CONSERVATION OF OIL
IN ORCHARD HEATING

Final Report
for Period July 1, 1978 - June 30, 1979

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August 1979

Prepared for the

UNITED STATES DEPARTMENT OF ENERGY

UNDER CONTRACT NO. ED-77-S-02-4397

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ABSTRACT

A philosophy of modeling and measuring has been applied to a search for ways by which the efficiency of heating orchards may be increased or heating may be avoided by developing acceptable alternatives to heating. A box model was used to test the sensitivity of the heated orchard to modification of some of the energy losses that dictate the efficiency of heating. Turbulent transport was found to be of a smaller magnitude than previously believed leaving room for additional attention to wind breaks and shelter belts as conservation techniques. The Orchard Foliage Temperature (OFT) model, a rigorous model of the radiant transfer as well as convective transfer in a heated orchard, was developed and described. The OFT determines the minimum burn rate necessary for a given percentage of protection and so may be used as a frost thinning guide. It also provides predictions of the effect of disrupting heat losses to the soil near and beneath heaters. A Sprinkling Application Rate (SPAR79) model was developed from existing models. SPAR79 predicts notably smaller application rates for the fusion sprinkling method. Rates predicted by SPAR79 were favorably

compared to those used in field tests. Sprinkling for bloom delay was also carried out. Bloom was delayed ten days. The combination of bloom delay and fusion appears to be a viable alternative to heating. A prototype frost alarm was developed and used for one frost season. Plans are to continue development of a radio transmitted alarm. Development of a microprocessor-based data acquisition and control system was begun for environmental monitoring and microclimate control. The possibility exists for use of dedicated single-board microcomputers by individual growers. These devices would provide potential for significant savings of fuel oil by controlling amounts of oil consumed for heating or eliminating burning oil by controlling sprinkling systems.

INTRODUCTION

PREVIOUS REPORTS

This is the third report submitted to the United States Department of Energy under Contract No. EC-77-S-02-4397 and constitutes the final report.

The first report, 4397-1, was a draft of a thesis describing the orchard foliage temperature model (OFT). The second report, 4397-2, was an annual report covering the period July 1, 1977, through June 30, 1978. It contained 191 pages and covered work accomplished during the first 80% of the funded period. Justification for the non-funded extensions were twofold. First, a proposal to extend the grant with additional funds was under consideration, i.e. under review and evaluation, when the initial funded period ran out (September 30, 1978) and the non-funded extension was to cover the period between the two funded periods. Secondly, a problem with getting the second installment of \$80,000 to the University during the time that ERDA was becoming DOE resulted in over 4 months delay in support for the ongoing research. The non-funded extension provided for more orderly conversion of those funds into support for the research, especially in the area of graduate student support.

While this report covers results developed during the entire period of the contract (both funded and non-funded) it will reference items reported in greater detail in the second report (the annual report) rather than repeat them in their entirety. This policy is especially true for the appendices, i.e. this report refers to appendices in the second or annual report rather than reproducing them as an appendix to this report.

HEATING FOR FROST PROTECTION

An exhaustive review of the literature describing heating for frost protection has been recently published (Martsolf, 1979). A draft of that article was included in the Annual Report as Appendix 6 (see pages 57-91 of Annual Report, 4397-2).

As the oldest but still the most reliable of the frost protection methods, heating continues to be practiced over a substantial portion of the U. S. (Martsolf & Scheu, 1978; Appendix 9 of Annual Report, 4397-2, pages 153-173). The art developed during a period when the cost of fuel was an order of magnitude less than it is today (Turrell, 1973). Consequently, practices were designed to minimize capital costs for heaters and auxiliary equipment with little attention given to the fuel requirement. These practices have become traditional and many persist to this day. There are definite opportunities to research the art of heating for frost protection with an express purpose of conserving fuel.

In 1977, the USDA (Garrett, 1977) estimated that over 6 million barrels of oil were consumed annually in heating for frost protection. Not only is that estimate likely to be low but the capriciousness of the location of the frosts results in very rapid consumption of fuel in localized areas during the frosts while remaining areas may have a storage problem. In the case of subtropical fruits the oil requirement occurs during the peak of the residential heating requirement, i.e. during the depth of winter. Thus decreases in the use of oil for frost protection will not only result in conservation of that resource but render the distribution of the resource more predictable.

The original proposal for this research effort concentrated on possibilities of increasing the efficiency of heating for frost

protection that might be tested in the one-hectare research orchard at the Rock Springs Agricultural Research Center (approximately 15 miles SW of the main campus of PSU). The underlying philosophy of the work was to develop a computer model that is sufficiently articulate about heater size, placement, orchard scale and weather parameters to use in the testing of some of the proposed techniques before trying them in the field. This philosophy has been summarized to single word guidelines as follows:

MODEL

• then

MEASURE

using the measurements (observations) to not only test the thesis but to refine the model, i.e. cycle back through the modeling and measuring steps toward a goal of making the model more closely mimic the real world.

The model on which the original proposal was based was the so called "Box Model" (Martsolf & Panofsky, 1975). This model partitioned the energy flows that dictated the orchard temperature into those through six imaginary facets of the box surrounding the orchard due to radiation, soil heat flow, mean air flow and turbulent transport. Some bulk measurements of the radiant transport through the top and sides of the box have indicated appreciable loss of the radiant output from heaters by this mechanism (Martsolf, 1976). More detailed measurements of the radiant flux from the heater stacks resulted in a more convincing estimate of the radiant fraction of the energy converted from the liquid fuel (Perry, et al., 1977). Starting with these insights into the radiant transfer within and throughout the orchard a more rigorous

description of the radiant transfer was modeled. This model concentrated on the geometry of the foliage and described probabilities of beams of radiation being intercepted by foliage elements. This model has been termed the Orchard Foliage Temperature model (OFT) and is to be published in September (Welles, et al., 1979). In order for the OFT model to predict foliage temperature the energy budget of each class of foliage elements was solved. It was necessary to make a statement about the convective transfer from these individual elements and further about the modification of the orchard air due to convection. Crawford's model (1964) had convincing subroutines for these transports. They were refined and incorporated into the OFT model. The convective transfer is handled in two steps. The first involves the convective transfer between the foliage element and the orchard air immediately surrounding the element. The second involves the heating of the orchard air above the temperature of the air surrounding the orchard. In this latter case an improvement was made in Crawford's model by discovering that solving for the orchard air temperature required an iterative process, i.e. the orchard air temperature is required for the solution. Additional information about the modeling results are left to the section of this report entitled, "Modeling", and several appendices referred to in that section.

It is not always apparent to those that are not directly involved in frost protection that one of the more difficult operations is to simply be on hand when the frost occurs. This is an especially difficult aspect of the problem in those areas of the country in which the fruit growing acreage is scattered and frost warning services, if they exist at all, are by necessity vague and broad in their forecasts.

In fact, only a relatively few of the very concentrated fruit growing areas, e.g. Florida and California, have sufficiently detailed forecasting and publication of those forecasts so that growers may rely heavily upon them in deciding when they should be in the field and alert their lighting crews. The frost alarm is badly needed in this situation. While some commercially produced alarms are available they leave appreciable room for improvement in the nature of the alarm. Most have concentrated on making their alarm reliable and the communication of the alarm to the grower. Most, if not all, are guilty of neglecting the exposure of the sensor. No spatial sampling is recommended. The sensor seldom resembles the foliage elements that are to be protected. Generally, shielding is ignored, i.e. the radiation error is not taken into consideration. The OFT model and careful measurement of orchard foliage temperature indicates that there is not a singular orchard temperature but rather a range of foliage element temperatures that may be considered. This report must include a description of an effort that has been made to communicate these needs to at least one commercial firm in the hope that an improved alarm may become available to the growers. A prototype of a telephone alarm was developed and one season's experience was gained with the device. Plans are continuing to develop a radio transmitted alarm. The company that cooperated on this phase of the research was Climatronics Corporation, Inc., Bohemia, New York.

The OFT model provided convincing evidence that the radiant output of orchard heaters, even though only approximately one-fourth of the energy of the fuel is transferred by radiation, is at least equally as important in protecting the foliage elements as is convection and in some cases is more than twice as important. The radiant output is

directly dependent upon the temperature and the extent of the radiating area. Consequently, an effort was made to try to develop some slight, i.e. inexpensive, modification of existing heaters in order to increase their radiant output. A cooperating company, Scheu Products of Upland, California, was involved in this aspect of the project. That firm was involved in the proposal, fabricated measurements and fabricated heater stack modifications and made some inhouse measurements of the modifications of the stack temperatures that resulted from the stack modifications.

