FACTORS AFFECTING SELECTION OF PROPER "LENGTH-OF-RUN" AS APPLIED TO FURROW IRRIGATION DESIGN *

by

D. M. Gray and C. E. Beer

Member C.S.A.E.

Research Associate, Agricultural and Home Economics Experiment Station, and Instructor Agricultural Engineering Department, Iowa State University, Ames, Iowa

General

With the increased interest in irrigation in Iowa during the past few years, a cooperative project between the Iowa Agricultural Experiment Station and the Soil Conservation Service was initiated in 1955 to obtain design criteria for furrow irrigation systems.

The influence of numerous inter-related factors makes furrow irrigation design a complex phenomenon. Proper design of a system is consequently inhibited because of the lack of understanding of many of the influencing factors and the inability to express their influence quantitatively (6). The length-of-run best suited for a particular field is affected by erosion and drainage hazards, soil type, slope of the furrow, furrow geometry, and input to the furrow. This paper presents the results of field envestigations illustrating the effects of several of these factors on the design of furrow irrigation systems on several alluvial soils in the Missouri River Flood Plain.

Field Efficiency

In system design, the efficiency of water application is of primary importance. Efficiency is defined as the per cent. of the total volume of water delivered to a field that is stored in the root zone and ultimately consumed by evaporation and/or transpiration (11, p. 12). The efficiency of a furrow irrigation system should fall within the range of 60-70 per cent (11, p. 12). The major water losses accrue from excessive deep percolation through the root zone in the area near the water supply and from overflow into the drainage ditch.

Furrow irrigation efficiency can be improved by proper system design and operation. In furrow irrigation, the time required to replace a given amount of water is computed after the entire furrow is wetted. Studies by the United States Department of Agriculture, Soil Conservation Service, summarized by Criddle (4) have been shown, for efficient irrigation, the rate of water input into the furrow should be such that the entire furrow is wetted in one-fourth the total irrigation time. After the entire furrow has been wetted, the input should then be reduced to a rate equal to the soil intake rate. This procedure permits only a minimum amount of water to flow as waste into the drainage ditch.

It is possible, however, for some soils to exhibit such intake patterns that a large amount of the required irrigation application will be absorbed almost instantaneously on passage of the wetted front. Under these conditions, continuation of irrigation with a reduced furrow input is questionable, and irrigation should be stopped as soon as the wetted front reaches the end of the furrow. The design length selected should be based on a practical compromise giving consideration to irrigation efficiency and scheduling.

Rate of Advance of Wetted Front

The rate of advance of a wetted front in a furrow may be expressed by the general relationship

$$T = CD^m \qquad 1.$$

where T = time,
C = coefficient,
D = distance, and
m = exponent.

The constant C and exponent m can be evaluated by plotting observed values of T and D on logarithmic paper. The magnitudes of these parameters are different for varying conditions depending on:

1. Input to the furrow,
2. Furrow geometry and slope, and
3. Soil type and conditions.

The effect of varying the furrow input on the rate of advance of the wetted front is shown in figure 3. The time required for the wetted front to traverse a given distance varies inversely with the furrow input.

Shibata (12) in Japan and Philip (10) in Australia have evaluated quantitatively the effects of furrow input and slope on the rate of advance of a wetted front for local soils of their countries. They suggested the following relations:

Shibata—

$$\log t = (1.608 - 0.106q) + iL/(B\text{-}A) \qquad 2.$$

where i = furrow gradient (per cent),
L = length of furrow (meters),
q = furrow input rate (litres/sec.),
t = time water requires for travel through distance L, and
A, B = coefficients.

Philip—

$$\log (1+Bt) = x/Aq^{0.72s0.20} \qquad 3$$

where t = time in minutes required for water to traverse the furrow distance x (ft),
q = furrow input rate (cfs)
s = furrow slope (ft/ft), and
A, B = coefficients.

From equations 2 and 3, it is apparent that the time required for water to travel a given distance in a furrow becomes shorter in proportion to the slope. The coefficients of equations 2 and 3 are dependent on furrow geometry and the intake characteristics of the soil. Their evaluation can be accomplished after field investigations have been conducted.

---

*

This paper has been prepared expressly for Canadian Agricultural Engineering and approved as Journal Paper No. J 3790 of the Iowa Agricultural and Home Economics Experiment Station, Ames, Iowa. Project No. 1247.

