the velocity of runoff, as determined by use of the Hazen-Williams formula, is as follows when a value of C equals 140, commonly accepted for smooth pipe, is used.

\[ V = (1.318)(140)(0.151^{0.63})(0.50^{0.54}) = 39 \text{ ft/sec} \]

Manning's formula for hydraulic flow is widely used for open channel flow. If it is applied with the same conditions as above, the following results are obtained.

\[ V = \frac{1.486}{n} R^{0.667} S^{0.5} \]

where \( n \) is a roughness factor for the channel and can be taken as 0.01 for smooth surfaces.

\[ V = \frac{1.486}{0.01} (0.151^{0.63})(0.50^{0.5}) = 31.9 \text{ ft/sec} \]

Both of these calculated values appear to be faster than one would expect. However, if the lower value of 31.9 ft/sec is assumed to be in order, one can determine the rainfall rate necessary to cause the channels to flow full. For these calculations a barn 40 feet wide with half of the rain flowing down either side will be assumed.

The volume of water flowing down one channel is 31.9 ft/sec \( \times \) 12 inches/ft \( \times \) 0.256 square inches = 90.3 cubic inches/sec. This would give a rainfall rate of about 1000 inches per hour, which obviously is never likely to occur. Even if these hydraulic formulas do not
give correct values for flows from roofs, it can be seen that much slower velocities could occur and still not cause the channels to flow full.

Pressure on roof because of falling rain

Again, little or no work has been done on this phase of the work, but the energy of falling rain drops and a study of their sizes and velocities have been subjects of investigations for years. Most of this work has been done on soil erosion and infiltration studies, but in the absence of more direct information, the principles involved can be applied here.

The kinetic energy of a falling raindrop is proportional to the product of its mass and the square of its velocity. Ellison (10) says that each falling raindrop that strikes the ground acts as a miniature bomb and splashes soil at its point of impact. Violent rainstorms have great capacity to splash the soil and to damage the land by this blasting action.

Nichols and Gray (21), commenting on raindrop energy, stated, "Erosion is initiated by the great force of raindrops as they strike the surface soil. The total force expended by heavy rain is tremendous. J. Otis' Laws (according to unfinished data) calculates that the velocity of falling rain is 20 mph. Two inches of rain an acre then would have 194,900,000 foot-poundals, or 6,000,000
ft-lb. of kinetic energy." They add that this is enough energy to raise a seven-inch layer of soil three feet. Quoting further, "Fortunately this terrific energy is dispersed both from point of time and space, but it is still important."

The energy of rainfall could be expected to be as great on a roof as has been described above for rain falling on the soil. The energy is probably dispersed in several ways. Some of the energy is probably used in speeding up the velocity of runoff, some in causing a slight vibration of the roof, and some in forcing water between the laps of the sheets.

If the rain is assumed to fall vertically as it would with no wind, it will exert a force on the roof which can be represented by a force vector A, as shown in Fig. 16. A portion of this force, which is not dispersed otherwise, can be broken into components B and C, these forces being perpendicular and parallel, respectively, to the roof surface. Force C, along the roof surface, probably is used in increasing the velocity of runoff.

Force B, the component perpendicular to the roof slope, exerts a pressure on all of the outside roof surface. However, this pressure is not, in all probability, exerted at, say for instance, point a. This pressure differential, while it probably is not very great, could be a factor in the total pressure which forces water over the corrugation
or to the top of a corrugation where an unsealed nail hole presents a point of leakage.

**Pressure differential between inside and outside of the roof**

The difference between the inside and outside pressures can add or subtract from the probability of lap leakage. If the pressure on the outside is greater than on the inside, the tendency would be for water to flow through the laps to the lower pressure. If the pressures were reversed, with the high pressure inside the barn, the tendency would be to prevent the water from flowing into the laps.

A large number of factors govern the relationship between these pressures. Some of the factors are the slope of the roof, whether the building is opened or closed, and the direction of the wind, in that a negative pressure is exerted on the leeward side and either a negative or positive pressure is exerted on the positive side depending on the slope of the roof.

**Wind pressures on roofs**

One of the more important factors in causing end or side lap leakage, in the writer's opinion, is the effect of wind pressure on the water on the roof. Certainly, a hard blowing wind can blow falling raindrops through a poor fitting lap. However, a good fitting lap should
prevent most of the leakage by rain blowing directly through the lap. It is believed that the big factor here is in the pressure of the wind causing a ponding to give a water head sufficient to materially aid in leakage and in exerting a normal pressure which acts as the falling rain pressure described previously in this report.

The science of wind pressure is still in the formulative stage (13). Recent experiments in wind tunnels and other observations made over a long period of time indicate certain relationships that exist between wind velocity and wind pressure. When the direction of wind is perpendicular to a surface the relationship between wind pressure and wind velocity may be given by the equation

\[ p = cV^2 g \]

The value of \( c \) has been experimentally determined to vary between the limits of 0.0025 and 0.004; it is generally assumed to be 0.0033 (12). \( Vg \) is the wind gust velocity in miles per hour. Barre and Sammet (3) give the recommended value of \( c \) as 0.00256, which is derived from the relationship between potential and kinetic energy.