About 2% of the energy used in orchard heating has been found to move into the soil under an orchard heater and is not returned to the orchard during the frost. Consequently, it is wasted. With an objective of eliminating this loss of energy, gravel and aluminum foil were placed on the soil surface under an orchard heater. When an air gap existed between the heater base and the aluminum foil, heat flux measurements and soil temperatures revealed that the aluminum foil shields reduced the heat loss at least 80% and in most cases cut it off completely. The gravel treatment was relatively ineffective. The OFT model was used to estimate that approximately 4% of the energy input into the orchard during a typical frost might be conserved by placing 3m diameter aluminum shields beneath auto clean stack heaters.

Management of the soil as a source of energy was investigated to evaluate possibilities for the conservation of oil currently used in frost protection. Two treatments involved the used of plastic and aluminum foil covers to trap solar energy. Maximum benefit was indicated for bare soil covered with plastic during the day and uncovered just before critical temperatures were reached at night. Bare soil and

plastic covered mowed grass gave an intermediate benefit while the mowed grass management scheme gave the least benefit.

ALTERNATIVES TO HEATING FOR FROST PROTECTION

During the summer of 1973, a renewal proposal was developed and submitted to DOE under the same title as this contract, i.e. CONSERVATION OF OIL IN ORCHARD HEATING. The proposed duration was 24 months beginning October 1, 1978. The amount requested was \$186,370. It proposed to continue work in progress on increasing the efficiency of heating for frost protection but greatly increase investigation of alternatives to heating. The proposal number was U7801526. The possibility of considering alternatives and testing some of the more exciting alternatives with conventional heating as a direct comparison in a nearby orchard was declared.

Several alternatives to heating for frost protection are available but deficiencies in knowledge concerning their performance retards their acceptance. One of the most promising alternatives is overhead sprinkling. During the frost the method capitalizes on the liberation of the heat of fusion of liquid water to ice. To differentiate between another method using overhead sprinkling as well, this method has been termed the "fusion" sprinkling method.

Recently interest has increased in utilizing evaporative cooling during periods when deciduous fruit crops are breaking dormancy and developing blossoms. Since the blossom maturation process is very temperature dependent the evaporative cooling retards or delays the bloom date and frost damage may be avoided.

A combination of these two mechanisms (evaporation and fusion) seems possible when frosts occur after the delayed bloom date. In arid

regions it has been possible to delay bloom by as much as 14 days. Without doubt such a delay would get the blossoms by the deepest frosts in the early spring and leave only the milder frosts to be dealt with by fusion. Fusion is quite effective against the mild radiation frost. It is the deep frost, i.e. the very low temperature frost, that is difficult to forestall with fusion. Consequently, the combination of bloom delay and fusion appears to be a viable alternative to heating for protection in the rolling terrain of the Northeast and the Northwest.

Variable rate sprinkling systems are needed to apply sufficient water to provide protection or effect delay. Such systems would avoid water logging the soil and associated drainage and pollution problems. Also they would avoid consuming energy in the moving of unnecessary water. Algorithms that describe the appropriate rate are needed as well. They would be especially useful in the provision of electronic control of the water application rate. Matching the sprinkling rate to atmospheric conditions would seem to avoid many of the disadvantages of overhead sprinkling for frost protection. Automated control for bloom delay systems is required. Substitution of sprinkling systems for heating systems may reduce energy consumption to less than 1% of that necessary to provide heat for protection.

MODELING

THE OFT MODEL

The Orchard Foliage Temperature (OFT) model has been developed as a direct result of this grant. Mr. Jon M. Welles was funded with a half-time research assistantship since the start of his work on this model under this grant. His Masters Thesis has been divided into two parts

for publication. The application portion will be published in the September issue of the Journal of the American Society for Horticultural Science (Welles, et al., 1979). The theory has been prepared for publication in the International Journal of Agricultural Meteorology. The manuscript has passed intra-departmental review and review by the Pennsylvania State Agricultural Experiment Station and received a Journal Series Number.

A rough draft of the theory article was included in the Annual Report to DOE as Appendix 8. The article as it has been reviewed and is currently being reviewed for publication in Agricultural Meteorology is included in this report as Appendix A. A rigorous approach is taken to describe the relative geometry of the individual foliage elements on the trees in the orchard and the stacks of the fired heaters. The repetitive geometric patterns within an orchard are capitalized upon where this is possible. The distribution of the foliage elements and the probability that they will intercept a beam of radiant energy from a particular area of a heater stack is handled stochastically. The result is a distribution of foliage temperatures. One of the more obvious theoretical results, however, is the realization that the heater stack does not behave as a point source. While that seems very obvious there has been rather universal use of the inverse square law to explain the decrease of the intensity of the radiant output from heater stacks with distance from the stack. Valli (1970) referred to the inverse square law in a rather convincing article to practitioners declaring that the radiant output from heaters was not important in the protection that they provided. For example, the inverse square law reduces the irradiance from a heater stack six times too much 1.5m from the center

of the heater stack (see Fig. 6 in Appendix A).

The applications article is entitled, "An Orchard Foliage Temperature Model". A copy of the galley proof of the article scheduled to be published in the September issue of the Journal of the American Society for Horticultural Science, Vol. 104(5):602-610, is affixed to this report as Appendix B. Characteristics of the one-hectare research orchard at the Rock Springs Agricultural Research Center, about 15 miles SW of the Main Campus of the Pennsylvania State University, were inputs to the model.

The model was asked to determine the relative importance of the radiant output of the heaters in modifying the temperature of the blossoms on the trees. On windy nights, i.e. wind speeds above 40 cm/sec, the blossoms on sparsely foliated trees near radiant heaters are elevated in temperature over twice as much due to the radiant fraction of the heater output than due to the convective output. As the wind diminishes and the foliage becomes more dense the relative importance of the radiant output decreases, but it is not until the far trees, i.e. over 10m from the nearest heater, are considered under calm conditions that the convective transfer becomes as important as the radiant heating. Reference to Fig. 7 in Appendix B not only describes these characteristics in more detail but indicates that with the Scheu Auto Clean Stack heaters the relative importance of the radiant fraction in protecting the foliage elements decreases slightly with burn rate. This prediction led to some effort by the heater manufacturer to attempt to increase the radiant fraction at lower burn rates (See Appendix E).

An old adage in frost protection publications has been that many small fires are much more effective than a fewer number of larger fires

(of course delivering an equal amount of heat per unit area). The OFT model was asked to verify this addage. The results were surprising (see Fig. 8d of Appendix B). Apparently the major effect is through the convective modeling of the plume rise; in this case Crawford's model was accepted. If the radiant fraction of smaller heaters can be made comparable with that of the larger heaters then the model forecasts that there are definite advantages to reducing the size of the individual fires and increasing their number.

Perhaps the greatest accomplishment of the OFT model was to reveal a myth that has been so implicit in management that it has never been questioned. The orchard does not have a singular orchard temperature but rather a distribution of temperatures exist. The range over which these temperatures extend is determined by burn rate, radiant fraction, wind, foliage density, inversion strength, radiant loss to not only sky but the soil surface as well, and several factors many of which have to do with the geometry of the trees and the heaters. In many locations on trees the range of temperatures varies over as much as 4C and in some select locations by as much as 7C. This introduces the concept of frost thinning. In other words, the OFT model provides convincing evidence that an intention to preserve all the blossoms on a frost night is economically unsound as well as a breach of conservation of energy.

The OFT model provides predictions of the effect of disrupting heat losses to the soil near and beneath heaters (see Appendix F). It also produces some insight into the feasibility of enhancing the storage of solar energy in the orchard soil (see Appendix G). These predictions are graphically depicted in Figures 8e and 8f of Appendix B. For example, a 2m radius disc of reflective aluminum beneath the Auto Clean Stack

heaters may be expected to reduce the required burn rate by approximately 8% under typical frost conditions. The burn rate was found to be very sensitive to increases in soil temperature, e.g. an increase in average soil surface temperature of 5C would decrease the required burn rate by approximately 20%. However, the net conservation of energy would be much greater because the heaters would not have to be lit as early. The OFT model is not articulate about the magnitude of this latter effect.

SPAR79

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. None of the existing models has all these characteristics. The Gerber and Harrison (1964) 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 had to be revised. This deficiency plus errors in other 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 justified the need to refine these models.

The Sprinkling Application Rate (SPAR79) model was developed from the existing models (Gerber and Harrison, 1964; Businger, 1965). SPAR79 uses 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. This model added consideration of humidity and ice accumulation to a refinement of the heat budget configuration of the earlier models. The effect of humidity was explicitly shown not to be 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. The Ph.D. dissertation by Katharine B. Perry describing this work in detail is included as Appendix D.