Acknowledgement: The authors wish to acknowledge the cooperation of the Soil Conservation Service for their assistance in the study.

Soil Intake Rate

The relationship between time, distance and physical factors for the movement of a wetted front is requisite for proper furrow design. In addition, the soil intake rate must be known to compute the time required to replace a given amount of water to the root zone.

The intake characteristics of soils have been studied by numerous investigators. For a given soil, the intake rate varies with surface conditions and the initial moisture content. Horton (7) originally proposed that the intake capacity of a soil decreased exponentially with time. His concept is expressed as follows:

$$I_t = I_g + (I_o - I_g)\, e^{-kt} \qquad 4.$$

whre I_t = intake capacity at any time t,

I_g = intake capacity at a constant rate,

I_o = intake capacity at "0" time,

k = exponent, and

e = base of natural logarithms.

This expression is extremely difficult to evaluate because of the difficulty in determining the intake capacity in the field. Brakensiek (3) has done some work in relating I_g, I_o and k to an antecedent precipitation index.

In general, for furrow irrigation work, the soil intake rate may be expressed mathematically in the form initially proposed by Kostiakov (8) given as follows:

$$I = aT^n \qquad 5.$$

where I = intake rate normally expressed in gals/min/100 feet,

a = coefficient,

n = exponent, and

T = time in minutes.

This form is not valid after the intake rate has decreased to a near constant value.

Present Length-of-Run Design

The present methods recommended for the design of furrow irrigation systems differ mainly with respect to the method used in estimating the intake rate of a soil. Criddle (5) and Bondurant (2) have suggested techniques for determination of the intake rate which are applicable in furrow irrigation work. For a given intake rate, the tital time T required to replace a given amount of soil moisture, I^T, is calculable by integration of the intake capacity equation. Using equation 5 and assuming n constant

$$I^T = \int_{t=0}^{T} aT^n\, dT = \frac{1}{n+1}\, aT^{\,n+1}$$

or

$$T = \left(\frac{I_T\,(n+1)}{a} \right)^{\frac{1}{n+1}} \qquad 6.$$

By employing the design criterion suggested by Criddle, the recommended furrow length may be obtained by solving equation 1 for the soil in question using 1/4T as obtained from equation 6.

Beer (1) suggested that the intake rate selected be based on characteristics of the entire length of the furrow. This recognizes that the rate may vary appreciably throughout the furrow length, not only because of variations in soil structure and type, but also because of the progressive decrease in the amount of the wetted surface. He assumed that the rate of movement of the wetted front with little or no infiltration may be expressed by the linear relationship

$$T' = C'D. \qquad 7.$$

The constant C' may be estimated by the slope of a line drawn tangent to the rate-of-advance curve and passing through the origin (see figure 1).

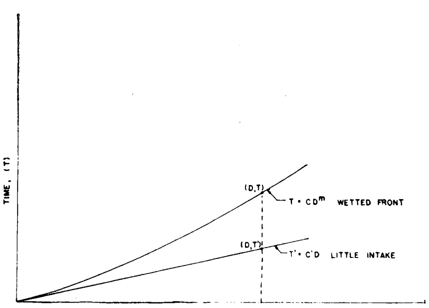

Figure 1.Estimation of furrow intake rate (1)

With an input q, the average intake rate, I, during time, T, required for the wetted front to travel distance D becomes

$$I = \left(\frac{T - T'}{T} \right) q. \qquad 8.$$

By applying these results in a manner similar to that used by Cridle, the proper length-of-run may be obtained.

It is evident that proper design requires prior information of the rate of advance and intake rate. The ultimate relationships would be mathematical equations expressing the rate-of-advance and the intake-rate curves as a function of measurable physical variants for a particular soil type. The results of a series of tests conducted on several Iowa soils indicated that certain factors within areas of similar soil and physical conditions reduce the possibility of combining data to a specific form. It is shown that the effects of surface cracking and soil moisture, surface sealing and test procedures significantly influence proper selection of length-of-run.

Test Procedures

Several field investigations were conducted on soils in the Missouri River Flood Plain. The procedure for determining the advance of the wetted front in a furrow was essentially the same as that outlined by Criddle and others (5, p. 4-5). Water was introduced into a furrow (test furrow) and the rate of advance of the wetted front obtained by measuring the time required to advance past previously established check points. Within the first 100-ft. reach, the check points were placed on intervals of 10-25 ft., depending on the furrow input. This was done to obtain better definition of the rate-of-advance curve within this length. Beyond station 1 + 00 (100-ft. distance from water supply), the advance was timed at 100-ft. intervals. Buffer furrows were simultaneously wetted on each side of the test furrow to reduce lateral seepage.