For design purposes, this pressure is converted to a pressure normal to the roof surface. This can be accomplished by any of several ways, two of which follow.

Dale (7) used the Duchemin Formula, commonly used by structural engineers, to evaluate the wind pressures normal
to a roof surface. Duchemin's formula is as follows:

\[
P_n = p \frac{2 \sin \theta_2}{1 + \sin \theta}
\]

where \( P_n \) is the pressure normal to a sloping surface, \( P \) is the pressure normal to a vertical surface, and \( \theta \) is the angle the roof makes with the horizontal. Using this formula, Dale computed the following values:

- \( P_n \) (30 m.p.h. and 30° slope) = 0.146" of water
- \( P_n \) (30 m.p.h. and 30° slope) = 0.329" of water
- \( P_n \) (40 m.p.h. and 30° slope) = 0.583" of water
- \( P_n \) (60 m.p.h. and 30° slope) = 1.313" of water

Dale concludes that these pressures might dam up water sufficiently deep to cause end lap leakage and could possibly cause side lap leakage.

Barre and Sammet (3) recommend that force coefficients be used with the formula \( p = 0.00256V^2 \) to obtain the values of pressures normal to sloping surfaces. The following table gives the recommended coefficients for shed-roof structures, or for gable roofs with very flat slopes.

An examination of this table shows that all normal pressures on the leeward side of a roof are negative, that the pressures on the windward side are positive for slopes greater than 30°, are negative for slopes less than 30°, and are 0 when the slope is 30°.
Table IV

Force Coefficients for Sloping Surfaces

<table>
<thead>
<tr>
<th>Slope</th>
<th>Force coefficient*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward slope</td>
<td>Leeward slope</td>
</tr>
<tr>
<td>20° or less</td>
<td>-0.60</td>
</tr>
<tr>
<td>Between 20° and 30°</td>
<td>0.06A-1.8</td>
</tr>
<tr>
<td>Between 30° and 60°</td>
<td>0.015A-0.45</td>
</tr>
<tr>
<td>Between 60° and 90°</td>
<td>0.45</td>
</tr>
</tbody>
</table>

*Positive values indicate inward load; negative values outward load. A is the slope of the roof in degrees. Table IV is reproduced from page 447 of reference (3).

Barre and Sammet (3), in addition to the above coefficients, give more, as shown in Table V. These values are to be used for roofs other than shed roofs or flat gambrel roofs.

This table indicates that positive pressures exist only on the lower roof and the vertical walls. These values were obtained by wind tunnel tests on model buildings at Kansas State College. For details of these tests, the reader should consult reference (11).

For a 30° roof slope, the wind pressure on the lower roof with a 60 m.p.h. wind would be as follows:

\[
P = 0.00256 CGw^2
\]

\[
P = (0.00256)(0.3)(60^2) = 27.6 \text{ p.s.f.} = 5.3'' \text{ of water.}
\]
Table V

Force Coefficients for Design Wind Load for Gambrel, Gothic, and Gable-Roof Farm Buildings

<table>
<thead>
<tr>
<th>Surface</th>
<th>Gambrel roof</th>
<th>Gothic roof</th>
<th>Gable roof</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Windward</td>
<td>Leeward</td>
<td>Windward</td>
</tr>
<tr>
<td>Wall</td>
<td>0.8</td>
<td>-0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Lower roof</td>
<td>0.7</td>
<td>-0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Upper roof</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.8</td>
</tr>
<tr>
<td>End</td>
<td>-0.8</td>
<td>-0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Gambrel and gable-roof barns have no "upper" and "lower" roof. However, at a point about half-way between eave and ridge, the pressure on gothic and gable roofs changes from positive to negative. The area of positive pressure is considered the "lower" roof; the area of negative pressure is considered the "upper" roof. Table V is reproduced from page 449 of reference (3).*

This value is considerably higher than that obtained using the Duchemin formula for similar conditions.

Experimentors J. O. Iringer and Chr. Nokkentved have indicated that all the pressures on a roof are negative when the slope of the roof is less than 45°. (12, page 153)

It is seen that considerable differences arise when various methods of calculating these pressures are used. This, however, is to be expected since wind studies are still in their infancy. Although these differences do exist in the methods of calculating wind pressures, they
all give positive pressures on the lower roof of the windward side of a barn. This portion of the roof is the critical part as far as leakage is concerned. It is at this location that both strong positive pressures and water concentration on the roof can be found.

The pressures calculated by Dale using the Duchemin formula and by this writer using the method given by Barre and Sammet (3) are believed to be instrumental in forcing water through the laps when the pressures are positive. This is done by increasing the pressure differential between the inside and outside of the roof. However, negative pressures on the roof are likely to decrease the leakage problem as far as the pressure differential is concerned. Again, on slopes of low value which give negative pressures, the rate of runoff is slower, causing a greater depth of flow.