SOIL HEAT FLOW

Two articles have been prepared by Fritton, et al. Manuscripts of these two articles were included in the Annual Report to DOE as Appendices 1 and 2. However, reviews have improved these reports to the extent that the current versions are included in this report as Appendices F and G.

The discovery of a large heat pulse beneath the Auto Clean Stack

heater led to a search for simple and inexpensive methods to avoid the sinking of energy into a loss mechanism. Aluminum foil shields and a layer of gravel, covering areas near and beneath the heaters of both 1m and 2m in radius, were tried. The gravel did relatively little as compared with the foil. The foil reduced the heat flux into the soil by amounts between 80 and 100%. It was found important to assure that an air gap exists between the foil and the soil surface to avoid the heat pulse into the soil. The OFT model was used to estimate the effect on the foliage temperature and ultimately the amount of energy that may be conserved by such a practice. If about 2% of the energy applied to the orchard through burning fuel is lost to the soil near the heater as estimated by Fritton and Martsof (1979) the OFT model predicts that the reflection of this energy off a 2m radius disc will result in at least a 4% conservation of fuel.

The second paper (Appendix G) describes investigations into soil management schemes designed to trap solar energy prior to the frost in the orchard soil. Both grass and bare soil plots were managed with both aluminum and clear plastic covers. Covering a bare soil results in a large increase in the heat available during the frost when the cover is removed. Covering grass results in modifying the situation toward that of a bare soil left uncovered. Maximum benefit resulted from the use of the clear plastic covers to trap solar energy during a clear day immediately preceeding the frost night. The surface was uncovered just prior to the onset of critical temperatures, i.e. during the frost.

It has been known for some time that the cultural practices involving the soil surface in the orchard have an appreciable effect on the susceptibility of the orchard to frost damage. This work is in

agreement with this concept. Any practice that exposes a soil with a high conductivity and low reflectivity to solar energy arriving at the surface will facilitate the storage of energy during the day. The high conductivity not only aids in the pumping of the heat down into the depths of the soil during the day but facilitates the delivery of heat back to the surface at night to retard the cooling of the soil surface and the air near the surface. It would appear that management of this process would aid in the protection of the orchard but is not likely to serve as the only protection device necessary for protection. Since it is not always clear the day before a frost occurs the management of solar trapping for frost protection is a supplemental technique only.

ORCHARD ATMOSPHERE

DATA ACQUISITION & CONTROL

The documentation of the orchard environment in both the heated and sprinkled blocks requires reliable data acquisition equipment. Sprinkling for bloom delay requires some automated control to assure that the sprinklers are on during periods during which the temperature is above a threshold value. It appears desirable to handle the fusion sprinkling systems by a controller that reacts to environmental parameters as well. The pipeline heating system has a pressure regulator at the pumping console that could be controlled by a system that makes the burning rate a function of the environmental demand for heat. Recently microprocessor circuitry has made it feasible to not only handle data acquisition and processing with such a unit but to use it to control the frost protection systems automatically.

During the period of this grant considerable effort has been

devoted to the development of a microprocessor-based system suitable for both data acquisition and controller functions. Details concerning the hardware and the software for such units are in Appendix H.

It is anticipated that this system will be used for two primary applications in frost protection research. In a heated orchard the system will access inputs from various environmental sensors such as thermocouples, radiometers, and anemometers. These inputs will be converted to a digital format with a 12 bit coding pattern and stored in a soft-sector diskette for subsequent processing either on-line or off-line. Some real time processing such as conversion from millivolts to engineering units will be performed before the data are stored on the diskettes.

In addition, time and space averages, peaks and trends can be obtained for use in the decision-making process relative to the firing operation in the heated orchard. The system has the capability of producing an output pulse to a telephone alarm system for alerting an operator to a potential frost hazard. During the time that the orchard is being heated the microcomputer will be used to estimate nozzle pressures required to attain desired foliage and blossom temperatures. These estimated pressures may be verified and adjusted by a positive feedback system. In subsequent years it is anticipated that stem servo valves may be used to automatically regulate nozzle pressures.

The microcomputer system will also be used to acquire data and control solenoid valves in an orchard being sprinkled for frost protection by either fusion or bloom delay techniques. In both of these approaches, models exist for predicting the required application rates based on inputs of temperatures, wind speed, and similar environmental

parameters. The microprocessor allows for real time processing of input parameters and outputs control pulses to the solenoid valves. The reliability of the predictive models may be established by positive feedback loops and direct adjustment of sprinkling rates are obtained by means of pulsing the solenoid valves. Such an approach has previously been difficult to achieve without the sophistication available in a micro-processor-based system.

The particular system being used for this series of applications is based on an IMSAI PCS80/30 Microcomputer Development System. This unit is configured with 32K bytes of random access memory, a dual double density floppy disk drive with a one megabyte capacity and a fortran software package. Digital data conversion is accomplished via a 12 bit A/D converter card. Control outputs are available in either a digital or analog form as required.

At the present time software is available for sequentially or randomly accessing 32 analog channels, digitizing them and storing the resulting conversions on the diskettes. In addition, programs are available for converting thermocouple signals to temperature values. Service routines are also available for averaging an operator specified number of scans and storing the result. Timing operations are maintained by a series of programs written to accumulate crystal pulses and convert them to real time equivalents.

Currently, efforts are under way to test the firmware of the various system components. It appears very likely that additional amplification is going to be required for channels being used for thermocouple inputs. The entire system should be available for field testing during the Spring of 1980. It is hoped that additional funding

will be secured to continue this research.

One of the most significant aspects of research dealing with application of microprocessors to frost protection is the possibility of providing small dedicated single-board microcomputers suitable for use by individual growers. These devices would afford the potential for significant savings of fuel oil by reducing amounts of oil consumed when heating. In some instances the burning of oil may be eliminated completely by making sprinkling for protection feasible. The models and software which are currently under development should allow such a concept of dedicated microprocessors to become a reality for frost protection purposes.

STACK TEMPERATURES

Under the modeling section of this report the need for information about the temperature of the heater stacks at lower burning rates was needed in order for the model to be useful in predicting the effects of such rates on the protection provided. Appendix E is a detailed report of measurements of stack temperatures at lower burning rates. With conventional heaters the stack temperatures seem to decrease sufficiently with decreasing burning rate so that the radiant fraction, i.e. the fraction of the total heat from the heater that is transmitted as a radiant flux, decreases with burning rate as well. The OFT model makes the need for developing methods of holding the radiant fraction up at lower burning rates quite convincing. Appendix E includes reports on the effect of inexpensive modifications to the stack on stack temperature. One of these modifications was a constriction added to the inside of the stack to decrease the velocity within the stack and hopefully increase the stack temperature. The second modification was

the addition of horizontal flanges on the outside of the heater stack. In the calm atmosphere of the manufacturer's laboratory the stack temperatures were increased quite significantly. However, as Appendix E indicates, in the field situation there appears to be sufficient drift or wind to nullify the effect of the external flanges. In the orchard situation there doesn't seem to be sufficient incentive to go to the expense of making the modifications that were tested. However, there may be slightly different modifications that will prove to improve the standard heater's performance at lower burning rates.

It should be emphasized that this portion of the grant work was accomplished in very close conjunction with one of the leading manufacturer's of orchard heaters, Scheu Products, Inc. of Upland, California. Consequently, if the improvement in the heater's performance at lower burn rates had been sufficient to warrant recommending such modifications these recommendations would have received immediate consideration by the manufacturer and may have been into the production schedule very shortly thereafter.

FROST ALARMS

While there are a few fruit and vegetable growing areas of the United States that receive good and reliable forecasts of impinging frost conditions in terms that growers are able to react to with confidence, most areas of the country are more often surprised by frost than are appraised of its possibility. In the ridge and valley terrains it would be difficult to set up frost warning services that may work as well as those in Florida, California and Washington even if the Government were willing to do so. The temperatures often vary by as much as 10C from one location in a mountainous valley situation to another

(Hocevar and Martsolf, 1971). At Penn State the very highly skilled forecasters in the Meteorology Department forecast minimum temperatures to be verified by the weather station that is on top of the Meteorology Building (Walker) on the main campus. That minimum is frequently as much as 5C above minimums observed in the orchards. The difference is not a constant, however.

Frost protection is a rather useless exercise unless the practitioner provides protection during every period in which it is necessary. Identifying such frost periods is not easy. An alternative or supplement is the frost alarm. In a section of this report entitled Data Acquisition and Control the electronics communication systems necessary to sense the atmospheric parameters and use them in decision making matrices were discussed. One of the key functions of a microprocessor controller may be to provide the practitioner with an alarm. The alarm may be useful for several things that the grower may want to be aware of such as power failure, pressure drops in irrigation or heating systems indicating possible leaks, as well as the presence of critically low temperatures in the orchard.