Small Parshall Flumes (2-inch and 3-inch throat diameters) were inserted in the test furrow at various locations and head measurements taken at selected times after the wetted front had passed through each flume. This enabled calculation of the discharge from the reach during the time interval. Care must be exercised in placement of the flumes to avoid unnecessary ponding.

In addition to the above measurements, the furrow input was checked periodically during each run. These measurements were averaged to provide a mean furrow input for the entire test. Supplemental data collected included:

1. Soil moisture samples at 6, 12, and 24-inch depths,
2. Soil samples for mechanical analysis, and
3. Slope of the test furrow.

Results and Discussion

The results of the field investigations are presented as rate-of-advance curves and mass-tintake curves (see figures 3 and 4). The use and application of the rate-of-advance curves is evident; however, the authors believe that a preliminary discussion of the mass-intake curves as they relate to this work will add clarity to the paper.

Mass-intake Curves

As shownn by equation 6, the mass-intake curve may be expressed in the equation form

$$I_T = \frac{1}{n+1}\, aT^{n+1}$$

If the slope of the intake-capacity curve "n" remains constant with time, the curve plots as a straight line on logarithmic paper (see figure 2, curve B). In which case, the equation of the line becomes

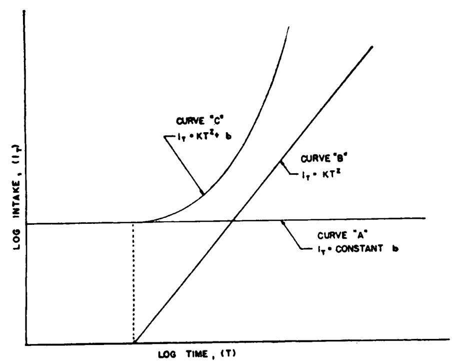

Figure 2. Mass intake curves

$$I_T = KT^z \qquad 9.$$

where $K = \frac{a}{n+1}$ and

$z = n + 1.$

The mass-intake curve of a soil is a useful tool for studying the disposition of irrigation water and can serve as an aid in the selection of criteria for the design and operation of a furrow irrigation system. The disposition of water is of special interest in heavy, clay soils which exhibit high shrinkage and tend to crack on drying. The following information is usually desired on these soils:

1. The intake rate after the initial filling of the crack voids,
2. Whether high intake rates are due to both the combined influence of the initial filling of the voids and continued intake to the soil,

   and
3. The storage volume of the cracks.

The above factors may be investigated by an analysis of the mass-intake curves as suggested by Phelan (9).. These curves may take various shapes. Curve A (figure 2) represents

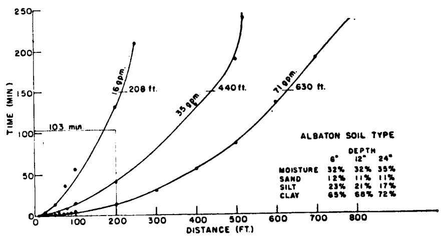

Figure 3.Rate-of-advance curves for Albaton soil type.

the instantaneous filling of the soil cracks followed by no intake. Curve B shows the normal pattern of cumulative intake of water to the soil as expressed by equation 9. Curve C il-illustrates the condition outlined in item 2, consisting of a summation effect of the instantaneous filling of the large voids (Curve A) and a continued rapid intake rate.

The characteristic shape of the mass-intake curve is important in establishing design and operation criteria. On a soil illustrating water-intake properties as shown by Curve A, the furrow input should be turned of soon after the wetted front traverses the furrow length. This avoids unnecessary wastage. Similarily, if the rate of accumulation were slow in a soil having intake properties as represented by Curve C, irrigation should be stopped shortly after the furrow is wetted, provided the volume of water stored in the large openings approaches the required irrigation application. Otherwise, the slope of the curve may be utilized in selecting a suitable cut-back rate. Furrow design on soils having normal intake properties, Curve B, can be accomplished in accordance with Criddle (4).