In a study of this nature, it must be kept in mind that the above methods are for structural design and that the component of the wind parallel to the roof surface has been neglected. However, this component probably is very important in that it is likely to be the one which causes ponding of water on the roof.
Laboratory Study of the Effects of Roof Slope on Lap Requirements

To make a laboratory study to determine the effects of roof slope on lap requirements, an apparatus was needed as follows:

1. A roof section on which the slope could be changed easily and on which the distance the water traveled between the laps could be detected.

2. A method of applying a constant rate of water to the section for all roof slopes.

3. A means of applying a wind of sufficient intensity to simulate actual wind conditions in Iowa.

Apparatus

Variable-pitch roof section. The variable-pitch roof section used for the preliminary tests, shown in Fig. 14, was used for these tests. As mentioned previously, the slope of the roof could be varied between horizontal and vertical. The legs of the frame were cut off as shown in Fig. 24 in order to get the roof section as low as possible. This was done for convenience in testing and has no special significance otherwise. As shown in Fig. 24, the roof
frame is fastened at either lower corner by a 1/2-inch bolt. The pitch of roof desired can be obtained by removing the bolts in the vertical 2"x4" members near the rear of the apparatus, raising or lowering the section to the proper pitch, and replacing the bolts.

The sheathing to which the 0.019" thick corrugated aluminum sheets were nailed was 2"x4" fir boards spaced 12 inches on center. This is a good roof deck, and although such a deck is recommended for 0.019" aluminum, it is seldom found on our farm buildings. The nailing pattern, laps, washers, etc., will be discussed under test procedure.

Water applicator. The manner in which rain falls on a roof, especially under storm conditions, is very unpredictable. Trying to simulate actual rain conditions would be beyond the scope of this study. The variable in this study was the roof slope; therefore, the means of applying water to the roof section was an apparatus whereby the amount of water could be varied to any reasonable amount, but could be held constant for tests on all of the various slopes of roofs.

A water trough, as shown in Fig. 22, was constructed for applying the water. Nineteen 1/2" pipes were fastened in the galvanized steel water trough with 1.26" on center spacings.

Water from these pipes gave a coverage on the roof slightly more than 27 inches wide. This was sufficient
Fig. 22. Valve for maintaining constant head of water in water applicator.

Fig. 23. Details of water applicator.
for testing one side lap.

The amount of water applied was controlled by the use of a sliding valve, made of galvanized steel sheet, and a butterfly valve with a float control for maintaining a constant head of water in the water trough. The sliding valve, as shown in Fig. 23, could be raised or lowered to control the flow out of the pipes by adjusting the nuts on the 3/8" rods attached to the sliding metal sheet. The float control for maintaining a constant head of water is shown in Fig. 22. This valve was located in a 2-1/2" pipe which was brazed to a 55-gallon barrel, which, in turn, served as a water reservoir. Fig. 24 shows the water applicator as it was set up for these tests.

**Wind source.** A 36" fan, as shown in Fig. 25, was used for blowing wind over the test section. The performance curves for this fan, as illustrated in Fig. 27b, show that it will produce approximately 30,000 cubic feet of air per minute at zero static head. To determine the maximum velocity of wind that could be obtained with the fan blowing into open space, a pitot tube was used with readings taken 3 feet in front of the fan. The readings were averaged and a velocity of approximately 35 miles per hour was calculated. Theoretically, the velocity at the fan outlet should be 48 miles per hour when the fan is delivering 30,000 c.f.m. The value of 48 m.p.h. was obtained by dividing the volume of air output by the area of the fan.
Fig. 24. Water reservoir with 2-1/2" pipe to water applicator

Fig. 25. The fan used as source of wind

Fig. 26a. The air duct
As could be expected, at a point several feet in front of the fan, the velocity was less than 48 m.p.h. because of the fanning out of the air stream, giving a larger cross-section of air for the same volume.

The velocity of 35 m.p.h. was not considered high enough for these tests; therefore, an air duct was designed and built as shown in Fig. 26a. The cross-sectional area was reduced from a 36" circle at the fan connection to a 15"x28" rectangle. This reduction was made over an 8 foot distance so that excessive static pressures would not be introduced into the system. From the performance curves of Fig. 27b, it can be seen that the output of the fan decreases rapidly with an increase in static pressure. There was the possibility, then, that decreasing the cross-sectional area by using a tapering air duct might actually decrease the velocity rather than increase it. This would be true if the static pressure were high enough to reduce the output of the fan to a point where the volume of output divided by the final cross-sectional area was a smaller value than the original volume divided by the original air stream cross section. However, the gradual taper used did increase the velocity to about 50 m.p.h. as shown under test procedure. A straight section of duct 4 feet long was used, in addition to the tapered section, for the purpose of reducing air turbulence.
Fig. 26b. Apparatus set up for running lap requirement tests

Fig. 27a. Water on roof section when no wind is blowing

Fig. 28a. Pitot tube and manometer used for measuring wind velocities
Fig. 27b. Performance curves for fan used as wind source.