The key characteristic of a good alarm system is reliability. Several alarms have been tried in this project. Some of these have been capable of passing a message by telephone to one or more of several phone numbers stored in its memory. Close coordination has taken place between our team and a commercial supplier of such instrumentation, Climatronics Corporation, Bohemia, New York. An effort is still in progress to develop a radio transmitted alarm for areas that do not have sufficiently reliable phone service for such an alarm. To achieve sufficient distance the possibility of a captive balloon to carry

sufficient antennae aloft to broadcast the alarm signal over nearby hills to the grower's residence is under development. The use of such a device may be appropriate because frosts occur during calm periods in the atmosphere. An alternative is to simply use the inversion tower for the antennae support. There have been recommendations for growers that practice frost protection to put up 50 ft inversion towers for decades.

There have been frost alarms available to growers for some time. They have most of the features that are desirable with a couple of significant exceptions. One of these is that all ignore the problem of sensor exposure. The commercially available sensors vary in size and shape as well as in their infrared emissivity. Consequently they do not react to the environment in the same manner. Additional work is needed to produce a sensor that reacts to the environment like a bud or blossom (or leaf). The alarm would be activated by leaf temperature then. Since leaf temperature varies in space the OFT model may be useful in developing some guidelines as to where such a sensor should be placed so that the appropriate distribution of temperatures may be predicted. Perhaps a chip may be burned with an algorithm that provides such information to the alarm by sensing wind and perhaps humidity as well as simply temperature. A critical factor in future alarms is how they sense the problem for which they are designed to sound the alarm.

BLOSSOM TEMPERATURE

In order to document the temperature of the plant part that is protected in the deciduous fruit orchard techniques of observing blossom temperature have been developed. Details of some techniques used in the sprinkled blocks are contained in Appendix D.

In using Crawford's model (Crawford, 1964) to compute the

convective exchange in the OFT model several interesting implications of the role that the orchard atmosphere plays in the orchard microclimate developed. In addition to realizing that the blossoms bathed by the orchard atmosphere were of quite different temperatures, one from another, it became apparent that parcels of air within the orchard atmosphere undoubtedly varied one from another. However, the OFT model rests on the continued assumption that there is a singular temperature of the orchard atmosphere. When the variation of the temperature within the orchard atmosphere is better understood it should be described more precisely in the OFT model.

While the OFT model was not refined to consider an orchard atmosphere that was variable in temperature in both time and space, the methods of measurement did respond to this new knowledge. Orchard temperature at the top of the box (Martsolf and Panofsky, 1975) was measured with loop thermocouples in parallel but displaced as much as 3 m one from another. The thermocouple loop was kept small in wire gauge, 36 AWG or smaller, and the 10 cm diameter loops were oriented perpendicular to the soil surface. Such thermocouple loops do not have sufficient radiation error at night to warrant aspiration. They provide spatial sampling and more spatial sampling is necessary to assess air temperature in the orchard.

Additional insights into the spatial variability of orchard temperature was developed through study of the turbulent transport through the top of the orchard (see Appendix J).

TURBULENT TRANSPORT

Drag anemometry and computerized data acquisition necessary to record wind velocity with this anemometry were used to measure turbulent

transport directly. The Box Model (Martsolf and Panofsky, 1975) indicated the turbulent transport through the top and the sides of an imaginary box surrounding the orchard to be fluxes that dictated the orchard microclimate. In fact, no model prior to the Box Model had partitioned the energy flows into their mean flow and turbulent components. Previous studies had produced sufficient information to arrive at turbulent transport estimates as a residual of the energy budget. These estimates indicated the flow to be large compared to mean flow or at least of comparable magnitude. However, not much confidence could be attached to such estimates because the errors of measurement of all the other parameters in the orchard microclimate accumulated to make the confidence limits on such estimates very broad.

Appendix J contains the details of direct measurement of the turbulent transport term in the heated orchard. A draft of an article on the work described in Appendix J has been approved for publication by the Pennsylvania Agricultural Experiment Station and is currently under review for publication in the Journal of the American Society for Horticultural Science.

While only a few observations of the turbulent flux were made, they do not support previous concerns that a major portion of the heat from the heated orchard was lost to the atmosphere above and around the orchard by turbulent transport. Less than 10% of the energy was accounted for by this mechanism. While more measurements are needed to add confidence to these observations they serve to point at the possibility that errors in the assessment of the mean flow terms may be present. If this is the case, then the possibilities of wind breaks and other methods that may be developed to disrupt the mean flow loss of

heat from the heated orchard, and especially the small acreage heated orchard, may be in order.

The spatial variation in the turbulent flux was a surprise. Apparently the plumes do not merge above the orchard as quickly as has been suggested. The atmosphere immediately downstream from a heater stack involves much more turbulent mixing and entrainment with the local atmosphere than does the air out in the open spaces between the heater plumes. Bland (1979) makes some estimates of the plume sizes and how rapidly they bend over in the orchard drift. These add to a thesis concerning the spatial distribution of temperature in the orchard.

SPRINKLING FOR FROST PROTECTION

A Sprinkling Application Rate (SPAR79) model has been developed by refining two previously published models, one by J. A. Businger (1965) and a related one by J. F. Gerber and D. S. Harrison (1964). SPAR79 determines 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). SPAR79 calculates this requirement by considering the heat balance of the plant part needing protection.

SPAR79 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. SPAR79 was tested by comparing its predicted sprinkling rates with those observed to be necessary for adequate protection in field studies. 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. (Appendix I) 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.

The data described in Appendix I 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 over a period of 10 days in May, 1978. 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. 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 distribution factor increased as blossom and leaf development proceeded.

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. 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 were 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.

Sprinkling for bloom delay has also been proposed as an alternative to heating for frost protection. Delaying the bloom period by several days decreases the possibility of severe frost occurring during bloom. Using sprinkling, delays of seven to seventeen days have been achieved in various geographic areas in the United States.

The first bloom delay research originated at Utah State University in 1972. Two predictive models, the Chill Unit model and the Growing Degree Hour model, were developed to predict phenological development for deciduous fruit species. The Chill Unit model, based on temperature, predicts the end of rest. Prediction of the date of the end of rest is critical for maximum bloom delay. The Growing Degree Hour model, also based on temperature, predicts phenological development after the end of rest. Within the Growing Degree Hour model, it is assumed that a linear relationship exists between temperature and plant development for a specific temperature range (4.4° to 25° C). Bud temperatures are converted to growing degree hour units and integrated over time. On the basis of temperature, it is possible to predict the date on which an orchard will reach a specific stage of development. A number of assumptions were incorporated into these models during their development at Utah State University. The temperature range was assumed to apply to all deciduous fruit species. Rootstock was assumed to exert no influence upon the number of chill units and growing degree hour units required for normal plant growth and development. Also, it was assumed that sprinkling did not alter plant response and the energy requirement to reach full bloom, i.e., sprinkled and nonsprinkled orchard blocks require an equivalent input to reach full bloom.

The objectives of the research were to examine the feasibility of bloom delay under humid central Pennsylvania conditions, and to provide a test for the Chill Unit and Growing Degree Hour models which were originally developed and used in an arid climate.

The Chill Unit model predicted the end of rest occurred on March 17, 1979 for "Delicious" apples. Sprinkling had been initiated in a .35 Ha orchard block ten days prior to the predicted date. Fruit buds collected on January 20, 1979, after 980 of 1234 Chill units had accumulated, were capable of resuming growth and reaching anthesis when provided with conditions favoring the resumption of growth. Fruit buds completed rest and were ready to resume growth nearly two months prior to the date predicted to be the end of rest for "Delicious" apples.

The Growing Degree Hour model accurately predicted phenological development in the nonsprinkled block. Approximately one day separated predicted and observed dates on which the orchard reached specific stages of development. The Growing Degree Hour model did not, however, make accurate predictions for the sprinkled orchard. The sprinkled block reached full bloom on May 20, 1979, ten days after the nonsprinkled orchard block. The model had predicted full bloom to occur in the sprinkled block on May 10, 1979, and only a delay of two days was to occur between sprinkled and nonsprinkled blocks according to the predictions made. The wide discrepancy indicates a recalibration of the model may be necessary for the sprinkled orchard block. The assumption that sprinkled and nonsprinkled blocks require equivalent energy input to reach full bloom also may not be valid.

Pollen viability, fruit set, and fruit size were examined in sprinkled and nonsprinkled blocks. Sprinkled "Golden Delicious" and "Rome Beauty" trees experienced a seven and two percent reduction in pollen viability when compared with nonsprinkled trees of the same variety. The fruit set of "Rome Beauty" was not affected by sprinkling; equivalent numbers of fruit were set in both sprinkled and nonsprinkled blocks. A delay in maturity was observed, when fruit length and diameter were examined in sprinkled and nonsprinkled blocks. Fruit length and diameter in the sprinkled block were .25 cm less than the nonsprinkled block.