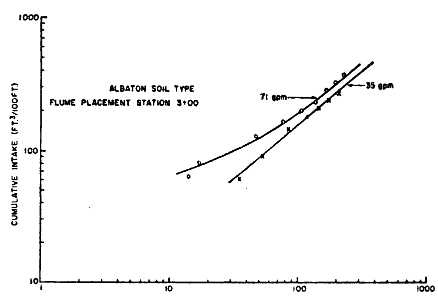

Figure 4.—Mass-intake characteristics of Albaton soil.

Since the intake "intercept" is directly related to the volume of large voids, it appears that the mass-intake curve of a soil may find additional value as a quantitative measure of the extent of cracking.

Effect of Furrow Input

The effect of furrow input on the rate of advance and furrow intake is exemplified in figures 3 and 4, respectively. With increasing input, the rate of advance of a wetted front in the furrow correspondingly increases. For the given conditions, at a common time of 150 minutes, the distances travelled by the wetted front were 208 ft., 440 ft., and 630 ft. for discharges of 16 gpm, 35 gpm, and 71 gpm. In design, it is desirable to use the largest non-erosive stream in wetting the furrow. The furrow design length thereby may be increased with higher inputs depending on the erosiveness of the soil and the capacity of the irrigation system. On this particular soil, no erosion was experienced with the input of 71 gpm. Figure 4 shows the effect of furrow input on mass intake. As would be expected the mass-intake curve for the higher discharge falls above that of the lower because of the increase in wetted surface and acting head. Some soil cracking is indicated by the flattening out of the curve for the higher discharge. Placement of the flumes at station 3+00 made it impossible to compute the intake quantities at shorter times.

Effect of soil type and surface sealing

The rate-of-advance curves for Haynie silt loam soil with the textural composition as listed are illustrated in figure 5. Frequently, it is errone-

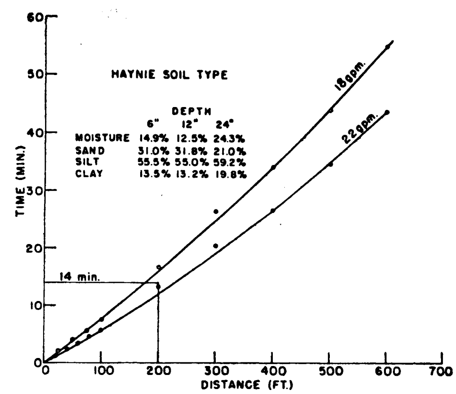

Figure 5. Rate of advance curves for Haynie soil type.

ously assumed that since a soil is "lighter" texturally, the intake rate will consequently be rapid, and the furrow design length correspondingly should be short. Comparing the rate-of-advance curves for the Albaton soil (68% clay) and the Haynie soil (13% clay), the times required for a wetted front to travel 200 ft. under approximately identical slope and input conditions were 103 minutes and 14 minutes, respectively on the two soils.

Although the input was extremely low (22 gpm) on the Haynie soil, fine particles of silt were carried in suspension. Intake rates as low as 0.15 inches per hour wer calculated, and it was estimated that it would require approximately 20 hours to replace two inches of soil moisture. It appeared that the low intake rate may be partially attributed both to a surface-sealing effect and the effect of furrow geometry (sharp, Vee-shaped). Nevertheless, for the conditions under which the tests were conducted, the furrow lengths for this soil may be designed significantly longer than those for the heavier Albaton. This design is the exact opposite of that which would be expected using a textural classification. It is recommended that the design length be selected either from field investigations on site or from information collected from systems located on soils having comparable intake and erosive properties.

Effect of soil moisture and soil cracking

The rate-of-advance curves presented in figure 6 are from runs comple-

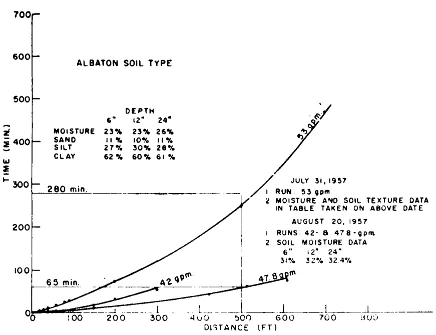

Figure 6. Rate of advance curves for Albaton soil type.

ted at the same location. The tests were conducted on different days with the soil moisture content a two different levels. The soil moisture content at 23 per cent. is very close to the wilting point, whereas at 32 per cent, it is in the upper part of the available moisture range. The effect of soil moisture on the rate of advance is shown by comparing the times required for the wetted front to travel 500 ft. on the two days. At the same input, the time was reduced from 280 minutes on the dry 23-per cent soil to 65 minutes on the moister 32-per cent soil. This difference may be attributed to soil moisture content and its effect on surface cracking.The importance of this factor cannot be overstressed, not only from the standpoint of design, but also from the standpoint of scheduling the irrigation. It is normally suggested that irrigation be started when the soil moisture content is in the range of 50-60 per cent available moisture. The progressive increase in time for the wetted front to travel a given distance as the soil drys out can result in disruption of the irrigation schedule and a serious moisture deficiency to the plants located in the parts of the field to be irrigated last.