Fig. 28b. Wind velocity readings.
Pitot tube and manometer. Severns and Fellows (24) recommend that a pitot tube be used for measuring high velocities of air flow where laminar flow exists. Although a straight section of air duct was used, as explained previously, to straighten out the air flow, complete laminar flow was not obtained. When efforts were made to measure the flow of air from the duct, the gauge fluid, which was water, was very unsteady in the manometer tube. This indicated that turbulent flow probably existed, and that some of the moving air was registering in the static holes of the pitot tube. To alleviate this trouble, a 1/2" pipe was ground to a fine edge, as shown in Fig. 28a, and placed over the pitot tube. It was expected that this pipe would prevent direct air flow into the static pressure holes on the side of the pitot tube, but would not interfere with its effectiveness in measuring static flow. After the change was made, the readings could be taken with the fluid in the manometer tube reaching a steady state. This steady state of the fluid indicated that turbulent flow was not entering the static pressure holes.

Test procedure

Condition of roof. One and twenty-six-hundreths-inch corrugated aluminum sheets 0.019 inch thick were applied to the roof deck with laps as shown in Fig. 29. Steel ring shank nails with neoprene washers were used to fasten the
sheets to the roof deck. These nails have head diameters 0.379" in diameter, have shanks 0.138" in diameter, and have 19 rings per inch. For a more complete description of the nail the reader is referred to Boyd (4), nail number 22, or to Kunze (15), nail number 3. The nailing pattern consisted of nails in the top of every fifth corrugation across the sheet and at each nailing girt, which were spaced 12 inches on center, up and down the sheet.

When the sheets were first nailed on, wedge-shaped neoprene composition washers were used for sealing the nail holes. These washers were two or three years old and had become quite hard. When the nails were driven down tightly to give a good seal, the soft 0.019" thick aluminum sheets collapsed and leakage at these points was excessive. Another roof covering was put on with flat neoprene washers being used. The flat washers were much more pliable than were the wedge-shaped washers; therefore, it was possible to drive the nails down fairly well before bending of the metal took place.

Rate of water application. According to David L. Yarnell (26), the maximum rainfall to be expected for a five-minute period once in 50 years in Iowa is 9 inches per hour. It was decided that this maximum amount would be used for running the end and side lap tests. For a barn 60 feet wide where half of the water drains one direction and half the other, a 9-inch-per-hour rainfall would cause
approximately 0.295 gallons per minute to flow down one corrugation. This gave 5.6 gallons per minute flowing from 19 pipes in the water applicator. The float valve was set so that a 6-inch head of water was maintained in the water trough for all tests. The sliding valve, as shown in Fig. 23, was then adjusted, by means of trial and error, so that the required flow was obtained. The same flow, as shown above, was used for running the tests at all slopes.

Wind velocity. The maximum wind velocity which could be obtained from the wind source previously described was desirable for running the side and end lap leakage tests. Wind velocities of more than 100 m.p.h. have been recorded in Iowa. However, the equipment available for these tests was not sufficient for producing such high velocities. The maximum velocity which could be obtained, and which was used for all of these tests, was approximately 50 m.p.h.

The measurements of the wind velocity were made approximately 3 feet in front of the wind tunnel, and across the wind section as shown in Fig. 28b. The pitot tube and manometer described previously were used for measuring the velocities. According to Severns and Fellows (24), an equation for converting velocity pressures to feet per second is as follows:

\[ v^2 = \frac{2g \ dw \ hv}{12 \ da} \]
Fig. 29. Observation holes in underlapped sheet for determining extent of water travel through laps.

Fig. 30. Points of end lap leakage with 50 mi./hr. wind.
where \( v \) = velocity, fps

\[ g = \text{acceleration due to gravity, } 32.15 \text{ ft per sec per sec} \]

\[ dw = \text{weight of one cubic foot of water} \]

\[ hv = \text{velocity pressure, in. of water} \]

\[ da = \text{density of flowing air, lb per cu ft} \]

Since the readings were taken in centimeters and \( v \) was desired in miles per hour, the formula was modified as follows:

\[
v = \frac{0.0305 \ g \ dw \ hv}{da}
\]

where all values are the same as above, except

\( v \) = velocity, m.p.h.

\( hv \) = velocity pressure in centimeters of water

The average velocity of flow in a duct represents the mean of all the velocities at various places in the section of the duct. The square root of the velocity pressure is involved in the calculation of velocity. Therefore, in arriving at the average velocity of flow, the average square root of the velocity pressures must be used. The following calculations show the average velocity pressures used for the tests. The readings are shown in Fig. 33b.

\[
\sqrt{hv_a} = \sqrt{\frac{\sqrt{3.5} + 3\sqrt{3.4} + 3\sqrt{3.6} + \sqrt{3.5} + \sqrt{2.9} + 3\sqrt{2.8} + 3\sqrt{2.6} + \sqrt{2.5}}{16}}
\]
\[ \sqrt{hva} = 1.754 \]
\[ hva = 3.07 \text{ cm. of water} \]

Using the equation above, the velocity is

\[ v^2 = \frac{0.0305 \times (32.16)(62.4)(3.07)}{0.75} = 2510 \]

\[ V = 50.2 \text{ m.p.h.} \]

This wind velocity of approximately 50 m.p.h. was used for the tests with the various slopes shown in Fig. 30.