SUMMARY

A philosophy of modeling and measuring has been applied to a search for ways through which the efficiency of heating orchards may be increased or to avoid heating by developing acceptable alternatives to the practice. The Box Model (Martsolf and Panofsky, 1975) existed at the beginning of the grant and was used to test the sensitivity of the heated orchard to modification of some of the energy losses that dictate the efficiency of heating. Turbulent transport was found to be of a smaller magnitude than previously believed leaving room for additional attention to wind breaks and shelter belts as conservation procedures.

The Orchard Foliage Temperature (OFT) model was developed as a direct result of this effort. It provides insight into the mechanisms within the orchard that the Box Model in its bulk approach to the situation was unable to describe except in mean terms. The OFT model focused attention on the possibility of large spatial variations in not only temperature but the fluxes of energy that are dictated by the temperature gradients. The myth of an orchard temperature was destroyed and in its place was built a concept of an orchard microclimate with layers of fluid air having varying temperatures and speeds.

The advent of microprocessor and microcomputer controllers places pressure on efforts to define sensors for the controllers and its alarms to provide algorithms within the computers with information that is usable. Spatial sampling of temperature or the development of relationships that will use wind speed, radiation, and perhaps humidity in deducing from sparse temperature information the distribution of these temperatures in space seems to be the next major requirement for research attention.

A Sprinkling Application Rate (SPAR 79) model for the fusion sprinkling method was developed from existing models by correcting and refining previous works. Consideration of humidity and ice accumulation was added to corrected versions of the existing models. A distribution factor, previously only estimated, was quantified. The model-predicted application rates were compared to field observations. Bloom delay in a humid climate was also carried out. The results obtained here suggest a combination of bloom delay and fusion may be a viable alternative to heating for frost protection.

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APPENDIX A

Modelling the Radiant Output of Orchard Heaters

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1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

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MODELLING THE RADIANT OUTPUT OF ORCHARD HEATERS

J. M. Welles, J. M. Norman, and J. D. Martsolf

Abstract

The radiant output from orchard heaters is an important factor in frost protection, although it is usually neglected in frost protection models. The basic theory for calculating radiant flux incident on a leaf which is arbitrarily positioned and oriented with respect to a radiation-emitting cylinder and disc is presented. A typical heater stack is shown not to emit as a point source; errors of a factor of six result from applying the "inverse square law". Therefore arguments based on point-source emission from orchard heaters are invalid. In fact such arguments have led to gross underestimates of the importance of the radiant output of orchard heaters.

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1 INTRODUCTION

2 Orchard heaters transfer energy to their surroundings radiatively
3 and convectively. The portion of the fuel's total energy that is con-
4 verted to radiant energy is known as the radiant fraction, and is
5 typically about one fourth (Perry et al., 1977). Most of the published
6 orchard heating models and energy budgets (Crawford, 1964; Gerber,
7 1969; Martsolf and Panofsky, 1975) deal only with the convective
8 portion of the heater's output. There is good agreement, however, that
9 the radiant output is an important contributor to orchard protection,
10 especially in windy conditions (Gerber, 1965; Kepner, 1951; Martsolf,
11 1974; Turrell, 1973; Wilson and Jones, 1969; Perry et al., 1977).
12 Through use of a computer model of orchard foliage temperatures (OFT
13 Model) that takes detailed account of radiation emitted by heaters,
14 Welles et al. (1979) found that the effects of heater radiation and con-
15 vection were comparable in determining foliage temperatures. In windy-
16 conditions with sparse foliage, heater radiation was found to be more
17 important than heater convection. The OFT model also indicates that
18 increases in radiant fraction (with resulting decreases in convective
19 output) have the net effect of increasing heater efficiency.

20 The purpose of this paper is to indicate how a heater's radiant
21 output can be modeled so that the irradiance of a leaf can be predicted
22 as a function of its orientation and position with respect to one or
23 more fired heaters. This is an integral part of the OFT model.

24

25

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1 VIEW FACTORS

2 The irradiance I (incident energy per time per area) on a leaf
3 from a heater can be expressed as

$$4 \quad I = \frac{W}{A_h} F_h \quad (1)$$

6
7 where W is energy per time emitted by a heater, A_h is heater stack
8 area, and F_h is the view factor for the heater as seen by the leaf. The
9 radiant flux (W/A_h) emitted by a heater can be expressed in terms of
10 burn rate and radiant fraction, or in terms of the mean 4th power
11 temperature of the stack:

$$12 \quad \frac{W}{A_h} = \frac{B_h k R_f}{A_h} = \epsilon_h \sigma T_h^4 \quad (2)$$

14
15 where $k=1.085 \times 10^4$ Watt-hours per liter for #2 diesel fuel. The view
16 factor F_h is the major hurdle in applying Equation 1. The view factor
17 may be thought of as the fraction of the leaf's hemispheric view (the
18 side of the leaf facing the heater) that is occupied by the heater.
19 Alternatively, it could be thought of as the fraction of radiant flux
20 leaving one side of the leaf that is incident on the heater. A good
21 general discussion of view factors may be found in Eckert and Drake
22 (1959).

23 The view factor for a heater is obtained from the sum of view
24 factors for a hollow cylinder (F_c) representing the stack and a flat
25 disc (F_d) which represents the upper end.

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$$F_h = F_c + F_d \quad (3)$$

The view factor between an arbitrarily oriented and positioned unit area (leaf) and a hollow cylinder (heater stack) can be calculated from (Fig. 1)

$$F_c = \frac{R}{\pi} \int_0^H \int_{-\cos^{-1}(R/D)}^{+\cos^{-1}(R/D)} \frac{\cos \beta_1 \cos \beta_2}{S^2} d\gamma dz \quad (4)$$

where $\cos \beta_1 = \sin \theta_L \sin \delta + \cos \theta_L \cos \delta \cos (\phi' - \epsilon)$

$$\cos \beta_2 = (D \cos \gamma - R)/S$$

$$\phi' = \tan^{-1}((Y_C - Y_L)/(X_C - X_L)) - \phi_L$$

$$\epsilon = \sin^{-1}\left(\frac{R}{f} \sin \gamma\right)$$

$$\delta = \tan^{-1}((Z - Z_L)/f)$$

$$S^2 = f^2 + (Z - Z_L)^2$$

$$f^2 = D^2 + R^2 - 2DR \cos \gamma$$

$$D^2 = (X_L - X_C)^2 + (Y_L - Y_C)^2$$

Equation 4 is cumbersome and must be evaluated numerically. Fortunately there is a simplified approximate expression for F that is valid for most orchard applications. Hamilton and Morgan (1952) give an analytic solution for the view factor for a special case of a cylinder and a unit area. For $\theta_L = \phi' = 0$, and $Z_L = H$ then the special case view factor F'_c becomes

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$$F'_C = \frac{1}{\pi C} \tan^{-1} \left(\frac{E}{\sqrt{C^2 - 1}} \right) + \frac{E}{\pi} \left[\frac{A - 2C}{C \sqrt{AB}} \tan^{-1} \sqrt{\frac{A(C-1)}{B(C+1)}} - \frac{1}{C} \tan^{-1} \sqrt{\frac{C-1}{C+1}} \right] \quad (5)$$

where $A = (C + 1)^2 + E^2$

$B = (C - 1)^2 + E^2$

$C = D/R$

$E = H/R$

Note that when the leaf height and the cylinder height are different, eq. 5 must be applied twice: once for a hypothetical cylinder of height Z_L , (yielding F'_C) and once for a hypothetical cylinder of height $Z_L - H$ (yielding F'_C (for height $Z_L - H$)). The difference of these two quantities is the view factor for the real cylinder of height H :

$$F'_C = F'_C \text{ (for height } Z_L) - F'_C \text{ (for height } Z_L - H) \quad (6)$$

The special case view factor F'_C can be generalized for arbitrary leaf orientation by assuming that the view factor is a maximum when the leaf is facing the cylinder midpoint, and varies as the cosine of the angle between the leaf normal and a line to the cylinder midpoint (Fig. 2). Thus, the maximized view factor would be $F'_C / \cos \delta'$. Stated

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another way

$$F_c = Q_c F'_c \quad (7)$$

where

$$\begin{aligned} Q_c &= \frac{\cos \alpha}{\cos \delta'} \\ &= \frac{\sin \theta_L \sin \delta' + \cos \theta_L \cos \delta' \cos \phi'}{\cos \delta'} \\ &= \frac{K}{D} \sin \theta_L + \cos \theta_L \cos \phi' \end{aligned} \quad (8)$$

since

$$\delta' = \tan^{-1} \left(\frac{K}{D} \right)$$

where K is the difference in height between the leaf and the cylinder midpoint (Positive in Fig. 1, negative in Fig. 2). Comparisons between eqs. (4) and (7) indicate a negligible difference (less than 1%) for cylinders of typical heater dimensions and leaf positions greater than 1.5 m in any direction away from the stack.

