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MASTER

Evaluation and Refinement of Sprinkler Application Rate Models Used in Frost Protection

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K. B. Perry

The Pennsylvania State University
University Park, PA 16802

1979

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The Pennsylvania State University

The Graduate School

Department of Horticulture

MASTER

Evaluation and Refinement of Sprinkler Application
Rate Models Used in Frost Protection

A Thesis in

Horticulture

by

Katharine B. Perry

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

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The signatories below indicate that they have read and approved the thesis of Katharine B. Perry.

Date of Signature:

Signatories:

April 12, 1979

J. David Martsolf
J. David Martsolf, Professor of
Microclimatology,
Chairman of Committee and
Thesis Advisor

April 12, 1979

Charles T. Morrow
Charles T. Morrow, Associate
Professor of Agricultural
Engineering, Member of
Doctoral Committee

17.4.79

Dennis W. Thomson
Dennis W. Thomson, Professor of
Meteorology, Member of
Doctoral Committee

Apr. 12, 1979

Roland R. Daniels
Roland R. Daniels, Associate
Professor of Horticulture,
Member of Doctoral Committee

12 Apr 79

Daniel P. Knievel
Daniel P. Knievel, Associate
Professor of Crop Physiology,
Member of Doctoral Committee

4/12/1979

Jack C. Shannon
Jack C. Shannon, Professor of
Horticulture Physiology,
Graduate Officer in Horticulture
and Member of Doctoral Committee

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ABSTRACT

Two models of the sprinkled orchard which predict, from a given set of atmospheric conditions, application rates required for successful frost protection were evaluated. Both models calculate the sprinkling requirement by considering the heat budget of a single horizontal leaf and extrapolating over the entire orchard. Several inconsistencies were isolated and discussed in detail. FORTRAN versions of both models were documented.

A Sprinkling Application Rate (SPAR79) model was developed from the previous models. SPAR79 used the heat budget approach to determine the rate of heat lost by the plant part through radiative, convective, and latent heat transfer processes at the actual plant part temperature and at the plant part's critical temperature. The difference between these two rates of heat loss is the rate at which heat must be added by the latent heat of fusion liberated as the applied water freezes. The method used to determine the latent heat transfer departed significantly from the previous models. This model added consideration of humidity and ice accumulation to a refinement of the heat budget configuration of earlier models. It was explicitly shown that humidity is not a contributing factor in the determination of application rates. Ice accumulation was shown to decrease the required application rate by 67% when it increased the characteristic plant part size from 0.2 to 2.0 cm. A distribution factor, a component of a factor previously only estimated, was shown to increase by 30% (from 1.0 to 1.3) as blossom and leaf development progressed. The application rates predicted by SPAR79 are notably smaller than those suggested in previous literature. Using Newton's law of cooling SPAR79 also predicts the maximum off time of a

pulsing cycle. Humidity does affect this determination.

Pulsed sprinkling for frost protection was carried out during six frost nights in spring 1977 and two in 1978. Eight 36-gauge chromel-alumel thermocouples measured sprinkled and unsprinkled blossom temperatures while application rate, pulsing cycle, wind speed and air temperature were simultaneously recorded during these nights. These blossom temperatures were plotted versus time. These observations illustrated that in order to provide adequate protection an appropriate application rate and pulsing cycle must be provided by the model.

Combining these results, it was concluded that by varying the distribution factor through the growing season and varying the application rate through a single frost night by pulsing, according to atmospheric parameters and ice accumulation, a significant decrease in amount of water applied may be realized. This decrease in water applied will alleviate ice buildup, water cost, soil drainage and nutrient leaching problems associated with sprinkling for frost protection.

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LIST OF SYMBOLS

- A $(2/L_i)(h_c + h_e + h_r)$, used in Businger model.
- a conversion factor for converting mass transfer to heat transfer and vapor pressure to density gradients.
- B coefficient of mass transfer.
- C heat capacity per unit area.
- $\ddot{C}$ constant in Gerber and Harrison model.
- C_p specific heat of air.
- c thermal conductivity of air.
- D characteristic dimension.
- D_v diffusion coefficient of water vapor.
- d boundary layer thickness.
- de/dT change in vapor pressure with respect to temperature.
- dm/dT change in mass of water to ice with respect to temperature.
- dR/dT change in radiation balance with respect to temperature.
- dT/dt change in temperature with respect to time.
- e average vapor pressure of e_m and e_l .
- e_a vapor pressure of air.
- e_l vapor pressure at leaf surface (T_l).
- e_m vapor pressure at leaf surface (T_m).
- e_s saturated vapor pressure of the air.
- Fe latent heat flux density.
- Gr Grashof number.
- g acceleration due to gravity.
- H total heat loss from a surface.
- $h=h_c$ coefficient of convective heat transfer.

h_e	coefficient of latent heat transfer.
h_r	coefficient of radiative heat transfer.
I	application rate.
K	convective heat transfer.
K_c	convective heat transfer at critical temperature.
K_l	convective heat transfer at leaf temperature.
k	thermal resistance.
L	latent heat of vaporization.
LE	latent heat transfer.
LE_c	latent heat transfer at critical temperature.
LE_l	latent heat transfer at leaf temperature.
$L_f = L_i$	latent heat of fusion.
Nu	Nusselt number.
P	atmospheric pressure.
P_n	chemical reactions (photosynthesis, respiration).
Pr	Prandtl number.
R	radiative heat transfer.
R_*	universal gas constant.
R_a	radiative heat transfer at air temperature.
R_c	radiative heat transfer at critical temperature.
Re	Reynolds number.
R_l	radiative heat transfer at leaf temperature.
R_w	specific gas constant for water vapor.
r_H	diffusion resistance for heat.
r_v	diffusion resistance for water vapor.
Sc	Schmidt number.
Sh	Sherwood number.

T	temperature.
T_a	air temperature.
T_b	blossom temperature.
T_c	critical temperature.
T_e	effective sky temperature.
T_{ec}	thermal expansion coefficient per degree (C).
T_g	ground temperature.
T_l	leaf temperature.
T_m	minimum tolerable temperature.
T_o	0°C.
t	time.
t_l	time required to freeze film of water on plant part.
u	kinematic viscosity.
v	wind velocity.
γ	psychrometer constant.
δ	thickness of water film.
ϵ	ratio of molecular weight of water to dry air = .622.
θ	angle between trajectory of drops and vertical.
λ	distribution factor.
ρ	density of air.
σ	Stefan Boltzmann constant.

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INTRODUCTION

The best method of frost protection is to avoid the problem if possible by good site selection. However, growing competition for good horticultural sites by homes, roads, shopping centers, factories, airports, etc., has lead to an increasing need for frost protection. Because it is colder near the ground, the tendency to produce fruit closer to the ground and in denser plantings for more efficient land use, pest control and harvesting has further increased this need.

Heating for frost protection has been relied upon for centuries. Increasing cost of fuel and its decreasing availability at any reasonable price provides incentive to increase the effectiveness of an alternative method of frost protection. Sprinkling has long been recognized as a possible alternative to the more popular heating for frost protection. In sprinkling for frost protection, heat lost from the plant part to its environment is replaced by heat released as the applied water freezes.

Two models exist which determine, from a given set of atmospheric conditions, the sprinkling rate required for successful protection (the amount of water required must supply enough heat by freezing to compensate for the heat lost by all other mechanisms, i.e., radiative, convective and evaporative heat losses). These models, one by J. A. Businger (1965) and one by J. F. Gerber and D. S. Harrison (1964), calculate the sprinkling requirement by considering the heat balance of a single horizontal leaf. Although the Gerber and Harrison model preceded the Businger model chronologically in the literature it was developed with knowledge of Businger's work as presented during the 5th

National Conference on Agricultural Meteorology in 1963. Consequently, the two models are similar.

An ideal sprinkling application rate model will accurately simulate a sprinkled orchard under frost conditions. The model's output of appropriate sprinkling rates for given atmospheric parameters must be reproducible. This output should be published so it is available to all frost protection practitioners. But none of the existing models has all these characteristics. The Gerber and Harrison model was used to produce a table of suggested application rates in Gerber and Martsolf (1965), and this table has been used successfully. However, this is because the application rates presented are, in general, overestimated. In order to reduce those problems caused by excess water applications, this table must be revised. This deficiency plus errors in both these existing models, their lack of reproducibility, exclusion of explicit consideration of humidity and the effect of ice accumulation and the quantification of a distribution factor all justify the need for further research.

In this research, existing models were critically reviewed and a refined model of the sprinkled orchard was developed. This model incorporates the consideration of humidity and ice accumulation into corrected versions of the previous models. Also, a distribution factor, a component of a factor which was previously only estimated, was more convincingly quantified. The refined model was tested by comparing its predicted sprinkling rates with those observed to be necessary for adequate protection in field studies.

LITERATURE REVIEW

Numerous investigators, among them Bagdonas (1978), Beahm and Kidder (1960), Blanc, et al. (1963), Businger (1965), Chesness, et al. (1968), Gerber and Harrison (1964), Gerber (1978), Harrison, et al. (1974), Rogers and Swift (1970), Rogers (1953), and Turrell (1973), have discussed the principles involved in sprinkling for frost protection. Hansen (1951), Kidder and Davis (1955) and Rogers (1962) discussed the practical applications of the method. Ballard and Proebsting (1972) suggested that advantages of sprinkling are significant even though risks are greater than with other frost protection methods. They stated that operational costs are lower than any other method; it is convenient and clean; and the possibility existed for multiple uses of the same system, i.e., drought control, heat suppression, fertilization, and pest control. Further, sprinkling is an energy-conserving method.

Ballard and Proebsting (1972), Gerber and Martsof (1965), Martsof (1974), Martsof and Tukey (1974), and Proebsting (1975) have pointed out disadvantages of this method. These disadvantages are: it is not precisely known when to start or stop, ice buildup causes limb damage, and the excess water causes soil drainage and nutrient leaching problems (Buchanan, et al., 1977).

When Rogers and Modlibowska (1950) began reporting their research on sprinkling as an anti-frost measure, opinions differed as to its effectiveness and practicality and little experimental evidence existed from which to make conclusions. The first known use of sprinkling for frost protection was in 1912 in the eastern United States where overhead spray protected tomato plants (Harrison, 1962). West and Edlefsen

(1917) reported unsuccessfully spraying an apricot tree in full blossom during a frost. All flowers on which ice had formed were killed, but flowers on nearby unsprayed trees were undamaged. Crowley (1925) successfully protected blueberries in frosts of 25°F (-3.9°C). Kessler (1936) was able to maintain plant temperatures at 30.2°F - 31.1°F (-1.0°C to -0.5°C) during a frost of 19.4°F to 21.2°F (-7.0°C to -6°C). Mercanton (1939) reported a successful experiment conducted by J. Gattlen in which small fruit trees, dahlias and vegetables were continuously sprinkled while air temperature remained below 0°C . No visible damage occurred and good crops were produced. Rosenberg (1974) tested sprinkling on tomatoes during a late fall frost in 1963 in Lincoln, Nebraska. The control plants were completely destroyed and the sprinkled plants survived. None of these reports stated the application rates.