Method used to detect distance water traveled through laps. Three-thirty-seconds-inch holes were drilled in the underlapped sheet as shown in Fig. 29. The size of the holes has no significance other than the fact that the holes needed to be large enough so that leakage would be excessive enough to give a positive leak when water came to the hole. With a very small hole, surface tension of the water and capillary attraction between aluminum and water could prevent the water from dripping.

In measuring the side lap where leakage would occur for the conditions set up for these tests, it was only possible to measure in increments of one corrugation, since any water which went over the top of a corrugation would flow on down into the valley of the corrugation by gravity flow. Therefore, the side lap was constructed with holes at 1/2-corrugation overlap and at 1-1/2-corrugations overlap, as shown in Fig. 29. The maximum side lap was 2-1/2 corrugations, where leakage, if it occurred, could be
detected at the edge of the under-lapped sheet.

To detect how far water traveled through the end laps, one 3/32" hole was drilled in the under-lapped sheet one inch from the lower end of the lap. Thereafter, holes were drilled every half-inch for 7 inches. When leakage occurred at a hole, a piece of scotch tape was stuck over the hole and observations were made to see if water traveled to the next hole. This procedure was repeated until the maximum point of leakage was established.

The test process. For each of 13 roof slopes, as shown in Fig. 30, tests were run with all variables except roof slope held constant. The procedure was the same for each slope. The water was turned on the roof section at a rate of 5.6 gallons per minute as explained under "Rate of water application", and the wind of 50 m.p.h. was started. Each test was run for 10 minutes and the maximum points of leakage for both side and end laps were recorded. The roof slope was changed after a test was completed and the process was then repeated for each successive slope.

Results of experimental tests.

With roof slopes of 3, 4, 5, and 6 inches per foot of run leakage occurred at the points of 1-1/2 corrugations overlap. At a slope of 7 inches per foot of run, and for slopes of 8, 9, 10, 11, and 12 inches per foot of run, leakage occurred only at points of 1/2-corrugation overlap.
At 14 inches per foot, and at 16 and 18 inches per foot of run, leakage again occurred at 1-1/2 corrugations.

Points of end lap leakage are shown in Fig. 30 for all of the slopes tested. A regression line was calculated and drawn for these points of leakage as shown in Fig. 30.

Discussion and analysis of results

With the wind and rain conditions assumed and used for these tests, it is seen that it is never feasible to use less than 1-1/2 corrugations of side lap when 1.26" corrugated aluminum is being used. With slopes of 6 inches per foot or less, leakage occurred with 1-1/2 corrugations, but did not occur with 2-1/2 corrugations. For slopes of 6 inches to 12 inches per foot of run, 1-1/2 corrugations prevented side lap leakage. When slopes of greater than 12 inches per foot of run were tested, leakage occurred at 1-1/2 corrugations of side lap.

As shown in Fig. 31, ponding of the water was quite excessive with a slope of 3 inches per foot of run. With flat slopes, the component of the wind parallel to the roof is fairly large and the component perpendicular is small. The ponding of water on the roof, combined with low rates of runoff, tends to give a head of water which causes side lap leakage. As medium roof slopes are reached, the ponding becomes less, as shown by Fig. 32, and the rate of runoff has increased to a point where the forces causing
Fig. 31. Action of water on roof with slope of 3 inches per foot

Fig. 32. Action of water on roof with slope of 8 inches per foot

Fig. 33. Action of water on roof with slope of 14 inches per foot
side lap leakage have decreased and less lap is required. When very steep slopes, such as 14 inches per foot, are approached, the direct pressures, or positive pressures, on the roof cause water to flow through the laps toward points of lower pressure.

As shown by the regression line of Fig. 30, the required end lap decreases with an increase in roof slope. With flat slopes, the wind blew directly into the lap. As the slope was increased the rate of runoff increased and the component of wind blowing directly into the lap decreased. The points from which the regression line was calculated are all, except point 6, fairly reasonable in giving a decreasing trend in the end lap requirements as the slope increases. No explanation is offered as to why a point at 6 inches per foot of run is higher than for any other slope. This irregularity only goes to further point out the uncertainties involved in wind studies on roofs. This is especially true where turbulent flow exists, as it did for these tests, and probably does under actual storm conditions.