Figure 7 shows the mass-intake curves for the two runs, 53 gpm and 48 gpm conducted on the two different days (25% moisture). The pre-

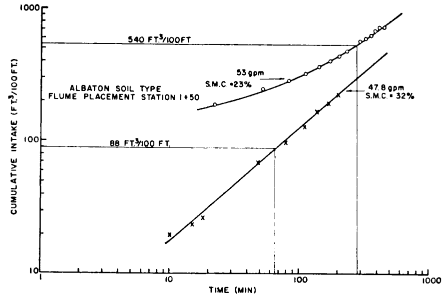

Figure 7. M ss intake characteristics of Albaton soil.

sence of soil cracks is evident by the flatness of the 53 gpm-input curve. This fact was substantiated by field observation. In places a meter stick could be pushed into the cracks to a depth of two feet. Again the flumes were not placed close enough to the water supply to obtain mass-intake values at the lower times. Thus, extrapolation of the curve to the ordinate was prohibited.

Calculations show that in the dry soil 19.5 inches of water were added to the soil profile in the reach of the furrow near the water supply during the time required for the wetted front to travel 500 ft. The amount of water held by this soil in the available moisture range to a five-ft. depth is approximately 10.2 inches.

Various procedures are available to offset the effect of soil cracking on the rate of advance of a wetted front. They include:

1. Increasing furrow input,
2. Increasing furrow slope, and
3. System design based on specific soil moisture conditions.

Effect of lateral seepage

In order to obtain length-of-run data it is necessary that great care be taken to control lateral seepage. This is the case particularly in those soils which subtend large lateral cracks. In such soils, unless a sufficient number of "buffer" rows are used on each side of the test furrow, inaccurate results will be obtained. The rate-of-advance was determined for a heavy, clay soil under two levels of lateral seepage control:

1. Two buffer rows on each side of the test furrow.
2. Twenty buffer rows on each side of the test furrow.

The average distance the wetted front moved in 300 minutes under the two conditions was 630 ft. and 713 ft., respectively. The difference became larger with increasing furrow length.

Summary

At the present time, there is a lack of published data on furrow irrigation studies. Proper design criteria in equational or tabular form can be established only after extensive field investigations. These tests are essential in order to accumulate sufficient results to enable separation of some of the variables involved and to study the influence of each individually on furrow length design.

The objective of this paper has been to forward quantitative results of the effects of a few of these factors on the selection of the proper length-of-run.

As shown, mass-intake curves can be of valuable assistance in deciding on a satisfactory design criteria.

Textural classification is not always a suitable index for design. Gross misjudgement in selection of the furrow design length can result with its use, especially on highly-erosive silt soils where surface sealing conditions may persist.

The influence of soil moisture and its effect on soil cracking cannot be overemphasized. Both engineer and irrigator must be cognizant of these variables and the design length selected and sytem operated accordingly. Further information is necessary on the inter-relationship between the cracking characteristics of heavy, clay soils and moisture content.

Finally, test runs must be carried out under conditions simulating as closely as possible, field irrigations. This is of special importance where lateral seepage is a problem.

Continued on page 40

Continued from page 38

countries, research facilities have developed from testing: in other countries, testing facilities have developed from research; the two are intertwined and not often distinguishable. Thus, performance testing facilities are of value to the agricultural engineering profession and industry as a whole. Where do designs for the mechanization of farm work stand today? How good are they and which are the best? How can their performance and value be improved? Is a certain development beneficial? To answer these types of question it is first necessary to investigate; impartial performance testing is needed as a source of information.