Kessler and Kaempfort (1940) protected strawberries, tomatoes and potatoes by sprinkling during frosts of 26.6°F (-3.0°C) and 19.4°F (-7.0°C). They suggested application rates of 4-6 mm/hr were more than adequate and probably 1-2 mm/hr would be sufficient. Weger (1947) using 1-2 mm/hr and Wanke (1951) using 3-4 mm/hr claimed these rates gave protection in most frosts. Jeffree (1950) recommended an application rate of 0.1 inch (2.5 mm) per hour to give protection in "normal" spring frosts, down to 16°F (-8.9°C).

Koeppner (1949) protected plants in a frost of 21.2°F (-6°C) which lasted 15 hours, with application rates not exceeding 4 mm/hr. Witte (1951, 1952) concluded an application rate of 1.5 mm/hr was adequate to protect plants down to 20.1°F (-6.6°C). Roberts (1950), reporting on three years of observations on sprinkling strawberries, claimed these

plants had been protected during frosts as severe as 12°F , 13°F and 15°F (-11.1°C , -10.6°C , and -9.4°C).

Rogers and Modlibowska (1950) maintained the temperature of apple blossoms between 31°F and 32°F (-0.6°C and 0°C) during a spring frost when the air temperature fell to 26.6°F (-3.0°C) with an average application rate of 4.2 mm/hr. They also concluded that, although a single wetting would not protect a blossom for long, continuous sprinkling was unnecessary. They stated that the safe interval between wettings depended mainly on the air temperature and thickness of ice on the blossom. Rogers (1953) and Rogers, et al. (1954) continued this research by conducting experiments to show the relationship between application rate and rise in temperature for given conditions and the performance of various types of sprinklers. They suggested that, in radiation frosts with a wind speed of 2 mph (0.9 m/sec) or less, an application rate of 2 mm/hr is adequate to protect apple blossoms from an air temperature of 26°F (-3.3°C); 4 mm/hr from 23.5°F (-4.8°C); and 6 mm/hr from 21.5°F (-5.8°C). Schultz and Parks (1957), testing sprinkling on blueberry plants in Santa Cruz County, California, concluded that overhead sprinkling will give protection from freezing to almost any crop that can carry the ice load; provided drainage is adequate to prevent damage to the crop from the extra water.

Rogers and Modlibowska (1961) presented a general discussion of sprinkling describing equipment, operation, costs, risks and rewards. In 1962, Rogers and Modlibowska (1962) described a thermostatically controlled sprinkling system which successfully protected blossoms and young fruitlets of two apple varieties. Rogers, et al. (1964) reported further studies with this system. Rogers (1962) described the

procedures used at the East Malling Research Station in Kent, England in their sprinkling for frost protection research.

Knorr and Jutras (1963) explained the disastrous results of the 1962 freeze in Florida and argued that much benefit can still be obtained from warming effects of freezing water only if the application rate is appropriate. Jutras and Knorr (1963) also suggested and described a multiple use sprinkling system for citrus nurseries. Dean (1963) successfully protected citrus nursery trees using sprinkling. Harrison and Dowling (1962) reported there was no formal evidence to show what degree of frost protection could be obtained on mature citrus trees in Florida, but growers in Arizona and California reported protection down to temperatures as low as 23°F. They stated that protection from radiation frosts was likely, but protection against windborne freezes remained uncertain. Harrison (1962) presented a similar report at the 9th Annual South Florida Citrus Institute. Harrison and Gerber (1966) did not recommend sprinkling as a tested and successful method for protection of tropical fruit crops in Florida. In contrast, Austin (1974), after four seasons of experience using sprinkling for frost control in the Dowd orchards in Michigan, concluded that overhead sprinkling was effective and practical for frost control. However, he stated the best frost control method is good site selection.

Sprinkler irrigation for cold protection of strawberries in Louisiana was reported by Braud and Hawthorne (1965). They stated that strawberries can withstand a very heavy ice load with no damage to the plants. Locascio, et al. (1967) also reported successful protection of strawberries by sprinkling in Florida. Gubbels (1969) reported successful protection of peas, potatoes and bean plants using

0.9-2.9 mm/hr application rates. Although an accepted practice for almonds, peaches, grapes (Meyer, 1969), artichokes and strawberries in California, Robinson (1971) suggested caution in using sprinkling on alfalfa and lettuce crops, especially as regards the choice of the type of sprinkler used. In 1972, an anonymous report of sprinkling being used on lime and avocado groves in Florida appeared in American Fruit Grower. The permanent overhead sprinkler system described doubled in use for frost protection and drought control. The plans for this operation included irrigating 3000 acres.

Hewett and Hawkins (1968) found sprinkling to be a successful means of protecting apricot buds, blossoms and young fruit from frost. They used three application rates (0.25, 0.31 and 0.38 cm/hr). Unrath (1975) conducted two years of orchard testing and determined that the amount of freeze protection depended on the amount of water applied and wind speed conditions. Unrath also described a versatile electronic controller for overtree irrigation systems activated under both cooling and frost protection conditions. He stated that the initial investment cost of an overtree irrigation system which can be used for both frost protection and drought control would be \$1000-\$1200 per acre.

Modlibowska (1975) reported 2.5 mm/hr gave complete protection of James Grieve and Cox's Orange Pippin apple varieties during a May, 1957 frost in which screen temperature fell to -2.6°C . Sprinkling to protect apple production in Washington's Yakima Valley has also been very successful (Miller, 1978). Bagdonas (1978) included a small section on sprinkling in his review of frost protection methods in Europe and Asia. The observations and results he described are similar and, in some cases, identical to those already discussed.

Braud, et al. (1977) conducted a study of different water application methods to devise and evaluate water distribution methods with freeze protection as the primary function. They stated that the water must be delivered to the foliage and branches in a manner which allows the development of a self-supporting ice mass. They concluded that a drilled lateral pipe providing direct spray upward gave the best protection. Commercial spray nozzles providing downward spray worked well, but they required riser pipe which was a source of trouble. Brewer (1973) suggested low sprinklers as an economic alternative to heating and wind machines in California, by warning that overhead sprinkling would cause serious ice damage.

Several publications which describe sprinkling systems in detail and how to buy, install and operate them are available. Among these are those by Dowling (1958), Schultz and Lider (1968) and Meyer and Marsh (1972).

In 1964, Wheaton and Kidder (1964) conducted experiments to determine the effect of evaporation on frost protection by sprinkling. They concluded that wind increased the quantity of heat lost by evaporation and cooled the temperature of a wet or ice-covered object below air temperature. Once all the water applied had frozen, the temperature of the plant part fell, approaching the wet bulb temperature. The wet bulb temperature is lower than dry bulb temperature and usually below the temperature at which damage will occur. Therefore, once sprinkling has been started, it must continue until the ice continues to melt when it is turned off (Martsolf, 1974).

This effect of evaporation was evident after the December 1962 freeze in Florida (Gerber and Harrison, 1964; Gerber and Martsolf,

1965). A survey after the freeze showed over 4,000 acres almost completely destroyed because inadequate application rates allowed tree parts to cool toward the wet bulb temperature, resulting in more damage in sprinkled groves than in unsprinkled groves (Dean, 1963). Similar damage occurred during the 1962 freeze in Riverside County, California where sprinkling was generally unsuccessful (Miller, 1963).

The disastrous results of the 1962 freezes proved the critical need for growers to know the capability of their particular system. A sprinkling system which cannot protect under the expected circumstances is better not turned on at all (Martsolf, 1974). Unfortunately, most sprinkling systems now in operation are not equipped for adjustable application rates. They are designed for worst-case circumstances which results in the application of excess water for all other cases.

Sprinkling rates suggested for successful protection (Gerber and Martsolf, 1965; Businger, 1965; Gerber and Harrison, 1964) have been determined from theoretical computations. The values in the table presented by Gerber and Martsolf (1965) which suggest sprinkling rates for a range of temperature and wind conditions expected during frosts were determined by using the model of Gerber and Harrison (1964). Merva (1975) developed the same equation for determining the rate at which energy must be transferred to the leaf as Businger (1965) did. Merva's development was more explicitly described, but he did not present independently determined results. Instead he presented Businger's (1965) Figure 5, values of mass transfer per degree of temperature required for given wind speeds. Merva did not discuss intermittent sprinkling as Businger (1965) and Gerber and Harrison (1964) did.

Chesness, et al. (1968) also presented a sprinkling rate equation

using a heat balance on a leaf model. Their leaf model was a thin flat plate, upon which nine predetermined conditions were imposed. Some of these conditions were unrealistic. For example, radiant exchange was considered negligible; however, radiant cooling is a major mechanism on frost nights. Also, continuous water application and continuous flowing water was given for the upper surface of the leaf with a dry under side, but the application of water in a sprinkled orchard is not continuous due to the rotating sprinkler heads, and Gerber and Martsolf (1965) state that if only the top part of the leaves and branches are covered with ice, damage can be expected to occur. Further, ice was prevented from forming on the model and this is the major source of the heat provided by the sprinkling method. Their results showed that heat-transfer equations based on the assumptions of constant surface temperature do not accurately predict the convective heat losses from the unwetted underside of the leaf model. They suggested that the combination of theory and field observations is necessary to obtain the final prediction equations.

Simultaneous with the research to be described here, Barfield and Lacey (1978) developed a model to predict sprinkling application rates for nighttime radiation frost protection. They determined the amount of water necessary to raise the plant temperature to air temperature and found it to be a function of the temperature difference between plant and air and the vapor pressure deficit.

A complex geometrical model of an orchard, the Orchard Foliage Temperature (OFT) model, which considers all exchanges of energy between a plant and its environment plus the effect of an array of orchard heaters was developed for use in the heating method of frost protection

(Welles, et al., 1977, 1978; Welles, 1978). The model was designed to assess the effect of various heater configurations on frost protection damage and thereby minimize fuel consumption. The model output is the fraction of the foliage with temperature below a given value, so it can also be used as a guide to frost thinning. The sophistication and complexity of the OFT make it more difficult to use than existing sprinkling models.