As mentioned previously, the critical leakage point on a roof is near the bottom of the roof where the amount of water is a maximum and positive pressures exist on the roof. For these tests a wind velocity of 50 m.p.h. was used. As given by the equation $p = 0.00256 c V_g^2$, the pressure on a roof is a function of the square of the wind
velocity, which indicates that leakage probabilities might be as high as four times as great for 100 m.p.h. winds as for the 50 m.p.h. winds. If this is true, both side and end laps would have to be increased materially to prevent leakage for such severe conditions. The question to be answered is one of deciding the severity of wind and rain conditions which can be feasibly and economically designed against. At any rate, if no factors other than the prevention of leakage govern the design of the roof, it is advisable to keep the slope between 6 inches and 12 inches per foot of run.

Observations made during research

**Leakage through nail holes of under-lapped sheets.** Although positive measurements were not made of this specific point, it appears that the hole of the under-lapped sheet is a point of possible leakage, especially where nail creep has permitted the joint to become loose. The writer was not able to get a perfect seal of the nail hole for any of the tests. However, as explained under "preliminary tests", leakage did occur at the nail hole of the under-lapped sheet.

**Sealing of nail hole.** When wedge-shaped washers were used, the corrugations bent before the washer was compressed sufficiently to seal the nail hole. The problem was alleviated by the use of flat washers, but perfect seals were
never obtained. If a leak-proof seal is to be made with 0.019 inch thick aluminum, it will be necessary to either use a very soft washer or to make the metal harder so that the washer can be compressed sufficiently to close the nail hole. In driving the nails into the tops of the corrugations, the metal bent in slightly, giving a funnel shape around the hole, which added to the difficulty of obtaining a sealed nail hole.

Rise of water between laps. When the end and side lap tests were run, water was observed around holes at higher levels than where actual leakage occurred. One factor which could have caused the water to go between the sheets and not cause leakage is capillarity. This is in line with the conclusions reached in this study that capillary water alone will not cause leakage.

Conclusions

The following conclusions are based upon the conditions of a 50 m.p.h. wind and water flowing from each corrugation at a rate of 0.295 gallons per minute. Corrugated aluminum sheets 0.019 inches thick, with corrugations 1.26 inches wide and 3/8 inches deep, were used.

1. The end lap required to prevent leakage increases at a rate of 0.175 inches for each inch per foot of run decrease in roof slope. This relationship is given by the formula $y = -0.175x + 4.58$, where $y$ is the maximum end lap
at which leakage occurred and \( x \) is the roof slope in inches per foot of run. (The curve is given on page 76 and a discussion is presented on pages 79 and 80.)

2. On a roof with a slope of less than 6 inches per foot of run, ponding, due to both wind action and slow rates of runoff, of water on the roof gives a hydraulic head which is sufficient to cause water to flow through side laps of 1-1/2 corrugations. On a roof with a slope of more than 12 inches per foot of run, direct positive wind pressures cause water to flow through side laps of 1-1/2 corrugations. The least severe combination of wind pressures and rates of runoff occurs on slopes of from 6 inches per foot to 12 inches per foot of run, where side lap leakage is prevented by 1-1/2 corrugations of overlap.

3. The probability of leakage on a roof is greater near the bottom of the roof where both positive wind pressures and large volumes of water are present.

4. When aluminum sheets only 0.019 inch thick are nailed to a roof deck, a very soft pliable washer is necessary if the nail hole is to be sealed. A hard washer causes the thin sheets to bend before a seal is obtained.

5. The nail holes in under-lapped sheets present points of leakage when water travels between the laps. These points of leakage are not as critical when the lapped sheets are held tightly together as when nail creep takes place and the lapped joints become loose.
RECOMMENDATIONS FOR FURTHER STUDY

1. Tests using corrugation sizes other than 1.26" should be run in the manner that the tests of this study were performed.

2. Leakage problems involving the use of V-crimp sheets and embossed sheets should be investigated.

3. The problem of leakage through nail holes in the under-lapped sheets should be investigated further.

4. The hardness of aluminum material needed to give a good nail hole seal with the present neoprene washers, or the characteristics required in washers to give good seals with the present aluminum roofing, or the needed combination of the two, should be given some study.

5. A study to determine the effects of corrugation shape on lap requirements could possibly aid in solving the leakage problem on metal roofs.
SUMMARY

Proper application of a roofing material is necessary if the roof is to satisfactorily serve its purpose, which is to keep out the weather elements for a reasonable number of years. Proper application of corrugated aluminum roofing, therefore, involves the sealing of nail holes and the using of proper side and end laps to prevent leakage on the roof.

Inspections of farm buildings in Iowa show that no correlation exists between the applied side lap and roof slope or between the applied end lap and roof slope. A number of buildings which were covered with sheet metal were found to leak when rains occur. Improper application was believed to be one reason for the dissatisfaction experienced by the owners of these leaky roofs.

Tests were conducted to determine whether or not capillarity would cause water to rise between the lapped sheets, and if so, to determine whether or not the capillary water would cause leaks. Although capillary water rises a small distance between the sheets, it was found that it does not drop from the sheets and cause leakage.