The view factor for the upper end of the stack F_d can be represented by (Fig. 3)

$$F_d = \frac{(Z_L - Z_d)}{\pi} \int_0^{R_d} \int_0^{2\pi} \frac{r \cos \beta_1}{S^3} dy dr \quad (9)$$

Use center section for NEBGUIDE

$$\cos \beta_1 = \sin \theta_L \sin \delta + \cos \theta_L \cos \delta \cos (\phi' - \epsilon)$$

$$\delta = \tan^{-1} ((Z_d - Z_L)/f)$$

$$S = [(Z_d - Z_L)^2 + f^2]^{1/2}$$

$$f^2 = D^2 + r^2 - 2 D r \cos \gamma$$

$$\phi' = \tan^{-1} ((Y_d - Y_L)/(X_d - X_L)) - \phi_L$$

$$D^2 = (X_d - X_L)^2 + (Y_d - Y_L)^2$$

$$\epsilon = \sin^{-1} \left(\frac{r \sin \gamma}{f} \right)$$

$$Z_d = \text{disc height (Zero in Figure 3).}$$

Eq. 9 must be evaluated numerically, but as in the case of the cylinder, an approximation based upon a special case may be used. When $\theta_L = 0$ and $\phi' = 0$, the view factor for the disc is F'_d (Hamilton and Morgan, 1952):

$$F'_d = \frac{J}{2} \left(\frac{1 + G^2 + J^2}{((1 + G^2 + J^2)^2 - 4 G^2)^{1/2}} - 1 \right) \quad (10)$$

where $G = R_d/D$, and $J = (Z_L - Z_d)/D$. The correction of F'_d to include arbitrary leaf orientation is analogous to the correction of F'_c to more closely approximate F_c :

$$F_d \approx Q_d F'_d \quad (11)$$

$$\text{and } Q_d = \frac{\sin \theta_L \sin \delta'' + \cos \theta_L \cos \delta'' \cos \phi'}{\cos \delta''} \quad (12)$$

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1 Since $\delta'' = \tan^{-1} ((z_d - z_L)/D)$, Eq. 12 may be rewritten as

$$2 \quad Q_d = \frac{z_d - z_L}{D} \sin \theta_L + \cos \theta_L \cos \phi' \quad (13)$$

4 The error in eq. (11) is smaller than that in eq. 7.

5 Summing the view factors for the side and the top of a heater
6 stack (eq. 3) implies that all the radiation received by the leaf comes
7 directly from the heater with no intermediate reflection from the heater
8 base, the ground, or reflectors on the ground. The amount of radiation
9 received by a leaf that comes from a reflector placed beneath a heater
10 can be appreciable (Welles et al., 1979), and thus is well worth
11 calculating. The radiant flux I_r reflected by a flat disc underlying a
12 heater that is incident on a leaf is

$$14 \quad I_r = \frac{W}{A_d} \rho_d F_u F_d^* \quad (14)$$

15 where A_d is the exposed area of the underlying disc, ρ_d is the disc
16 reflectivity, F_u is the fraction of the radiant energy emitted by the
17 stack that is incident on the disc, and F_d^* is the view factor for under-
18 lying disc as seen by the leaf. If eq. 9 is used to calculate F_d^* , the
19 blockage of part of the disc by the stack is accounted for by adjusting
20 the limits of integration. If the approximation (eq. 11) is used,
21 stack blockage may be accounted for in two ways: The first
22 way reduces the view factor for the entire disc by an amount equal to
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Use center section for NEBGUIDE

1 the view factor for a cylinder of height Z^* , where

$$2 \quad Z^* = Z_L \left(\frac{R_d + R_c}{R_d + D} \right) \quad (15)$$

4 and Z^* is never allowed to exceed cylinder height H . The other way is
5 to simply reduce the disc area (for purposes of the view factor calculation)
6 tion) by an amount equal to the area blocked by the cylinder. This
7 adjusted disc radius is

$$8 \quad r = (R_d^2 - \frac{A}{\pi})^{1/2} \quad (16)$$

9 where A is the area blocked by the cylinder:

$$11 \quad A \approx \frac{\pi}{2} R_c^2 + 2 R_c X \quad (17)$$

13 where

$$14 \quad X = \begin{cases} R_d & (\text{if } Z^* < H) \\ \frac{H (R_d + D)}{Z_L} - R_c & (\text{if } Z^* = H) \end{cases}$$

16 The view factor F_u between the cylinder and the underlying disc is

17 (Fig. 4)

$$19 \quad F_u = \frac{1}{\pi H} \int_0^H \int_{R_c}^{R_d + \xi} \int_{-\xi}^{+\xi} \frac{z r (r \cos \theta' - R_c)}{S^4} d\theta' dr dz \quad (18)$$

22 where

$$23 \quad S^4 = (z^2 + R_c^2 + r^2 - 2 R_c r \cos \theta')^2$$

$$24 \quad \xi = \cos^{-1} (R_c / r)$$

25 Note that the lower limit of the integration over z is not zero if the
cylinder does not rest on the disc.

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1 The total heater view factor F_h (including a surface reflector)
 2 is given by

$$4 \quad F_h = F_c + F_d + \frac{A_h}{A_d} \rho_d F_u F_d^* \quad (19)$$

5 This model neglects radiation emitted or reflected by bowl covers or
 6 bases of heaters. At higher burn rates especially, this assumption
 7 will cause underestimates of irradiance, leaving it on the "safe" side
 8 in a frost protection model. Fig. 5 illustrates the relative con-
 9 tributions of the three components of eq. 19 for a specific example.

11 INVERSE SQUARE LAW

12 Radiant flux decreases in inverse proportion to the square of the
 13 distance from a point source. Heater stacks are not point sources.
 14 Valli (1978) deduced that the emitted radiation from orchard heaters
 15 was not important in frost protection by assuming that radiant flux
 16 density decreased as the inverse square of the distance from the heater.
 17 Fig. 6 contains a comparison between the irradiance on a vertical leaf
 18 as a function of distance as computed by an inverse square relation
 19 and by an integrated view factor. Note that the inverse square
 20 relation reduces irradiance too rapidly, resulting in underestimates
 21 of a factor of six at distances beyond 1.5 m.

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1 COMPARISON WITH MEASUREMENTS

2 Wilson and Jones (1969) measured radiant flux with a net radiometer
3 traversed in a 260° arc over a return stack heater. Effective view
4 factors (Fig. 7) were calculated by dividing the mean measured flux at
5 a given angle by the emitted radiant flux (eqs. 1 and 2). These view
6 factors (denoted "measured") are comparable to those obtained using the
7 theoretical equations in this paper. The return stack heater was
8 assumed to be a cylinder (the return stack was neglected) of length
9 1.05 m and radius 0.096 m. The stack was assumed to sit on a flat disc
10 of equal temperature of radius 0.2 m; this was to simulate the combined
11 effects of bowl covers, and reflection from the ground. A more
12 elegant treatment of the radiative environment was not done due to
13 lack of information about details of the experiment. At moderate
14 burn rates theory and measurement agree quite well. The cause for the
15 peak of the 1.25 gal/h curve to occur at a lower angle is not known.

16 [^]
 (4.73 l/h)

Use center section for NEBGUIDE

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Use center section for NEBGUIDE

1	PARTIAL LIST OF SYMBOLS	
2	A_d	area of disc (m^2)
3	A_h	area of heater stack (m^2)
4	B_h	heater burn rate ($l\ h^{-1}$)
5	F_c	view factor of cylinder
6	F'_c	special case cylinder view factor
7	F_d	view factor of disc
8	F'_d	special case disc view factor
9	F_d^*	view factor between a cylinder and an underlying disc
10	F_h	view factor for a heater as seen by a leaf
11	F_u	view factor for a disc underlying a cylinder
12	H	heater stack height
13	I	irradiance on a leaf ($W\ m^{-2}$)
14	I_r	leaf irradiance that has been reflected from a surface underlying
15		the heater ($W\ m^{-2}$)
16	k	1.085×10^4 watt hours per liter
17	R	heater stack radius (m)
18	R_d	disc radius (m)
19	R_f	radiant fraction
20	T_h	heater stack temp. (K)
21	W	Energy per time emitted by a heater (W)
22	Z_d	disc height (m)
23	(X_L, Y_L, Z_L)	coordinates of a leaf
24	(X_c, Y_c)	horizontal coordinates of a cylinder
25	(X_d, Y_d)	horizontal coordinates of a disc

Use center section for NEBGUIDE

1	z^*	height of a hypothetical cylinder (m)
2	ϵ_h	heater emissivity
3	θ_L	leaf elevation angle
4	ϕ_L	leaf azimuth angle
5	δ'	inclination angle from a leaf to a cylinder mid point
6	δ''	inclination angle from a leaf to a disc mid point
7	ρ_d	disc reflectivity
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Given: $X_L, Y_L, Z_L, \theta_L, \phi_L$
 X_C, Y_C, H, R

Figure 1. The geometry for calculating the view factor between an arbitrarily oriented unit area (leaf) and a cylinder (heater stack). θ_L is leaf elevation angle (measured positively up from the horizontal), ϕ' is leaf azimuth angle with respect to the heater.