Martsolf (1974) and others (Gerber and Harrison, 1964) have noted the need for sprinkling systems with adjustable application rates, so that water is conserved. Von Pogrell and Kidder (1959) stated that an "excessive application is wasteful, may damage the soil structure and leach out plant nutrients." They found that an increase in protection was obtained with higher application rates, holding the application intervals constant or an increase in frequency of sprinkling, holding the application rate constant. In laboratory tests, Beahm and Kidder (1960) also observed that the same quantity of water applied more frequently in small doses resulted in higher efficiency. They attributed this to a higher percentage of the total water applied adhering to the plant part providing more heat as it froze. They also noted that when the amount of water applied was below that necessary to maintain a constant plant temperature all the water freezes and there is a dry period before the next application of water during which the plant cools toward the wet bulb temperature. Burckhardt (1963) described this work of von Pogrell and Kidder in his chapter on sprinkling for frost protection in Frostschutz im Pflanzenbau. Wheaton and Kidder (1965) also concluded that increasing the frequency of application lowered the temperature to which protection was possible and reduced the temperature

fluctuation of the plant part.

Both Businger (1965) and Gerber and Harrison (1964) presented equations which determine the time period between water applications so that the plant part does not cool below its critical temperature (also termed minimum tolerable temperature and minimum permissible temperature). Critical temperature is the temperature below which, of the plant parts held for 30 minutes or more, a percent will be killed, e.g., if for blossoms $T_{90} = -2.2^{\circ}\text{C}$ then, of the blossoms held below -2.2°C for 30 minutes or more, 90% will be killed. Critical temperature for each species depends on plant variety and stage of development. Water within a plant is at a water potential lower than that of free water so intracellular freezing which causes damage generally does not occur at temperatures above -2°C . This is why critical temperatures are generally below 0°C .

An interval between wettings naturally occurs in systems currently in use because the sprinkler heads rotate. From analogy with pipeline heating systems, Martisolf (1974) suggested "pulsing" the system to achieve greater efficiency, i.e., use less water for adequate protection. Pulsing takes advantage of the margin between 0°C and the critical temperature by turning the system off between wettings and allowing the plant part to cool below 0°C but not go below the critical temperature (Perry, et al., 1977). The "off" period must be sufficiently long to conserve water, but not so long that the plant part cools below its critical temperature. Similarly, the "on" period must be short enough to conserve water, but long enough to distribute the water sufficiently (Perry, et al., 1977). Time variability is provided by pulsing the system, i.e., the application rate may be adjusted to

atmospheric conditions (Gerber and Martsolf, 1978b).

Spatial variability is also important. Generally, it has been assumed that the distribution of droplets in space, i.e., the application rate, should be uniform over the treated area (Businger, 1965; Gerber and Harrison, 1964). However, applying water only where it is needed, i.e., at the trees, and not over the entire orchard may further decrease the water required for successful protection (Martsolf, 1974; Perry, et al., 1977). The system used in this research provides an application rate variable in both time and space.

EVALUATION OF EXISTING MODELS

Currently application rates are considered in terms of a uniform rate in space and time. Two models, one developed by Businger (1965) and the second, a subsequent adaptation by Gerber and Harrison (1964), determine a predicted sprinkling rate for successful protection given the input parameters: plant part temperature, minimum tolerable temperature, air temperature, wind speed and plant part size. Both also determine the minimum time period between water applications for a successful pulsed sprinkling rate, i.e., total off period of a pulsing cycle. Thus there are two primary outputs from each model; the predicted sprinkling rate and the maximum time between water applications or total off time of the pulsing cycle. These key publications are the basis of the current suggested sprinkling requirements. Both consider the heat balance of a single flat surface or sphere and extrapolate over the entire orchard.

Businger Model

Businger's model, presented as a flow chart in Figure 1, has been programmed in FORTRAN, see Appendix A. In order to test the programming of Businger's model (Figure 5, Businger, 1965) his variable "A" versus wind speed relationship was recreated using the programmed model (Appendix A) output. The results are presented in Figure 2. Although not exact, the two sets of graphs are reasonably close. After communication with Dr. J. A. Businger (1978), it was assumed the FORTRAN version of Businger's model in Appendix A is the same as the original framework for purposes of this work. According to the same communication (Businger, 1978), Businger used the Nusselt numbers as

Figure 1. Flow chart of Businger (1965) sprinkling rate model as programmed in Appendix A.

Figure 2. Sprinkling rate required per degree C temperature difference between plant part and minimum tolerable temperature as a function of wind speed for characteristic sizes of vulnerable plant parts. "A" was calculated by programmed Businger model (see Appendix A). The dashed lines were traced from Businger's Figure 5 (1965).

given in his Figure 4 (Businger, 1965), starting with 2.0 and then using the curve for cylinders from McAdams (1954).

Some characteristics of Businger's model (1965) follow. Businger stated that when the surface of the leaf is wet, the vapor pressure at the surface is equal to the saturation vapor pressure at the leaf temperature. In this case, he declared the coefficient of mass transfer, B , to be a function of wind speed and shape of the leaf as is h , the coefficient of sensible heat transfer. Therefore, he assumed the ratio B/h to be constant for a given range of temperatures as follows:

$$B/h = 6.3 \times 10^{-5} \text{ cm}^2 \text{ dyn}^{-1} \text{ } ^\circ\text{C}$$

at normal temperature and pressure. Thus, determining h also determined B . The calculation of this constant is not obvious from Businger's (1965) publication. A verification of this constant was carried out as follows. Businger presents equation (4) to express the latent heat flux density. It is restated here

$$Fe = \frac{LB (e_1 - e_a)}{R_w T}$$

Similarly, Monteith (1973) presents equation (11.6) as restated here.

$$\begin{aligned} H &= K + LE \\ &= \frac{\rho C_p (T_2 - T_1)}{r_H} + \frac{\rho C_p (e_2 - e_1)}{r_v} \end{aligned}$$

Equating Fe and LE the expressions for latent heat flux density from Businger and Monteith, one can solve for B and then the constant, B/h ,

as follows:

$$\frac{LB}{R_w T} = \frac{\rho C_p}{\gamma r_v}$$

$$B = \frac{\rho C_p R_w T}{L \gamma r_v}$$

Substituting $\gamma = (C_p P) / (L \epsilon)$ and $h = (\rho C_p) / (r_H)$ from Monteith (1973),

$$B/h = (r_H / r_v) ((R_w T \epsilon) / (C_p P))$$

If $R_w = 0.461 \text{ J g}^{-1} \text{ } ^\circ\text{K}^{-1}$,

$C_p = 1.81 \text{ J g}^{-1} \text{ } ^\circ\text{K}^{-1}$,

$\epsilon = 0.622$,

$P = 1000 \text{ mb} = 10^6 \text{ dyn cm}^{-2}$,

$T = 273^\circ\text{K}$ and

$r_H / r_v = 1.0$ (Monteith (1973), page 136 and 220) then

$$B/h = 7.8 \times 10^{-5} \text{ cm}^2 \text{ dyn}^{-1} \text{ } ^\circ\text{C}.$$

This value of B/h is 24% larger than Businger's value.

Businger also stated that for temperatures near and slightly below 0°C , h_e (the coefficient of latent heat transfer) is equal to approximately $0.46 h$, i.e.

$$\frac{h_e}{h} = 0.46.$$

He used the following equation to calculate this ratio.

$$h_e = \frac{L^2 e B}{R_w^2 T_m^3}$$

Businger may have used $L=540 \text{ cal/g}$, which will result in $h_e=0.46 h$. But if the value $L=597 \text{ cal/g}$ for the latent heat of vaporization at 0°C and the value of B/h given above is used, the relationship becomes $h_e = 0.69 h$, see Appendix B. This means the coefficient of latent heat

transfer is approximately 70% of the coefficient of convective heat transfer for a wet surface under frost conditions. The 0.46 h in Businger's publication is an error. It should be $h_e = 0.69$ h.

Following equation (9) in Businger (1965) there are two typesetting mistakes. An exponent of -1 has been left off the C in both the calorie and erg version of the units of h_r .

More errors, two of which are apparently typesetting mistakes, occur in Businger's (1965) 'Intermittent Sprinkling' section.

First, in an unnumbered equation (between equations (11) and (12)) for the difference between the total time period of the sprinkling cycle and the time required to freeze the film of water an " L_i " was omitted from the denominator of the R.H. side. Second, in the units given for C, the heat capacity per unit leaf area, in the example of the application of the equation for the total period of the sprinkling cycle, a C^{-1} was omitted.

Third, the given results of the published example do not correspond exactly with results obtained here. The value $t=1.36$ minutes was obtained versus Businger's $t=1.5$ minutes, see Appendix C.

Equation (11) which Businger presents for determining t, the total off period of the sprinkling cycle, is apparently based on Newton's law of cooling (Purcell (1972), pg. 866-867). Businger's equation (11) may be developed by transient heat transfer analysis as described in Holman (1963) (page 56-59). Holman (1963) describes a lumped-heat-capacity method by which he determines his equation (4.2) to be a solution. Holman's equation (4.2) is equal to Businger's equation (11). The solution presented in Holman (1963) constitutes an independent verification of Businger's equation (11). Businger (1965) used T_1 as

the temperature of the plant part when equilibrium is reached, but Wheaton and Kidder (1964) stated the ice coated plant part reaches the wet bulb temperature, T_{wb} , which is below T_1 (see page 8). Using T_1 as the equilibrium temperature will cause an underestimate in the calculation of the total off period and thereby suggest the use of more water by having the sprinklers on for a longer time.

Gerber and Harrison Model

The Gerber and Harrison model (1964) was developed with knowledge of Businger's work. The following discussion of errors in the Gerber and Harrison (1964) publication developed through communication with J. F. Gerber through J. D. Martsolf (Gerber and Martsolf, 1978a). Therefore, the errors designated to be typesetting errors are known to be just that. A discussion of these errors in the Gerber and Harrison (1964) model follow. First, equation (3) defining latent heat flux, LE, is rearranged using the substitution $h_e = ah_c (de/dT) = (ah_c Le)/(R_w T^2)$. This substitution term for h_c was omitted from the first term on the R.H. side of the resulting unnumbered equation which directly follows equation (3) in the publication. Also the "L" latent heat of evaporation appears as L_f , latent heat of freezing, and the exponent of T is incorrectly given as -2. Gerber and Harrison's unnumbered equation after equation (3) should read

$$LE = -((e_s - e_a)(h_e R_w T^2 / Le) - 2h_e(T_a - T_1))$$

Second, similar corrections must be made in equations (5) and (6).