Furthermore, this suggestion that independent performance testing is a beneficial and, in fact, highly desirable activity applied particularly in the case of Canada since machinery costs constitute a high proportion of farm expenditure in the large agricultural industry, and because an important agricultural machinery manufacturing industry exists yet imports of agricultural equipment are necessarily appreciable. The same reasons can be advanced in favour of agricultural engineering research in which performance evaluation of existing designs is an essential part.

Continued from page 23

Literature Cited

1. Beer, C. E. Infiltration and flow characteristics as applied to furrow irrigation design in Iowa. Unpublished M.S. Thesis. Iowa State University Library. 1957.

2. Bondurant, J. A. Developing a furrow infiltrometer. Agric. Engr. 38: 602-604. Aug. 1957.

3. Brakensiek, D. L. Estimation of surface runoff volumes from agricultural watersheds by infiltration theory. Unpublished Ph. D. Thesis. Ames, Iowa. Iowa State University Library. 1956.

4. Criddle, W. D. A practical method of determining proper lengths of runs, sizes of furrow streams and spacing of furrows on irrigated lands. U.S. Dept. of Agric., Soil Cons. Service, Provisional Report. Mar. 1951.

5. Criddle, W. D. and others. Methods for evaluation of irrigation systems. U.S. Dept. of Agric., Soil Cons. Service, Agr. Handbook 82: 1-23, Apr. 1956.

6. Hansen, V. E. and others. Report of committee of hydraulics of surface irrigation. Paper presented at Winter Meeting, Amer. Soc. of Agr. Engr., Chicago, Ill. Dec. 1956.

7. Horton, R. E. An approach toward a physical interpretation of infiltration capacity. Soil Sci. Soc. Amer. Proc. 5: 399-417, 1940.

8. Kostiakov, A. N. On the dynamics of the coefficient of water percolation. Trans. 6th Cong. Intl. Soc. Sci. Russian Part A, 17-21, 1932.

9. Phelan, J. T. Irrigation Engineer, S.C.S., U.S.D.A. Lincoln, Neb. Personal Communication. 1959.

10. Philip J. R. A quantitative approach to the hydraulics of primary flow furrow irrigation. Paper presented to Irrigation Course, Yanco Experiment Farm, Deniliquin, N.S.W., Aust. Oct. 1952. (Photostat).

11. Quackenbush, T. H. and others. Conservation irrigation in humid areas U.S. Dept. of Agr., Soils Cons. Service, Agr. Handbook 107: 1-13, 38-41, 1957.

12. Shibata, K. Unsteady flow between furrows. Abstract from Reclamation and Melioration, Agr. Engr. Soc. of Japan; Tokyo, Japan. No. 1 p. 7. 1956.

HONORARY MEMBERSHIP

Lifetime Honorary Memberships in the Society were awarded to two pioneers in Agricultural Engineering in Canada:

Dr. E. A. Hardy and Professor G. L. Shanks.

EVAN A. HARDY

A native of Iowa, he came to the University of Saskatchewan after graduation from Iowa State College in 1917. He later obtained a Master of Science degree in engineering and was Head of the Agricultural Engineering Department until 1951. From the time of the first agricultural engineering graduate in 1924, the name of Professor Hardy and the University was almost synonymous to the rural people of Saskatchewan. His enthusiastic demonstrations by means of Horse pulling contests, proper hitching and use of farm machinery and tractor drawbar tests, contributed to the effective and rapid mechanizing of prairie farms. His practical approach to engineering problems associated with agriculture gained him respected recognition by industry. His adopted Province and University awarded him an Honorary Doctor's degree in 1957 recognizing his contribution to the Province and to Canada. In 1951 he accepted an assignment to Ceylon with the Food and Agriculture Organization and is continuing agricultural engineerinfi work in that area.

GRAHAM LAWSON SHANKS

A native of Manitoba he graduated from the Manitoba Agricultural College in 1912 and started a teaching career on the staff of the School of Agriculture at Vermilion, Alberta, before joining the Royal Air Force in 1917. He returned to the Manitoba Agricultural College and was appointed Head of the Agricultural Engineering Department in 1921 and continued until his retirement in 1955. He completed studies for a Master of Science degree at Iowa State College in 1931 including a thesis "The Cause and Prevention of Accidents to Operators of Farm Machinery". Along with a continuing interest in rural electrification in western Canada he conducted research on crop spraying machinery which has received international recognition.

Professor Shanks was present at the meeting to accept the award. Professor Hardy had hoped to attend but sent his regrets at being unable to leave his post in Ceylon.