Figure 2. The view factor for a unit area and a cylinder as given by Hamilton and Morgan (1952) assumes the unit area normal to be along the X axis. Assuming the view factor to be increased by the secant δ' to it's approximate maximum value when the normal points at the cylinder midpoint, the view factor for an arbitrary orientation is this maximum value times the cosine of the angle α .

Given: $X_L, Y_L, Z_L, \theta_L, \phi_L$
 X_d, Y_d, R_d

Figure 3. The geometry for the calculation of the view factor between a unit area and a disc. The height of the disc, Z_d , is zero in this Figure.

Given: R_c, H, R_d

Figure 4. Geometry for the calculation of the view factor of a disc as seen by a cylinder; i.e., what fraction of the radiant flux leaving the cylinder will be intercepted by the disc. In ⁽¹⁸⁾~~Equation 16, eq. 16~~ the angle θ has already been integrated (0 to 2π) yielding 2π .

5
Figure 5. Irradiance I (W m⁻²) as computed on a vertical leaf 2.0 m above the ground at distance d (m) from a heater emitting 10^4 W m⁻². The heater is sitting on a disc of reflectivity 0.9 and radius 0.5 m. $I = 10^4 F_h$.

6
 Figure 7. Irradiance I (W m^{-2}) as a function of distance on a vertical leaf as computed by an inverse square relation ($I = 10^4 \left(\frac{0.1}{d}\right)^2$) and by an integrated view factor ($I = 10^4 F_h$). Here, F_h just includes the cylinder sides.

Figure 7. Comparison between "measured" (from Wilson and Jones (1969)) and computed view factors for a unit area traversing an arc over a heater.

APPENDIX B

An Orchard Foliage Temperature Model¹

See J. Am. Soc. Hort. Sci. 104(5):602-610
1979

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¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

APPENDIX C

Intermittence in Sprinkling for Frost Protection¹

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1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

Intermittence in Sprinkling for Frost Protection¹

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1979

Introduction

During sprinkling for frost protection an interval between wettings naturally occurs in most sprinkling systems currently in use because the sprinkler heads rotate. Two sprinkling rate models, one by J. A. Businger (1965) and another related one by J. F. Gerber and D. S. Harrison (1964), include equations which determine the maximum time that may elapse between wettings which does not allow the plant part to cool below its critical temperature, the point where damage occurs. In 1974, pulsing sprinkling systems to achieve greater efficiency, i.e. use less water for adequate protection was suggested. By pulsing, a system becomes a variable rate system and so the application rate may be varied to meet existing atmospheric conditions. Thus, no more water than is needed is applied. This will help reduce limb breakage from ice-buildup and "wet feet" associated with sprinkling for frost protection.

Determination of the Appropriate Pulsing Cycle

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 towards its critical temperature (Figure 1). This

¹Appendix to final report to the U.S. Department of Energy under contract No. EC-77-S-02-4397 from a paper presented to the 76th Annual Meeting of the American Society for Horticultural Science, July 30-August 4, 1979, in Columbus, Ohio.

Figure 1. Theoretical blossom temperature during pulsing where t_1 , freezing period, plus t_2 , cooling period, equal t , the total off period of the pulsing cycle. T_c is critical temperature of the blossom and T_{wb} is wet bulb temperature.

off period must be sufficiently long to conserve water, but not so long that the plant part cools below its critical temperature. It is the sum of the time required to freeze the applied water (t_1), and time (t_2) during which the ice coated plant part cools to its critical temperature.

The equation to determine off time, published by Businger (1965), is the same as the equation used here (Equation 1), except for two changes. First, the dry leaf temperature (T_1) was replaced by the critical temperature (T_c) in determining the freezing period, t_1 , because the plant part is at the critical temperature, not dry leaf temperature when this freezing period begins. Second, the dry leaf temperature was replaced by the wet bulb temperature (T_{wb}) in determining the cooling time, t_2 , because the plant part is cooling toward the wet bulb temperature.

$$t = t_1 + t_2$$

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

The off time is a function of the same atmospheric parameters as the sprinkling rate. In Equation 1, A is a composite of the radiative, convective, and evaporative heat loss coefficients, T_o is 0 C, T_c is critical temperature, C is the heat capacity of the plant part and L_i is the latent heat of fusion; but, in addition, the wet bulb temperature is a factor also. Thus, the humidity of the orchard air has a small effect on the off time.

The two most significant parameters involved in determining the off time are the wet bulb temperature and the wind speed, which is involved

in the determination of A through the heat loss coefficients. As the humidity increases, i.e. T_{wb} increases, the off time is increased, because not as much evaporative cooling occurs (Figure 2). As the wind speed increases, however, the off time decreases, due to increased rate of heat loss (Figure 3).

Field Tests

Both sprinkled and unsprinkled apple blossom temperatures were monitored during sprinkling for frost protection at the Rock Springs Agricultural Research Center located in central Pennsylvania. In addition, application rates and pulsing cycles were recorded, see Figure 4. Figure 4 depicts a sprinkled blossom temperature and corresponding application rate and pulsing cycle for a May 4, 1978 frost. The time period of most interest is between 3:30 and 4:00. In order to examine this period more closely a section of Figure 4 has been expanded (Figure 5).

During the period between 3:30 and 4:00 (Figure 5), although the sprinkling rate was adequate, the 4 minute off time was greater than the predicted maximum off time of 2.8 minutes. 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, overall cooling occurred.

Another way to view the effect of sprinkling and pulsing is to consider degrees of protection. Degrees of protection are the degrees a representative sprinkled blossom is above a representative unsprinkled blossom (Figure 6). Again, between 3:30 and 4:00, no protection was provided. This demonstrates the importance of the appropriate pulsing cycle, even when the application rate is sufficient.

Figure 2. Maximum off time for a pulsing cycle as a function of wet bulb temperature.

Figure 3. Maximum off time for a pulsing cycle as a function of wind speed.

Figure 4. Sprinkled blossom temperature, mean application rate, and pulsing cycle vs. time during a 1978 frost.

Figure 5. Expanded period from 3:30-5:00 for a sprinkled blossom temperature, mean application rate, and pulsing cycle vs. time during a 1978 frost.

Figure 6. Average degrees of protection provided by sprinkling during 1978 frost.

Conclusion

Pulsing provides a method by which the amount of water required for sprinkling for frost protection may be reduced, but it is essential to determine not only the appropriate amount of water to be applied, but also the appropriate pulsing cycle to make it work successfully.

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

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1979

Introduction

Reducing the burning rate to decrease fire size has been suggested as a technique to increase efficiency of heating for frost protection. This argument is based largely upon the reduction in the depth of the mixed layer within the inversion and ignores the effect on the radiant output of the heaters. An orchard foliage temperature (OFT) model may be used to estimate the effect of the burning rate reduction on the radiant transfer to the foliage if the relationship between burning rate and stack temperature is given. Measurement of stack temperatures at 1.6 l/hr and 1.8 l/hr revealed stack temperatures appreciably lower than would be estimated by linearly extrapolating from higher rate data for much of the heater stack area. Radiant fractions decreased as a consequence of the lower stack temperatures. The introduction of constrictions within and or flanges on the outside of the stack to increase the area radiating as well as decrease the vertical flow due to bouyance up the sides of the stack failed to increase the stack temperature sufficiently to keep the radiant fraction constant with burning rate. Apparently, heater scale reduction will be necessary to keep radiant efficiency constant with reduction in burning rate beneath

¹Appendix to final report to the U.S. Department of Energy under contract No. EC-77-S-02-4397.

2 l/hr.

Reviews of heating for frost protection methodology (Crawford, 1964; Turrell, 1973; Martsolf, 1979) have indicated that the adage, large numbers of small fires are better than smaller numbers of larger fires, has been known and respected for some time. Minimizing the heater fire size necessary to provide protection is an energy conservation technique. Incentive to use such techniques is rapidly increasing with the cost of fuel.