Equation (5) should read:

$$0 = C(dT/dt) + (R_a - 2h_r(T_a - T_1)) - ((e_s - e_a)(h_e R_w T^2 / Le) - 2h_e(T_a - T_1)) - 2h_c(T_a - T_1)$$

Equation (6) should read:

$$C(dT/dt) = 0 = -IL_f + (R_a - 2h_r(T_a - T_m)) - ((e_s - e_a)(h_e R_w T^2 / Le) - 2h_e(T_a - T_m)) - 2h_c(T_a - T_m)$$

Third, equation (11) (the unnumbered equation between (10) and (12)) is a set of standard cooling formulae. A missing minus sign and small "c" where a capital "C" should be are the errors in the first formula. Also the stipulation $t < t_1$ is reversed for both formulae. They

should read:

$$T = T_o \exp(-((L_2 \delta / C)(t - t_1))) \quad \text{for } t > t_1$$

$$T = T_o \quad \text{for } t < t_1$$

Finally, equation (13) is the equation for the total period for a pulsing cycle. The digit, "2", is missing. Equation (13) should read:

$$t = k(L_f 2 \delta) / (T_o - T_a) + (C / L_f 2 \delta) \ln(T_o / T_m)$$

The third and final error involves $(L_1 2 \delta) / C$, the constant in Gerber and Harrison's cooling formula (equation 11). The dimensions of this constant should be sec^{-1} to obtain a dimensionless exponent, but $(L_1 2 \delta) / C$ has dimensions $^{\circ}\text{C}$. This is an error. To make this constant the same as that used by Businger (1965) and Holman (1963), Gerber and Harrison (1964) should have used $1/(kC)$, where k is their thermal resistance having units of $\text{cm}^2 \text{ min cal}^{-1} ^{\circ}\text{C}$ and C is heat capacity in units of $\text{cal cm}^{-2} ^{\circ}\text{C}^{-1}$. Substituting $(1/(kC))$ for $(L_1 2 \delta) / C$ in equation (11) in Gerber and Harrison (1964) will correct this error. The same correction must also be incorporated into equation (13).

Results of the Gerber and Harrison model have been published as Table 5 in Gerber and Martsolf (1965), a table of precipitation rates for various wind speeds and temperatures of a dry leaf. The Gerber and Harrison model, presented as a flow chart in Figure 3, was programmed in FORTRAN as was Businger's, see Appendix D. To verify this programming, Table 5 in Gerber and Martsolf (1965) was recreated from the program. The resulting table and the data from Table 5 of Gerber and Martsolf (1965) are given as Table 1.

Through personal communication with the authors (Gerber and Martsolf, 1978a) it was learned that a lower limit of 0.25 cm/hr was chosen and rounding was performed. The values produced by the

Figure 3. Flow chart of Gerber and Harrison (1964) sprinkling rate model as programmed in Appendix D.

Table 1. Composite table of application rates (cm/hr) from programmed Gerber and Harrison (1964) model (GH) (see Appendix D) and Table 5 of Gerber and Martsof (1965) (GM). Asterisk designates the pair is considered equal.

Temp. of Dry Leaf °C	WIND SPEED IN M/SEC											
	0 to .5		1 to 2		2.5 to 4		5 to 7		9 to 11		15	
	GM	GH	GM	GH	GM	GH	GM	GH	GM	GH	GM	GH
-2.8	.25 *	.18	.25	.39	.25	.56	.25	.75	.50	.96	.75	1.17
-3.3	.25 *	.21	.25	.46	.36	.67	.51	.89	1.01	1.15	1.53*	1.40
-4.4	.25 *	.28	.41	.61	.76	.88	1.02	1.18	2.04	1.51	4.06	1.84
-5.6	.30 *	.34	.61	.76	1.27	1.09	1.52*	1.46	3.04	1.87	4.56	2.27
-6.7	.41 *	.41	.76	.90	1.52	1.29	2.03	1.73	4.06	2.22	6.09	2.70
-7.8	.51 *	.47	1.02*	1.04	1.78	1.49	2.54	2.00	5.08	2.56	7.62	3.12
-9.4	.66	.56	1.27*	1.25	2.29	1.79	3.30	2.40	6.60	3.07	9.90	3.74
-11.7	.86	.69	1.78	1.52	3.05	2.18	4.32	2.92	8.64	3.73	12.96	4.54

programmed version (Appendix D) of the Gerber and Harrison model (1964) were taken to be equal to the values in Gerber and Martsolf (1965) if: 1) they were less than 0.25 cm/hr when Gerber and Martsolf (1965) used 0.25; 2) they were within 10% of the Gerber and Martsolf (1965) value or; 3) when they were rounded off to the nearest tenth of a cm they equalled the Gerber and Martsolf (1965) value rounded to the nearest tenth of a cm. Using these criteria only 10 of the 48 entries (21%) were verified. However, it is important to note that Table 5 in Gerber and Martsolf (1965) has been used successfully since its publication. Although most of the values for wind speeds greater than 5 m/sec are overestimated, this portion of the table represents very extreme and rare frost conditions, and so has had very limited use. If one considers the portion of the table for wind speeds less than 5 m/sec, 8 of the 24 entries (33%) were verified. It is this portion of the table which has been used for designing the constant application rate systems in use today.

It appears from the table that Gerber and Martsolf took their predicted rate for 5 to 7 m/sec and doubled and tripled it for the 9 to 11 and 15 m/sec wind speed rates, respectively, i.e. they appear to have assumed the relationship between wind and application rate to be linear. However, Gerber and Martsolf (1978a) state that this was not the case. By comparing the table values with the values in Figure 3 of Gerber and Harrison (1964), it is apparent that the two do not coincide. It was surmised that the coefficient of sensible heat transfer was varied for different wind speed intervals, but it is not clear how. The relationship between wind speed and application rate is not linear because the heat transfer rate increases with the square root of the

wind speed, not linearly (Gates, 1962). Therefore, the Gerber and Harrison model in the form in which it was published by them in 1964 probably was not used to create Table 5 in Gerber and Martsolf (1965).

One or both of two situations seem most likely to have resulted in the differences. 1) Hand calculation may have contributed to some inaccuracy and/or 2) some assumptions may have been made that were not declared in the Gerber and Harrison (1964) article.

Both models incorporate a factor to allow for plant parts being exposed to different surroundings, i.e., some "seeing" sky, others ground, some of the water running off the plant parts and the plant parts being different shapes and sizes. This factor referred to as a multiplier by Gerber and Harrison (1964) and a factor by Businger (1965), was symbolized by α in both publications. Merva (1975) also used α , referring to it as a safety factor and naming it the runoff coefficient. This factor is an important one and yet has not been quantitatively determined in any of the literature to date. Failure to determine this factor is not surprising when one considers the complexity of the system it seeks to describe. The channeling of water into the tree canopy creates non-uniform coverage within the tree, causing variations in the blossom temperatures. These variations are apparent in the data taken during a 1977 spring frost (Figure 4). This is especially enlightening because the literature implies uniformity of blossom temperatures with adequate coverage (Businger, 1965; Gerber and Martsolf, 1965; Gerber and Harrison, 1964). However, note that although the blossom temperatures are quite variable they are, on the whole, above the critical level. This factor will be discussed again in the section entitled, "Development of SPAR79 Model."

Figure 4. Blossom temperatures of six sprinkled blossoms vs. time during sprinkling.

REFINED MODEL

Development of SPAR79 Model

SPAR79 (SPrinkling Application Rate 1979) model was refined from the two models evaluated in the previous section, i.e., the Businger (1965) and Gerber and Harrison (1964) models.

The energy budget approach provides the information necessary to determine the rate of heat lost by the plant part which must be replaced by the latent heat of fusion, liberated by the freezing of the applied water, in order to maintain the plant part at its critical temperature. The critical temperatures used in this work were taken from Ballard, et al. (1973).

Leaves, twigs, buds, blossoms and young fruit are typical plant parts which are damaged by frost. Blossoms and young fruit are especially important when deciduous crops such as apples are considered. However, the results obtained for a leaf, simulated by a flat horizontal plate, can also be applied to the spherically shaped buds, blossoms and fruit or cylindrically shaped twigs.

Conservation of mass and energy dictate that, at any point in time and space, the input and output of the heat transfer processes, the net chemical reactions (photosynthesis, respiration) and the warming or cooling of the plant must balance (Raschke, 1960) as the following equation illustrates:

$$LE + K + R + P_n + dT/dt = 0 \quad (1)$$

where LE=latent heat transfer (latent heat of vaporization multiplied by rate of evaporation),

K =convective heat transfer,

R =radiative heat transfer,

P_n =net photosynthesis and respiration, and

dT/dt =warming or cooling of the plant.

Photosynthesis rarely uses more than 2% of the absorbed radiation during the daytime. Under frost conditions (night time) net photosynthesis may be assumed to be zero. Respiration rarely results in measurable temperature effects. Therefore, P_n can be deleted simplifying the problem. Three methods of energy transfer are considered to be acting on the plant part. Rearranging equation (1) yields

$$-dT/dt = LE + K + R \quad (2)$$

The radiant energy balance at the dry leaf temperature (T_1), R_1 , may be described as follows:

$$\sigma T_e^4 + \sigma T_g^4 - 2\sigma T_1^4 = R_1 \quad (3)$$

where T_e =effective sky temperature,

T_g =ground temperature,

T_1 =leaf temperature and

σ =Stefan-Boltzmann constant (1.355×10^{-12} cal/(cm² sec °K⁴)).

At the critical temperature, T_c , equation (3) becomes

$$\sigma T_e^4 + \sigma T_g^4 - 2\sigma T_c^4 = R_c \quad (4)$$

The difference in the radiant balance at the dry leaf and critical temperature is R, the rate at which the energy lost by radiation must be replaced to maintain the critical temperature. Therefore

$$R = R_1 - R_c = 2\sigma(T_c^4 - T_1^4) \quad (5)$$

To relate this to the actual temperature difference rather than the difference of the fourth powers of the temperatures, many investigators (Raschke, 1960; Gerber and Harrison, 1964; Merva, 1975) suggest the

following approach. Assume the leaf is at the air temperature and then correct this by adding the product of the tangent of the radiation temperature curve and the difference in leaf and air temperature:

$$\begin{aligned} R_l &= R_a + 2(dR/dT)(T_a - T_l) \\ &= R_a + 2h_r(T_a - T_l) \end{aligned} \quad (6)$$

where $h_r = dR/dT = 4\sigma T_a^3$. Then

$$R_l - R_a = 2h_r(T_a - T_l) \quad (7)$$

Similarly,

$$R_c - R_a = 2h_r(T_a - T_c) \quad (8)$$

Subtracting (8) from (7) yields

$$R = R_l - R_c = 2h_r(T_c - T_l) \quad (9)$$

Sensible heat transfer may be determined from the familiar convective heat transfer equation:

$$K_l = -2h_c(T_l - T_a) \quad (10)$$

and

$$K_c = -2h_c(T_c - T_a) \quad (11)$$

therefore

$$K = K_l - K_c = 2h_c(T_c - T_l) \quad (12)$$

where h_c is the convective heat transfer coefficient. There are numerous sources in which one can find methods for determining h_c (Businger, 1965; Gates, 1962; McAdams, 1954; Merva, 1975; Monteith, 1973). The following procedure follows methods described by Monteith (1973) and Gates (1962).