Tests show that the side and end laps required to prevent leakage vary with the roof slope. A wind of approximately 50 m.p.h. was blown over a roof section while
water was being applied to the section at a rate such that water flowed from each corrugation at a rate of 0.295 gallons per minute.

When 1.26 inch corrugated aluminum roofing is used, the required end lap varies with roof slopes according to the formula \( y = -0.175x + 4.58 \), where \( y \) is the end lap and \( x \) is the roof slope.

The minimum side lap required to prevent leakage occurs on roofs with slopes between 6 inches and 12 inches per foot of run. The least severe combination of wind pressures and rates of runoff occurs on roofs with these slopes.

To obtain a leak-proof seal of the nail hole when 0.019 inches thick aluminum is used, it is necessary to use a very soft washer. A hard washer causes the corrugation to buckle before the washer compresses enough to seal the hole.
LITERATURE CITED


ACKNOWLEDGMENTS

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For the suggestions and aid extended by Professor Merle Esmay, Professor S. H. Byrne, Mr. Frank Lanham, and Dr. Frank E. Brown, the author is grateful.

Appreciation is also expressed to the Aluminum Company of America whose financial support made the project possible.
APPENDIX
APPENDIX

This information is a compilation of the data obtained during the field survey through northwestern Iowa. Forms No. 11 were used for recording the information gathered as the buildings were inspected. The numbers refer to characteristics shown on Form 11. For example, read down to item K and over to number 2 under Farm No. 1. On Form 11, K-1 shows that the material to which the sheet metal was fastened was 3/4" thick. The same procedure should be followed for obtaining the results of any roof examined.

The following abbreviations are used:

1. C. - Corn
2. Per. - Permanent
3. G. P. - General Purpose
4. Gran. - Granary
5. Impl. - Implement
6. Stor. - Storage
7. Bldg. - Building
## Form Used for Recording Field Observations of Sheet Metal

### SHEET METAL

**Form No. 11** To Accompany Form No. 1 Building No. Photo No. No._
Report by ___________________________ Survey Date, Month __ Year __ No.

### DESCRIPTION

**A. Application:**
- (0) Interior wall surface
- (1) Interior ceiling surface
- (2) Exterior wall surface
- (3) Roofing

**B. Material:**
- (0) Plain sheet steel
- (1) Galvanized steel
- (2) Tinned steel
- (3) Painted steel
- (4) Tempered steel
- (5) Aluminum
- (6) Copper
- (7) Other

**C. Type of sheet:**
- (0) Plain
- (1) Corrugated
- (2) Vee Crimp
- (3) Other

**D. Width, inches:**
- (0) 18"
- (1) 24"
- (2) 26"
- (3) 30"
- (4) 36"
- (5) Other

**E. Length, feet:**
- (0) 4
- (1) 6
- (2) 8
- (3) 10
- (4) 12
- (5) Other

**F. Gauge:**
- (0) 20
- (1) 22
- (2) 24
- (3) 26
- (4) 28
- (5) Other

### INSTALLATION

**G. Joint type:**
- (0) Lapped and nailed
- (1) Flat seam
- (2) Raised seam
- (3) Corrugation lap
- (4) Vee lap
- (5) Soldered
- (6) Other

**H. Slope of surface, inches per foot:**
- (0) 0"
- (1) 2"
- (2) 3"
- (3) 4"
- (4) 5"
- (5) 6"
- (6) 7"
- (7) 8"
- (8) Vertical
- (9) Other

**I. Width of lap, inches:**
- (0) 1"
- (1) 1½"
- (2) 2"
- (3) 2½"
- (4) 3"
- (5) 4"

**J. Fastened to:**
- (0) Wood sheathing, solid
- (1) Wood sheathing, spaced
- (2) Old siding or shingles
- (3) Siding, joist, girder, 16" o.c.
- (4) Siding, joist, girder, 24" o.c.
- (5) Siding, joist, girder, 30" o.c.
- (6) Furring strips, 16" o.c.
- (7) Furring strips, 24" o.c.
- (8) Other

**K. Thickness of material fastened to, inches:**
- (0) ½"
- (1) 3/8"
- (2) 1"
- (3) 1½"
- (4) 2"
- (5) Other

**L. Type of material fastened to:**
- (0) Yellow Pine
- (1) White Pine
- (2) Hemlock
- (3) Poplar
- (4) Fir
- (5) Spruce
- (6) Oak
- (7) Beech
- (8) Maple
- (9) Other

**M. Condition of material fastened to:**
- (0) Sound
- (1) Warped
- (2) Checked and split
- (3) Decayed
- (4) Unable to inspect
- (5) Other

**N. Building paper beneath:**
- (0) Yes
- (1) No
- (2) Unable to inspect

**O. Accessories:**
- (0) Starting strip
- (1) Corner strip
- (2) Trim strip
- (3) Flashing
- (4) Other

**P. Fasteners:**
- (0) Plain nail
- (1) Cement coated nail
- (2) Galvanized plain nail
- (3) Copper nail
- (4) Lead coated nail
- (5) Finish wire nail
- (6) Finish aluminum nail
- (7) Galvanized roofing nail
- (8) Aluminum roofing nail
- (9) Other