The coefficient h_c forms part of the Nusselt number, Nu , a nondimensional value describing the ratio of the characteristic dimension D , to the boundary layer thickness, d . Since $d = c/h_c$ (Monteith, 1973),

$$h_c = \frac{cNu}{D} \quad (13)$$

where c is the thermal conductivity of air (at 0°C , $c=5.78 \times 10^{-5}$ cal $\text{cm}^{-1}\text{sec}^{-1} \text{ } ^\circ\text{C}^{-1}$). Gates (1962) (also see Monteith (1973) Eq. 9.3) presents the following evaluation for Nu for the case of a flat plate in forced convection in laminar flow:

$$Nu = .664(Re)^{1/2}(Pr)^{1/3} \quad (14)$$

where Re =Reynolds number = $(vD)/u$ (v =wind velocity, u =kinematic viscosity= $0.133 \text{ cm}^2/\text{sec}$) and

$$Pr=\text{Prandtl number}=(C_p \rho u/k).$$

Once the Nusselt number has been determined h_c may be calculated from equation (13).

Monteith (1973) (Table A.5, page 224) and McAdams (1954) (page 259-260) present equations to determine Nu for cylinders and spheres in forced convection. These are useful in considering twigs (cylinders) and blossoms or young fruit (spheres).

The methods of determining the radiative and convective heat transfer rates described above are not significantly different from those used by Businger (1965) and Gerber and Harrison (1964), but several of the evaluations have been made explicit. However, the method of determining the rate of latent heat transfer deviates appreciably from previous models.

The rate of latent heat transfer depends on the rate at which vapor can be transferred across the boundary layer. Monteith (1973) (equation 11.6) stated that, if the state of the surface is given by T_1 and e_1 and the state of the air by T_a and e_a , the latent heat loss from the surface is:

$$LE = (2\rho C_p / \gamma)((e_1 - e_a) / r_v) \quad (15)$$

where ρ =density of air at $0^\circ\text{C}=1.292\text{kg/m}^3$;

C_p =specific heat of air at $0^\circ\text{C}=1.01\text{ J/(g}^\circ\text{C)}$;

γ =psychrometer constant= $C_p P / L\varepsilon = (1.01\text{ J/(g}^\circ\text{C)})(1000\text{ mbar}) /$

$((2501\text{ J/g})(.622)) = .646\text{ mbar}^\circ\text{C}^{-1}$ at 0°C ;

P =atmospheric pressure;

ε =ratio of the molecular weight of water vapor to dry

air = .622;

e_1 =saturation vapor pressure at the leaf surface;

e_a =vapor pressure of the air;

r_v =diffusion resistance for water vapor.

Equation (15) reduces to the following when components of γ and the equation of state ($P=\rho R_s T$) are substituted

$$LE = (L\varepsilon / R T r_v)(e_1 - e_a) \quad (16)$$

$$r_v = d / (D_v \text{Sh}) \quad (\text{Monteith, 1973}) \quad (17)$$

where d =characteristic size of the plant part,

D_v =diffusion coefficient of water vapor = $0.212\text{ cm}^2/\text{sec}$ and

Sh =Sherwood number.

The Sherwood number is a non-dimensional parameter related to mass transfer in a moving air stream in the same manner that the Nusselt number is related to convective heat transfer. It is the ratio of actual mass transfer to the rate of transfer that would occur if the same concentration difference existed across a layer of still air. Monteith (1973) evaluates Sh in his equation 9.2 as follows:

$$\text{Sh} = .664 \text{Re}^{1/2} \text{Sc}^{1/3} \quad (18)$$

where Sc =Schmidt number= u/D_v (Monteith, 1973, Table A.2).

The saturation vapor pressure at the leaf surface is determined

from an empirical relationship obtained from Thomson (1977):

$$e_1 = 6.11 \exp((17.269T_1)/(T_1+237.30)) \quad (19)$$

which determines e_1 in mbar. Therefore,

$$LE_c - LE_1 = LE = (2\rho C_p / \gamma r_v)(e_c - e_1) \quad (20)$$

Equation (20) suggests that the humidity of the air will not be directly related to the amount of latent heat that must be replaced by the heat of fusion. The humidity of the air affects the two quantities (LE_c and LE_1) equally so when the difference is taken its effect cancels out. This same conclusion was reached implicitly by Businger (1965) and Gerber and Harrison (1964) but they did not present it explicitly. Because it was not explicitly handled in the literature, humidity was believed to be an aspect of the sprinkled orchard models, which had not been considered (Martsolf and Gerber, 1978a; Barfield and Lacey, 1978). Barfield and Lacey (1978) developed an equation showing that the latent heat flux from a leaf occurs due to the temperature difference between the leaf and air as well as the vapor pressure deficit of the air. However, Barfield and Lacey (1978) determined the sprinkling rate required to raise the leaf temperature to air temperature, i.e., replace all the heat being lost from the leaf to its environment as it cools. Thus their equation for latent heat flux rightfully involved the actual vapor pressure of the air, i.e., humidity. However, it has already been explained that to successfully protect the plant part it need only be raised to the critical temperature, so only the difference between the energy lost at the critical and actual temperature must be supplied by the heat of fusion.

Combining equations (9), (12) and (15) into equation (2) results in

$$-dT/dt = 2((\rho C_p / \gamma r_v)(e_c - e_1)) + (h_c + h_r)(T_c - T_1) \quad (21)$$

If dT/dt is to be zero a sufficient quantity of heat must be supplied through the heat of fusion, i.e.,

$$I = L_1 dm/dt \quad (22)$$

where dm/dt is the rate at which water freezes to the plant part per unit horizontal area and I is minimum sprinkling rate. A distribution factor, λ , may be incorporated to account for nonuniform coverage. This distribution factor is a component of the α factor used by Businger (1965), Gerber and Harrison (1964) and Merva (1975). Therefore,

$$I = \lambda L_1 dm/dt = \lambda dT/dt \quad (23)$$

or

$$I = \lambda dm/dt = (\lambda dT/dt)/L_1 \quad (24)$$

where I is minimum sprinkling rate in cm/hr required for successful frost protection.

If blossoms are considered, Businger (1965) stated equation (24) should be multiplied by a factor of 2 to account for the spherical object rather than a flat plate. He argued convincingly that a spherical object will intercept more of the applied water than a flat plate if the falling drops have a horizontal velocity component. The minimum sprinkling rate may be modified to account for this.

$$I = 2\cos\theta((\lambda dT/dt)/L_1) \quad (25)$$

where θ is the angle between the trajectory of the drops and the vertical. However, in many cases $2\cos\theta$ will be close to one and the uncertainty may be incorporated into the distribution factor. Therefore, equation (24) was selected as appropriate.

The need to quantitatively describe the distribution factor is documented in the literature (Gerber and Harrison, 1964; Businger, 1965). To do this, data were obtained from a field test described in

Jarrett, et al. (1978). These data were observed application rates in a 75-point, three-dimensional grid within a tree canopy during sprinkling. These observations were repeated at three stages of leaf and blossom development ranging from tight cluster to post-bloom (Ballard, et al., 1973) over a period of 10 days in May, 1978 (Table 2). These rates observed in the field (I_f) were divided by rates identically observed in a laboratory without the presence of the tree (I_o). The result was a distribution of the amount of water actually applied relative to the amount of water applied without interference by the tree canopy, i.e., a distribution of fractions, (I_f/I_o). The reciprocal of the average fraction (I_o/I_f) was taken to be the distribution factor for 50% protection. If this reciprocal was less than 1.0 the distribution factor was taken to be 1.0, (Table 2). After ranking the fractions from low to high, the value above which 90% of the fractions were ranked was determined to be the distribution factor for 90% protection. The average fractions greater than 1.0 are due to the channeling of water within the canopy. The distribution factor increases as blossom and leaf development proceed.

Differences between average fractions at a given stage of development were significant. Duncan's modified least significant test determined the average fractions at stage 4-6 and 7-8 were not significantly different from each other but were significantly different from stage 9.

To determine the maximum off time, t , for a pulsing cycle Businger's equation (12) (Businger, 1965) was modified by replacing T_1 with T_c in determining t_1 , time required to freeze the film of water, and replacing T_1 with T_{wb} in the determination of t_2 , time required to

Table 2. Average fraction and distribution factor for 50% and 90% protection as a function of stage of development.

<u>STAGE OF DEVELOP.</u>	<u>AVERAGE FRACTION*</u>	<u>DISTRIBUTION FACTOR</u>	
		<u>(50%)</u>	<u>(90%)</u>
4-6	1.21	1.0	1.8
7-8	1.09	1.0	2.7
9	0.77	1.3	3.7

4-6 = Tight cluster to full pink

7-8 = First to full bloom

9 = Post-bloom

* $(\text{amount of water applied in field}) / (\text{amount of water applied in laboratory without trees})$

cool the ice coated plant part to its critical temperature. The resulting equation for t is:

$$t = \frac{1}{A} \left\{ \frac{0.06}{T_o - T_c} + \frac{C}{L_i} \ln \frac{T_o - T_{wb}}{T_c - T_{wb}} \right\} \quad (26)$$

where $h_e = LE/(T_c - T_l)$

$A = (2/L_i)(h_r + h_c + h_e)$

$T_o = 0^\circ\text{C}.$

Outputs of SPAR79 Model

The SPAR79 model, presented in a flow chart in Figure 5, was programmed in FORTRAN. The listing appears in Appendix E. The subsequent predicted sprinkling rates follow.

Predicted Sprinkling Rates and Off Times for Pulsing Cycle

A table similar to Table 5 in Gerber and Martsof (1965) has been produced from this model (Table 3). For this table the critical temperature was taken to be -2.8°C (27°F) which is the critical temperature for 10% kill for Golden Delicious apples during the tight cluster to post bloom stage (Ballard, et al., 1973); air temperature was set equal to dry leaf temperature plus 2.2°C (4°F), a typical difference for radiation frost nights (Gerber and Martsof, 1965; Landsberg, et al., 1974); characteristic plant part size was set at 0.2 and 2.0 cm; and the distribution factor was set at 1.0. This designation of the distribution factor equal to 1.0 allows the table to be used throughout the growing season as the distribution factor changes by simply

Figure 5. Flow chart of SPAR79 model as programmed in Appendix E.

Table 3. SPAR79 model output: Predicted application rates for two characteristic sizes, D=0.2 and 2.0 cm; critical temperature, $T_c = -2.8^\circ\text{C}$ (27°F); air temperature, $T_a = T_l + 2.2^\circ\text{C}$; and distribution factor, $\lambda = 1.0$.

Application Rate Required for Frost Protection
In CM per HOUR

Wind Speed in M/SEC

T_l ($^\circ\text{C}$)	0 - 0.5		1 - 2		2.5 - 4		5 - 7		9 - 11		15	
	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0
-3.3	.08	.03	.19	.07	.28	.09	.38	.12	.49	.16	.60	.19
-4.4	.25	.09	.59	.20	.86	.28	1.17	.38	1.50	.49	1.84	.59
-5.6	.42	.15	.98	.33	1.43	.47	1.93	.63	2.48	.80	3.04	.98
-6.7	.57	.21	1.36	.45	1.98	.65	2.67	.87	3.44	1.11	4.21	1.36
-7.8	.73	.26	1.72	.58	2.52	.83	3.40	1.11	4.37	1.42	5.35	1.72
-9.4	.96	.34	2.26	.76	3.29	1.08	4.46	1.45	5.73	1.85	7.01	2.26
-11.4	1.25	.45	2.94	.99	4.30	1.41	5.81	1.89	7.48	2.42	9.14	2.94

multiplying the table value by the existing distribution factor. These predicted application rates are also presented graphically as functions of wind speed and dry leaf temperature (Figure 6).

Off times for a pulsing cycle were determined and plotted as functions of wind speed (Figure 7) and wet bulb temperature (Figure 8). The off time depends on the same input parameters as the sprinkling rate with the addition of the wet bulb temperature. Thus, the humidity of the orchard air has an effect on the off time of a pulsing cycle, however, the effect is almost negligible (Figure 8).

Effect of Ice Accumulation on Application Rate

The buildup of ice on the plant part was also examined using this model. The time of sprinkler operation and ice accumulation through a frost night was simulated by increasing the characteristic size of the plant part. The resulting effect of ice accumulation on the required application rate is illustrated in Figure 9. As the characteristic size increases from 0.2 to 2.0 cm the required application rate decreases from 1.05 to 0.35 cm/hr, a decrease of 0.70 cm/hr (67%).

Sensitivity Tests

The effect of the characteristic size, D , on the predicted application rate was discussed in the previous section on the Effect of Ice Accumulation on Application Rate. As the characteristic size increases by ice accumulation through a single night or fruit development through a growing season, the corresponding predicted

Figure 6. Predicted application rates as a function of wind speed for given dry leaf temperatures ($D=0.2$, $T_c=-2.8$ C, $\lambda=1.0$)

Figure 7. Maximum off time for a pulsing cycle as a function of wind speed with other input parameters held constant.

Figure 8. Maximum off time for a pulsing cycle as a function of wet bulb temperature with other input parameters held constant.

Figure 9. Effect of ice accumulation on application rate.

application rate is reduced. The sensitivity of the SPAR79 model to three other main inputs will now be discussed. These three inputs are dry leaf or blossom temperature, T_1 , critical temperature, T_c , and wind speed, v .

A 0.9°C increase or decrease in T_1 results in a corresponding 0.04 cm/hr increase or decrease in the predicted application rate. This means SPAR79 directly responds to the dry leaf or unsprinkled leaf or blossom temperature. A 0.2°C increase or decrease in T_c results in a corresponding 0.08 cm/hr increase or decrease in the predicted application rate. This is also a direct response. If wind speed is changed by 0.25 m/sec the application rate changes by 0.01 to 0.03 cm/hr. This is not a linear response because the heat transfer rate increases with the square root of the wind speed.

FIELD TESTS

Materials and Methods

Blossom temperatures (sprinkled and unsprinkled), air and dew point temperatures, and wind speed were monitored in a 0.7 Ha apple orchard at Rock Springs Agricultural Research Center during operation of the sprinkling system. One-half of the block is equipped with individual sprinklers over each tree (Olsen B400 set 3 m x 5.5 m). The system was designed to facilitate adjustment of the application rate in time by either regulating the pressure over a 10-fold range (34.5 kPa to 345 kPa) or by pulsing the system on and off by electronically actuated valves or both. Water is delivered by gravity feed from a catchment pond above the orchard elevation. Further, this system provides an application rate which varies in space (Figure 10) by providing the most water at the point the foliage and blossoms requiring protection are most dense, where the trees overlap within rows.

A 36-gauge (0.127 mm diameter) chromel-alumel thermocouple was threaded through the ovary of each of eight Golden Delicious apple blossoms and connected to a VIDAR data acquisition system (DAS) (Model 5423/643 D-DAS) according to the scheme in Figure 11. (For a detailed discussion of the thermocouple in agricultural research see Lorenzen (1949)). The thermocouple was connected to a 20-gauge extension wire shielded with a polyvinyl jacket by a standard screw-in connector covered by a neoprene jacket for waterproofing. The reference thermocouple was connected to the extension wire by solder and the extension wire-copper lead (16 gauge) connection was made on a buss bar

Figure 10. Spatial distribution of application rate at top of trees for sprinkler system used in field tests.

Figure 11. Thermocouple circuit used to measure blossom temperature (T_b) during 1977 sprinkling for frost protection. (Double walled boxes designate areas of equal temperature.)

in specially designed climate resistant metal boxes. The reference junction used in Spring 1977 data collection was an ice bath in a 1-quart thermos bottle. However, in 1978, an insulated box was used. The scheme illustrated in Figure 11 was modified by soldering the TC leads directly to the shielded pair copper wire forming the reference junction inside a heavily insulated box. Any temperature gradient that may have formed among the reference junctions was minimized by wrapping the junctions with stranded copper wire and then surrounding them with plastic insulation material. The temperature of the references was measured by a copper-constantan thermocouple interrogated by the microprocessor based Esterline-Angus DAS (Model PD2064) which recorded the air and dewpoint temperatures and wind speed on printed paper tape (Figure 12). Also for the 1978 season, the thermocouple circuit was improved by using insulated chromel thermocouple wire to insure that the only junction made was at the bead inside the blossom.

Four of the eight thermocouples were placed in blossoms in a sprinkled downwind tree (D6), two in an unsprinkled downwind tree (D17), and two in a sprinkled upwind tree (R11) for the 1977 season (Figure 13). For the 1978 season the two thermocouples in R11 were moved to D6. (The prevailing wind in this block on nights of frost is from the northwest.)

The VIDAR DAS, located inside an instrument trailer, digitized the analog thermocouple signals and recorded them on magnetic tape (7-track, 556 BPI, odd parity). Each scan was triggered by a timer which activated a scanner, a series of switches which interrogated up to ten channels. The analog signal was converted to a digital signal by an integrating digital volt meter and recorded sequentially on the 7-track

Figure 12. Thermocouple circuit used to measure blossom temperature (T_b) during 1978 sprinkling for frost protection. (Double walled box designates area of equal temperature.)

Figure 13. Position of trees in which blossom temperatures were monitored by thermocouples during sprinkling for frost protection.

● TREES SELECTED FOR MONITORING BLOSSOM TEMPERATURE

magnetic tape. This 7-track tape was copied onto a 9-track standard label tape which was compatible with the Pennsylvania State University's IBM SYSTEMS 370/168, replaced by an IBM 3033 in September, 1978. Then the voltages were converted to temperatures. These temperatures were plotted versus time using a Tektronix 4662 flatbed plotter attached to the IBM 3033 by a GenCom 300Q typewriter terminal and the Computation Center's FORTRAN IV programs, PLOTIT and CONTK¹.

The dates and times of data collection are given in Table 4. Sprinkling was carried out six out of the ten periods in which data were collected during 1977. The 1978 season was relatively mild. On May 3 and 4 data were collected because the air temperature dropped below 0°C allowing ice to form, but the blossoms were between the 1/2-inch green and tight cluster stage and did not require protection. The 1978 data were not recorded on magnetic tape because the VIDAR system tape drive was malfunctioning so only the printed paper tape was available. These data were manually entered into Batfiles in the Remote Job Entry (RJE) system of the IBM SYSTEMS 370/168.

¹Write-ups explaining these programs in detail are available from the Pennsylvania State University Computation Center, University Park, PA 16802.

Table 4. Dates and times of blossom temperature data collection.

<u>DATE</u>	<u>TIME</u>	<u>SPRINKLED (yes or no)</u>
April 27, 1977	0440 - 0645	yes
April 28, 1977	2252 - 2259	yes
April 28, 1977	2302 - 2309	yes
April 28-29, 1977	2316 - 0022	yes
April 29, 1977	0036 - 0845	yes
April 30, 1977	0049 - 0800	yes
May 8, 1977	0325 - 0734	yes
May 8-9, 1977	1955 - 0522	no
May 9-10, 1977	2019 - 0612	no
May 12, 1977	0318 - 0538	no
May 15, 1977	0201 - 0704	yes
May 15-16, 1977	2221 - 0600	no
June 4, 1977	0508 - 0645	yes
May 3, 1978	0245 - 0542	yes
May 4, 1978	0148 - 0700	yes

Results and Discussion

Blossom temperatures versus time for a frost night in April, 1977 and one in May, 1978 are shown in Figures 14-20. These two nights were particularly interesting and provided field results with which one may evaluate the model predictions. Figure 14 is a temperature plot of a sprinkled blossom and Figure 15 is the temperature plot of an unsprinkled blossom during the April 28-29, 1977 frost. The blossoms were between the first pink and first bloom stage (Ballard, et al., 1973) on this night. Figure 16 shows the difference between the average temperature of the six sprinkled blossoms and the one unsprinkled blossom. This is considered the "degrees" of protection provided by sprinkling. Sprinkling was successful in protecting the six observed blossoms, however, it is significant to note the variation of protection (Figure 4). This demonstrates the variability within the tree canopy. The blossom in Figure 14 was in the sprinkled edge tree (R11) and the blossom in Figure 15 was within the unsprinkled block (D17) (Figure 13). The blossom in Figure 14 was exposed to sky and ground and the blossom in Figure 15 was exposed to surrounding blossoms and leaves.

The existing conditions during the April 28-29, 1977 frost were minimum dry leaf temperature, $T_1 = -3^{\circ}\text{C}$ (26.6°F); characteristic size, $D = 0.2$ cm; distribution factor, $\lambda = 1.8$ for 90% protection and wind speeds between 1 and 2 m/sec. The SPAR79 model predicts an application rate of 0.19 cm/hr for 50% protection and 0.34 cm/hr for 90% protection. The 90% rate was exceeded in all the field application rates, except between midnight and approximately 3:30. During this period the blossom temperature varied as much as 2°C , but protection was obtained by

Figure 14. Sprinkled blossom temperature ($^{\circ}\text{C}$), mean application rate (cm/hr), and pulsing cycle vs. time during 1977 frost.

Figure 15. Unsprinkled blossom temperature ($^{\circ}\text{C}$) vs. time during 1977 frost.

Figure 16. Average degrees ($^{\circ}\text{C}$) of protection provided by sprinkling during 1977 frost.

Figure 17. Sprinkled blossom temperature ($^{\circ}\text{C}$), mean application rate (cm/hr), and pulsing cycle vs. time during 1978 frost.