**Q. Washer:**
- (0) None
- (1) Lead
- (2) Leather
- (3) Neoprene
- (4) Rubber
- (5) Fiber
- (6) Metal
- (7) Other

**R. Size of Fastener:**
- (0) 1d
- (1) 2d
- (2) 3d
- (3) 4d
- (4) 5d
- (5) 6d
- (6) 8d
- (7) Other

**S. Fastener, spacing at edge, inches:**
- (0) 6"
- (1) 8"
- (2) 12"
- (3) 1½"
- (4) 20"
- (5) 24"
- (6) Other

**T. Fasteners, center spacing, average surface per sq. inch per fastener:**
- (0) 100"
- (1) 200"
- (2) 400"
- (3) 600"
- (4) 800"
- (5) 1,000"
- (6) Other

**U. Fasteners, distance from edge of material:**
- (0) 1/4"
- (1) 1/2"
- (2) 3/4"
- (3) 1"
- (4) 1½"
- (5) 2"
- (6) Over two

**V. Fastener penetration:**
- (0) Penetrates sheathing
- (1) Does not penetrate sheathing
- (2) Unable to inspect

**W. Surface finish:**
- (0) None
- (1) Aluminum paint
- (2) Zinc paint
- (3) Lead base paint
- (4) Other
- (5) Unable to classify

**X. Average years between painting:**
- (0) 3
- (1) 6
- (2) 9
- (3) 12
- (4) 15
- (5) Over 20 years

**Y. Age in years**

**Z. Basis for entry in item "Y":**
- (0) Occupant knows
- (1) Occupant's estimate
- (2) Enumerator's estimate
Form Used for Recording Field Observations of Sheet Metal Sheet 2.

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
<th>Option 5</th>
<th>Option 6</th>
<th>Option 7</th>
<th>Option 8</th>
<th>Option 9</th>
<th>Option 10</th>
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<td>Estimated service life remaining with normal maintenance, years:</td>
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<td>1-999</td>
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<td>Present condition: (0) Very good (1) Good (2) Fair (3) Poor (4) Very Poor</td>
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<td>Sheet disintegrating: (0) Corrosion at contact with fastener (1) Corrosion at contact with resin in sheathing (2) Corrosion with masonry (3) Corrosion in contact with manure (4) Normal weathering (5) Condensation (6) Other</td>
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</tr>
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<td>Surface damage: (0) Weathering (1) Abrasion by livestock (2) Abrasion by machinery (3) Rubbed by sliding door (4) Gnawed by rodents (5) Contact with manure (6) Lack of paint (7) Other</td>
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<td>Edge torn or broken: (0) Fasteners too near edge (1) Fasteners too large diameter (2) Sheet damaged in driving fastener (3) Insufficient fasteners (4) Distortion of frame (5) Lateral pressure (6) Wind damage (7) No corner protection (8) Other</td>
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<td>Sheet buckled or warped: (0) Distortion of frame (1) Insufficient fasteners (2) Sheet too thin (3) Abnormal lateral pressure (4) Insufficient backing (5) Other</td>
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<td>1-999</td>
</tr>
<tr>
<td>II</td>
<td>Failure of fastenings: (0) Fastenings rusted or corroded (1) Nails not held by base (2) Spacing too wide (3) Head too small (4) Fasteners damaged in installation (5) Fasteners too short (6) Other</td>
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<td>1-999</td>
</tr>
<tr>
<td>JJ</td>
<td>Holes along edge at fasteners: (0) Yes (1) No</td>
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<td>KK</td>
<td>Time since previous wind damage, yrs.: (0) 1 (1) 2 (2) 3 (3) 4 (4) 5 (5) 5-10 (6) 10-15 (7) Over 20 yrs.</td>
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<td>LL</td>
<td>Percent of roof damage: (0) 0 (1) 5 (2) 10 (3) 15 (4) 20 (5) 30 (6) 40 (7) 50 (8) 75 (9) 100</td>
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<td>MM</td>
<td>Location of damage: (0) Scattered spots (1) Knee ends (2) General (3) At eaves (4) At ridge (5) Other</td>
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<td>NN</td>
<td>Previous insurance claims: (0) None (1) During first year (2) Second year (3) Third year (4) 3 to 5 years (5) 5 to 10 years (6) 10 to 15 years (7) 15 to 20 years (8) 20 to 25 years (9) Over 25 years</td>
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<td>OO</td>
<td>Material: (0) Asphalt shingles (1) Cement-asbestos shingles (2) Wood shingles (3) Asbestos roll roofing (4) Built-up roofing (5) Galvanized sheet steel (6) Aluminum (7) Tile (8) Other</td>
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### Results of Observations of Sheet Metal Roofs

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