Figure 18. Expanded period from 3:30-5:00 for sprinkled blossom temperature ($^{\circ}\text{C}$), mean application rate (cm/hr), and pulsing cycle vs. time during 1978 frost.

Figure 19. Unsprinkled blossom temperature ($^{\circ}\text{C}$) vs. time during 1978 frost.

Figure 20. Average degrees ($^{\circ}\text{C}$) of protection provided by sprinkling during 1978 frost.

sprinkling at the less than 90% protection rate. Pulsing partially accounts for the variability of temperature on a single blossom. Varying wind speed and runoff effects also contribute to blossom temperature variation.

From 00:09 to 3:23 the pulsing cycle was 1 1/4 minute on, 1 1/4 minute off. This off period was less than that determined by Equation (26) to be the maximum. Although the blossom (Figure 14) did not reach the critical temperature there was variation in its temperature through time. At 3:23 the cycle was changed to 2 minutes on, 1/2 minute off; then at 3:55 to 1 minute on, 1/4 minute off; and at 4:22 to constantly on. These cycles were effective, but used an excess amount of water.

Figure 17 is a temperature plot of a sprinkled blossom during a frost May 4, 1978, and Figure 18 is a portion of the same temperature plot expanded. Figure 19 is an unsprinkled blossom also during the frost May 4, 1978. Figure 20 is the degrees of protection provided by sprinkling during this frost. In addition, Figures 21 and 22 show the aspirated air temperature and wind speed versus time for this morning. During this morning the air temperature dropped below 0°C allowing ice to form and thereby observing the effects of sprinkling. The blossoms were between the half-inch green and tight cluster stage, however, and did not require protection. If the critical temperature is taken to be -0.6°C (31°F) for purposes of computing a sprinkling rate; average dry leaf temperature, $T_1 = -1.5^{\circ}\text{C}$ (29.2°F); characteristic size, $D = 0.75$ cm, distribution factor (50% protection), $\lambda = 1.0$, average air temperature, $T_a = -0.5^{\circ}\text{C}$, and wind speed between 1 and 2 m/sec the predicted application rate is 0.19 cm/hr. This application rate was most closely approached between 3:30 and 4:00. However, during this period the

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pulsing cycle was not adequate (Figure 18). The on period was 1 minute and the off period was 4 minutes. Equation (26) predicted 2.82 minutes to be the maximum safe off time. Thus the off period was too long and allowed the blossom to cool more than it could warm during the on period and subsequent freezing period. Therefore, the overall effect was gradual cooling. No protection was provided by sprinkling during this period (Figure 20). This demonstrates the importance of the appropriate pulsing cycle, even when the application rate is sufficient. At 4:00 the cycle was changed to 1 minute on, 1 1/2 minutes off; at 4:30 to 1 1/2 minutes on, 1 minute off; and at 5:00 to constantly on. All these rates and pulsing cycles provided protection. At 5:30 the wet bulb temperature was -1.11°C so it was safe to shut off the sprinklers.

SUMMARY AND CONCLUSIONS

A refined Sprinkling Application Rate (SPAR79) model of the sprinkled orchard which predicts application rates and maximum off times for pulsing cycles required for successful frost protection from given atmospheric parameters was developed through a critical evaluation of existing models. SPAR79 uses an energy budget approach to determine the rate of heat lost by the plant through radiative, convective, and latent heat transfer processes at the actual plant temperature and at the critical plant temperature. The difference between these two rates of heat loss is the rate at which heat must be added by the latent heat of fusion liberated as the applied water freezes. The subsequent equation for the predicted sprinkling rate, I , is:

$$I = (\lambda/L_i) (2((\rho C_p)/\gamma r_v)(e_c - e_l)) + (h_c + h_r)(T_c - T_l) \quad (27)$$

where λ = distribution factor

L_i = latent heat of fusion

ρ = density of air

C_p = specific heat of air

γ = psychrometer constant

r_v = diffusion resistance for water vapor

e_c = saturation vapor pressure at T_c

e_l = saturation vapor pressure at T_l

h_c = convective heat transfer coefficient

h_e = latent heat transfer coefficient

T_c = critical temperature

T_l = leaf temperature

This model was developed by critical review of previous work,

particularly that of Businger (1965) and Gerber and Harrison (1964). Through this review many typographical and other errors in the existing models were corrected. In the development of the model, the effect of humidity was explicitly shown not to be a contributing factor in the determination of application rates, but was shown to be important in calculating the off period for a pulsing cycle. Also, the fact that sprinkling need only raise the plant temperature to the critical temperature and not air temperature or 0°C , as some literature implies, was documented. Ice accumulation was estimated to decrease the required application rate as much as 0.70 cm/hr for a ten-fold increase in the characteristic dimension of the plant part by ice buildup.

Data obtained from Jarrett, et al. (1978) were used to quantify a distribution factor, which accounts for the effect of development of blossoms and leaves on the runoff of some of the applied water. These data estimated this distribution factor for 50% and 90% protection. It was found to increase from 1.0 to 1.3 for 50% protection and from 1.8 to 3.7 for 90% protection as the growing season and blossom and leaf development progressed.

Sprinkling for frost protection was carried out during six frost nights in spring of 1977 and two frost nights in May, 1978. Eight 36-gauge thermocouples monitored sprinkled and unsprinkled blossom temperatures during these frosts. Simultaneously, wind speed and air temperature were recorded. The millivolt data from the thermocouples was recorded on magnetic tape for analysis at the computation center. Blossom temperature versus time plots were constructed. These field observations, together with simultaneously observed application rates and pulsing cycles, provided data upon which to assess the SPAR79 model.

The technique of pulsing the system on and off complicated this assessment, but significant conclusions have been made.

A complete sprinkling application rate model must predict both an application rate and a pulsing cycle for the given conditions. The appropriate timing of the pulsing cycle is crucial to the success of a predicted application rate, i.e., although an application rate may be sufficient, an inappropriate pulsing cycle can override this and cause damage. The application rates predicted by the refined model are notably smaller than those suggested in previous literature. It has been demonstrated that by varying the distribution factor through the growing season and varying the application rate through a single frost night, according to atmospheric parameters and ice accumulation, a significant decrease in the amount of water applied may be realized.

The sophistication of the OFT model has not been applied to the problem of modeling the sprinkled orchard. This author's knowledge of the OFT suggests that its modification for application to sprinkling could greatly enhance the study of the sprinkled orchard and significantly improve the models developed to date. It is strongly suggested that future work involve modification of the OFT for use in sprinkling research.

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APPENDIX A

LISTING OF BUSINGER SPRINKLING RATE MODEL (1965)
PROGRAMMED IN FORTRAN


```

/*USERID KBP02
// EXEC FWCG
//SYSIN DD *
***** BUSINGER PRECIPITATION MODEL *****
C ****DECLARE ALL VARIABLES TO BE REAL
      REAL LI,D,K,M,NU
      REAL*8 H,B,HE,HR,A
C ****SET THE CONSTANTS.
C ***** = STEFAN-BOLTZMANN CONSTANT IN LANGLEY/DEGREE KELVIN TO THE
C ***** 4TH TIMES MINUTES.
      S=8.132E-11
C *****LI = LATENT HEAT OF FUSION IN CAL/G.
      LI=80
C *****K = THERMAL CONDUCTIVITY OF AIR IN CAL/(CM*SEC*C)
      K=5.78E-05
C *****M = KINEMATIC VISCOSITY OF AIR IN (CM*CM)/SEC
      M=0.13
C *****TA=AIR TEMPERATURE IN DEGREES C.
      TA=0.0
C *****LOOP THROUGH 4 PLANT PART SIZES, D=CHARACTERISTIC SIZE IN CM.
      DO 2 J=1,4
        V=0
        IF(J.EQ.1)D=0.2
        IF(J.EQ.2)D=0.5
        IF(J.EQ.3)D=1.0
        IF(J.EQ.4)D=2.0
C *****LOOP THROUGH WIND SPEEDS (V) 0 TO 500 CM/SEC.
      DO 1 I=1,500
        V=V+1
C *****RE = REYNOLDS NUMBER (DIMENSIONLESS).
      RE=(V*D)/M
      IF(RE**0.385.LE.2.436) GO TO 5
      IF(RE.LE.40)GO TO 6
      IF(RE.LE.4000)GO TO 7
      IF(RE.LE.40000)GO TO 8
      IF(RE.LE.250000)GO TO 9
      GO TO 10
C *****NU=NUSSELT NUMBER. EQUATIONS FROM MCADAMS, 1954,
C ***** PAGE 260.
      5 NU=2.
        GO TO 11
      6 NU=0.821*(RE)**0.385
        GO TO 11
      7 NU=0.615*(RE)**0.466
        GO TO 11
      8 NU=0.174*(RE)**0.618
        GO TO 11
      9 NU=0.0239*(RE)**0.805
        GO TO 11
      10 PRINT 13
        GO TO 1
      11 CONTINUE
      13 FORMAT(' ',RE OUTSIDE LIMITS')
C *****H = CONVECTIVE HEAT TRANSFER COEFFICIENT, IN

```

```
C ****      CAL/(CM*CM*SEC*K)
      4  H=NU*(K/D)
C ****HE = LATENT HEAT TRANSFER COEFFICIENT (UNITS SAME AS H).
      HE=0.46*H
C ****HR = RADIATIVE HEAT TRANSFER COEFFICIENT, DIVIDING BY
C ****      60 CONVERTS IT TO A PER SEC VALUE (UNITS SAME AS H).
      HR=(4*S*(TA+273)**3)/60
C ****A = COMBINATION OF THE HEAT COEFFICIENTS AND HEAT OF FUSION.
C ****      UNITS ARE MM/(HR*C).
      A=(2/LI)*(H+HE+HR)*36000
      WRITE(9,1300)A,V,D
1300 FORMAT(' ',F20.10,2X,F6.2,2X,F3.1)
      1 CONTINUE
      2 CONTINUE
      STOP
      END
//DATA.FT09F001 DD UNIT=BAT,FILES=($B1,$B2,$B3,$B4)
```

APPENDIX B

DERIVATION OF RELATIONSHIP BETWEEN COEFFICIENT OF LATENT HEAT TRANSFER AND COEFFICIENT OF SENSIBLE HEAT TRANSFER

$$h_e = \frac{L_e^2 B}{R_w^2 T_m^3}$$

Substituting 1.55×10^{-3} (h) for B:

$$= \frac{(597)^2 \text{ cal}^2 / \text{g}^2 (6.11 \text{ mb}) 7.8 \times 10^{-5} \text{ cm}^2 / \text{dyn (h)}}{(.11)^2 \text{ cal}^2 / \text{g}^2 \text{ } ^\circ\text{C}^2 (273.15^\circ\text{K})^3}$$

$$h_e = 0.69 \text{ h}$$

Where h_e = coefficient of latent heat transfer, and h = coefficient of sensible heat transfer.

APPENDIX C

COMPUTATION OF TOTAL OFF PERIOD OF SPRINKLING CYCLE FROM EQUATION
PRESENTED IN BUSINGER (1965)

Given in Businger's (1965) example:

$$\begin{aligned} T_m &= -3^\circ\text{C} \\ T_1 &= -6^\circ\text{C} \\ L_1 &= 80 \text{ cal/g} \\ V_1 &= 100 \text{ cm/sec} \\ L &= 2 \text{ cm} \\ A &= 1.2 \text{ mm/(hr } ^\circ\text{C)} = .12 \text{ g/(cm}^2\text{Chr)} \\ C &= 0.2 \text{ cal/(cm}^2\text{C)} \end{aligned}$$

$$\begin{aligned} t &= \frac{1}{A} \left\{ \frac{0.06}{T_o - T_1} + \frac{C}{L_1} \ln \frac{T_o - T_1}{T_m - T_1} \right\} \\ &= \left\{ \frac{1}{1.2 \text{ mmhr}^{-1}\text{C}^{-1}} \frac{0.06}{6^\circ\text{C}} \right\} + \left\{ \frac{0.2 \text{ calcm}^{-2}\text{C}^{-1}}{80 \text{ calg}^{-1}} \ln \frac{+6\text{C}}{+3\text{C}} \right\} \\ &= \frac{0.06 \text{ mm}}{1.2 \text{ mm/(hr C)}(6\text{C})} + \frac{0.2 \text{ calcm}^{-2}\text{C}^{-1}}{(.12 \text{ gcm}^{-2}\text{C}^{-1}\text{hr}^{-1})(80 \text{ cal/g})} \ln 2 \\ &= \frac{.01}{1.2} \text{ hr} + \frac{(.2)}{(.12)(80)} \text{ hr} \quad (.6931) \\ &= .0083 \text{ hr} + .0144 \text{ hr} \\ &= .0227 \text{ hr} \end{aligned}$$

$$t = 1.36 \text{ minutes}$$

APPENDIX D

LISTING OF GERBER AND HARRISON SPRINKLING RATE MODEL
(1964) PROGRAMMED IN FORTRAN

```

/****GERBER AND HARRISON  SPRINKLING RATE MODEL
// EXEC FWCG,PARM=NOSOURCE
//SYSIN DD *
      REAL L,K,HSUBC,LF,I,LEF
      PRINT 2
2      FORMAT('      TL(F);  U(MPH);      I(IN/HR)')
C*****READ IN TL AND U IN DEGF AND MPH:
6      READ(5,3,END=7)TL,U
3      FORMAT(F3.0,F4.1)
C*****CONVERT TO CGS UNITS, I.E. DEGC AND CM/SEC
      U=U*44.7
      TL=(TL-32)*(5./9.)
C*****LET K BE THE THERMAL CONDUCTIVITY OF AIR AT 0C IN
C      CAL/CM/S/C (BUSINGER, 1965).
      K=5.78E-5
C*****PUT IN SIGMA IN CAL/SQ CM/S/K**4
      SIGMA=.1355E-11
C*****LET LF BE THE LATENT HEAT OF FUSION IN CAL/GM
      LF=80.
C*****LET TM BE MINIMUM TEMP TO WHICH THE LEAF IS PERMITTED IN C
      TM=0.
C*****LET TA BE THE AIR TEMPERATURE AND ASSUME EQUAL TO 0C
      TA=273.15
C*****LET V BE THE KINEMATIC VISCOSITY IN SQ CM/SEC
      V=.133
C*****LET CP BE SPECIFIC HEAT OF MOIST AIR IN CAL/GM/K
      CP=.24*1.88
C*****PR IS PRANDTL NUMBER (SEE GATES, 1962).
      PR=(.72)*1.88
C*****CDLDOT IS A CONSTANT IN THE COMPUTATION OF HSUBC
      CDLDOT=0.664
C*****G IS ACCELERATION DUE TO GRAVITY, CM/(SEC*SEC).
      G=980
C*****TEC IS THERMAL EXPANSION COEFFICIENT, PER C.
      TEC=.003670
C*****LET L BE THE CRITICAL LEAF DIMENSION IN CM
      L=2.
C*****R IS GAS CONSTANT, CAL/(G*C).
      R=0.107951
C*****LET LEF BE THE LATENT HEAT OF EVAPORATION AT 0C
      LEF=597.47-0.5653*TM
      TA=TA-273.15
C*****HR IS THE RADIATIVE HEAT TRANSFER COEFFICIENT
      HR=4*SIGMA*TA**3
C*****E IS THE AVERAGE VAPOR PRESSURE IN DYN PER CM*CM.
      E1=(6.11*EXP((17.269*TM)/(TM+237.30)))*1000
      E2=(6.11*EXP((17.269*TL)/(TL+237.30)))*1000
      E=(E1+E2)/2
C*****RE IS REYNOLDS NUMBER (SEE GATES, 1962).
      RE=(U*L)/V
C*****GR IS GRASHOF NUMBER (SEE GATES, 1962).
      GR=(TEC*G*L**3*(TA-TL))/V**2
      Q=PR*GR
      IF(GR.GT.RE**2) GO TO 4

```



```

      GO TO 5
      PRINT 9
9      FORMAT(' ', 'FREE CONVECTION EQUATIONS REACHED')
4      IF(Q.LT.20000000) HSUBC=(K/L)*.54*(Q)**0.25
      IF(Q.GE.20000000) HSUBC=(K/L)*.14*(Q)**.3333
      GO TO 8
C*****HSUBC IS CONVECTIVE HEAT TRANSFER COEFFICIENT.
5      HSUBC=(K/L)*.66*RE**0.5*PR**.3333
C*****LET BETA BE BUSINGER'S CONSTANT BETA/HSUBC IN (CM*CM*C)/DYN.
8      BETA=6.3E-5
      A=BETA*(LEF/(R*(TM+273.15)))
C*****HE IS LATENT HEAT TRANSFER COEFFICIENT.
      HE=(A*HSUBC*LEF*E)/(R*(TM+273.15)**2)
C*****I IS SPRINKLING RATE IN IN/HR.
      I=(2./LF)*(HR+HSUBC+HE)*(TM-TL)*3600./2.54
      TL=TL*9./5.+32
      U=U/44.7
      PRINT1, TL, U, I
1      FORMAT(' ', 3F10.2)
      GO TO 6
7      STOP 99
      END
/*
//DATA.INPUT DD *

```

APPENDIX E

LISTING OF REFINED SPRINKLING RATE MODEL (SPAR79)
PROGRAMMED IN FORTRAN

```

/****SPAR79 SPRINKLING RATE MODEL
// EXEC FWCG,PARM=NOSOURCE
//SYSIN DD *
    REAL L,K,HC,LF,I,LI,HR,NU,LE
C*****LET K BE THE THERMAL CONDUCTIVITY OF AIR AT 0C IN
C    CAL/CM/S/C (BUSINGER, 1965).
    K=5.78E-5
C*****PUT IN SIGMA IN CAL/SQ CM/S/K**4.
    SIGMA=.1355E-11
C****LET LI BE THE LATENT HEAT OF FUSION IN CAL/GM
    LI=80
C*****LET TC BE CRITICAL TEMPERATURE IN C.
    TC=-2.8
C*****LET V BE THE KINEMATIC VISCOSITY OF AIR IN CMXCM/SEC
    V=.133
C*****DV=COEFFICIENT OF DIFFUSION IN CMXCM/SEC
    DV=.212
C*****RHO=DENSITY OF AIR AT 0 C IN G/CUBIC CM
    RHO=1.292E-03
C*****CP=SPECIFIC HEAT OF AIR AT 0 C IN CAL/G/C
    CP=1.01*.239
C*****GAMMA=PSYCHROMETER CONSTANT IN DYN/CMXCM/C
    GAMMA=646.
C*****L=CHARACTERISTIC SIZE PARAMETER IN CM.
    L=2.
C*****ALPHA IS THE RUNOFF FACTOR.
    ALPHA=1.0
    PRINT 2
2    FORMAT('      TL(F); U(MPH);      I(IN/HR)')
C*****READ IN TL (LEAF TEMPERATURE) AND U (WIND SPEED) IN
C*****DEG F AND MPH.
6    READ(5,3,END=7)TL,U
3    FORMAT(F3.0,F4.1)
C*****CONVERT TO CGS UNITS, I.E. DEGC AND CM/SEC.
    U=U*44.7
    TL=(TL-32)*(5./9.)
C*****LET TA BE THE AIR TEMPERATURE AND ASSUME EQUAL TO TL + 2.2 C.
    TA=TL+2.2+273.15
C*****HR IS RADIATIVE HEAT TRANSFER COEFFICIENT.
    HR=4*SIGMA*TA**3.
C*****RE IS REYNOLDS NUMBER (SEE GATES, 1962).
    RE=(U*L)/V
C*****PR IS PRANDTL NUMBER (SEE GATES, 1962).
    PR=(CP*V*RHO)/K
C*****NU IS NUSSELT NUMBER (SEE GATES, 1962).
    NU=.664*(RE)**.5*(PR)**.333
C*****HC IS CONVECTIVE HEAT TRANSFER COEFFICIENT.
    HC=(NU*K)/L
C*****SC IS SCHMIDT NUMBER (SEE GATES, 1962).
    SC=(V/DV)
C*****SH IS SHERWOOD NUMBER (SEE MONTEITH, 1973).
    SH=.664*(RE)**.5*(SC)**.3333
C*****RV IS DIFFUSION RESISTANCE FOR WATER VAPOR (SEC/CM).
    RV=L/(DV*SH)

```

```
C*****EC AND EL ARE SATURATION VAPOR PRESSURES IN DYN/(CM*CM)
C*****FOR TC AND TL, RESPECTIVELY.
      EC=(6.11*EXP((17.269*TC)/(TC+237.30)))*1000
      EL=(6.11*EXP((17.269*TL)/(TL+237.30)))*1000
C*****LE IS RATE OF LATENT HEAT TRANSFER.
      LE=((RHO*CP)/(GAMMA*RV))*(EC-EL)
C*****I IS THE PREDICTED SPRINKLING RATE IN IN/HR.
      I=ALPHA*2*((LE+((HC+HR)*(TC-TL)))/LI)*3600/2.54
      TL=TL*9./5.+32
      U=U/44.7
      PRINT1,TL,U,I
1      FORMAT(' ',3F10.2)
      GO TO 6
7      STOP 99
      END
/*
//DATA.INPUT DD *
```

APPENDIX E

Radiant Fractions for Orchard Heaters at Low Burn Rates and With Modified Stacks to Conserve Fuel¹

W. L. Bland, J. D. Martsolf, and K. B. Perry

The Pennsylvania State University
University Park, PA 16802

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