The Orchard Foliage Temperature (OFT) model predicts the minimum fire size necessary for protecting a given percentage of the foliage elements if the relationship between fire size and stack temperature is also given (Welles, et al., 1979). Perry, et al. (1977) provided stack temperature versus burning rate relationships for several stack heaters for rates of 2.2 l/hr and above. This paper reports the stack temperatures and computed radiant fractions (RF) for burning rates less than 2.2 l/hr. These rates extend the range of the OFT model and make its predictions of energy savings due to low burning rates more convincing.

Evaluation of a simple heater stack modification envisioned to increase the heater stack temperatures--and so the RF of the heater--was performed. Air in contact with the stack side is warmed by conduction and rises by buoyancy, carrying heat away from the stack. Disruption of these vertical air movements might result in higher stack temperatures. Horizontal flanges projecting about eight cm around the stack at three levels were installed on a Scheu Auto Clean Stack heater to determine if such a technique would increase the radiant fraction for a given burning rate.

Radiant fractions resulting from the low burn rates are calculated. Comparison with RF values provided by Perry, et al. (1977) and conclusions from Welles, et al. (1979) yield insight into heating efficiency and burn rate. Finally, an error analysis of the technique used to estimate radiant fractions is presented.

Materials and Methods

A network of ten iron/constantan 30 gauge thermocouples measured stack temperatures at five levels as indicated in Figure 1. The thermocouples were silver soldered onto the stack as in Perry, et al. (1977).

Radiant energy output was calculated by the Stefan-Boltzmann Law. The stack was divided into five bands limited by imaginary horizontal lines around the stack midway between adjacent sets of points. Temperatures reported by the two thermocouples in each band were averaged and this value taken as representative of that area's temperature during each three minute scan interval. The radiant fraction (RF) was determined by dividing the radiant output by the total energy input.

Total energy input was calculated from the fuel pressure and nozzle size by the relationship reported by Martsolf (1976). A type-setting error in the paper by Martsolf (1976) caused an incorrect conversion between kiloPascals (kPa) and pounds per square inch (psi) to be indicated. The correct relation is $100 \text{ psi} = 690 \text{ kPa}$.

Shielded and aspirated thermocouples provided a measurement of ambient air temperature. Sensitive cup anemometers measured wind speed at the heater height. The experiment was conducted during the clear night of June 6, 1978, at the Pennsylvania State University's Rock

Figure 1. Scheu Auto Clean Stack heater diagrammed to indicate the heights of the thermocouple sensing levels above the base of the heater stack and the location of the added flanges and plume diffuser.

Springs Agricultural Research Center near Pine Grove Mills, Pa.

Modifications made to the stack are depicted in Figure 1. The sheet metal rings rested on screw heads protruding from the heater stack. Scheu Products Company, Inc., Upland, Ca., supplied both the heater and the modifications.

The plume diffuser (see Figure 1) has been used for the past decade on heaters in the research orchard at the Rock Springs Agricultural Research Center near the main campus of The Pennsylvania State University. Its purpose is to shield the stack from much of the rainfall that would otherwise collect in the heater bowl. There is a good possibility that it disrupts the buoyant plume causing the plume to mix with its environment (entrainment) within a more shallow layer than if the diffuser were not present. Finally, and possibly the most attractive feature, is that it eliminates the need to remove the stack caps from the heaters prior to lighting, a labor and time saving feature.

Results and Discussion

Temperatures recorded on the modified stack generally fell within the standard deviations of the unmodified stack temperatures. When this was not the case, the modified stack was cooler. Laboratory measurements made by the heater manufacturer, Scheu Products Company, Inc., Upland, Ca., indicated a slight increase in stack temperatures due to the modifications. It is believed testing under field conditions negated the beneficial effects of the modifications. Wind speed during the measurements presented here averaged about 1.5 ms^{-1} , in contrast to the presumably calm conditions in the Scheu Laboratory. However, Perry, et al. (1977) were able to show no significant effect of wind speed on

stack temperature. Though there was always some wind drift during the field tests of Perry, et al. (1977). Perhaps even low wind speed disrupts the vertical flow that prevents the modifications from functioning as envisioned at the low burn rates. Under field conditions, both the lower ambient air temperature and decreased background radiation may result in departures from laboratory data.

Stack temperatures of an unmodified stack are plotted in Figure 2 and the corresponding radiant fractions are plotted in Figure 3. Both stack temperature and RF values at burn rates greater than 1.8 l/hr are from Perry, et al. (1977).

An error analysis was performed on the RF estimates. The absolute error on RF was calculated according to the procedure described by Fritton (1974). Uncertainty in temperature of each stack area was estimated by the standard deviation of the averaged temperatures for a particular site on the heater stack. Errors in area measurement and temperature interpolation are included in the area value error, taken to be $\pm 5\%$ of each stack area. Oil pressure measurements were given an uncertainty of $\pm 2\%$, which includes both gauge reading errors and calibration errors. The possibility of nozzle wear or clogging altering the oil flow rate is not addressed by this error.

At an oil pressure of 345 kPa (~ 1.6 l/hr) the stack temperatures yielded a radiant output of 2546.17 ± 308.83 W. Total energy output was calculated by the relationship described in Martsolf (1976) based on a pressure of 345 kPa ± 1.9 kPa. This pressure yields the 1.6 l/hr flow rate, which when multiplied by 10850 Whr/l (the energy content of the fuel oil), resulted in a total energy output of 17355 W. The radiant fraction obtained by dividing the radiant output by the total output

Figure 2. Stack temperatures as a function of burn rate and location on stack from this study (▲) and Perry, et al. (1977) (Δ).

Figure 3. Radiant fractions (%) of an unmodified stack at five burn rates (l/hr). Radiant fraction values at burn rates greater than 1.8 l/hr are from Perry, et al. (1977).

yielded $14.7 \pm 2.5\%$. About 20% of the error in the RF is from uncertainty about the radiant output, the rest from possible error in the pressure. Appreciable uncertainty surrounds estimates of RF made in the manner described here. A similar analysis yielded a RF of $21.0 \pm 3.9\%$ at 421 kPa pressure (1.8 l/hr).

The OFT model provides convincing evidence that as the RF decreases so also the efficiency of the heater in providing protection to the foliage elements decreases. Consequently, with the Scheu Auto Clean Stack heater a reduction in burning rate beneath 2 l/hr should not be expected to necessarily increase the heating efficiency. Two factors seem to be of opposite effect. A decrease in burning rate would seem to decrease the depth of the mixed layer (Crawford, 1964) and as long as that layer does not decrease to the point that the tree layer is no longer covered the decreasing of the burn rate would seem to increase the heating efficiency per unit of input energy. This paper indicates that for the size heater tested there is an opposite effect on the radiant fraction. The heater seems to lose the ability to maintain stack temperatures that permit an acceptable portion of the energy to be transmitted by radiation, i.e. the radiant fraction decreases more rapidly with burn rate at the lower end of the scale. While confidence in the radiant fraction determinations also decreases with burn rate there still appears to be ample evidence that the radiant fraction is really decreasing as the burn rate drops beneath 2 l/hr and to question whether such a procedure is advisable from an efficiency standpoint.

Conclusions

If heating for frost protection is to be continued it would seem advisable to consider the development of a heater of a smaller size that

may be able to develop high stack temperatures at lower burning rates. The simple modifications attempted in this research did not seem to compensate for the decrease in the RF at the lower burning rates. However, tests were not made during very calm conditions and it may be found that the modifications do compensate during such conditions.

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APPENDIX F

Reducing Energy Loss Under an Orchard Heater¹

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1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

Reducing Energy Loss Under an Orchard Heater^{1/}

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Received for publication _____. Paper No. _____ of
the Journal Series of the Pennsylvania Agricultural Experiment
Station. Supported by U.S. Department of Energy Research Contract
EC-77-S-02-4397, Northeast Regional Project NE-48, and Hatch project
2207. Authorized for publication _____.

2/
Associate Professor of Soil Physics and Professor of Microcli-
matology, respectively.

1
2 Additional index words. Frost protection, energy conservation,
3 soil heat flux.

4 Abstract. About two percent of the energy used in orchard heating
5 moves into the soil under an orchard heater and is wasted. With an
6 objective of eliminating this loss of energy, gravel and aluminum
7 foil were placed on the soil surface under an orchard heater. When
8 an air gap existed between the heater base and the aluminum foil, heat
9 flux and temperature measurements showed that the aluminum foil treat-
10 ment reduced heat flux into the soil by 80-100%. The gravel treatment
11 was relatively ineffective.

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2 Orchard heating has historically been a favorite frost protection
3 technique. Under the increasing fuel costs of today, this method is
4 being analyzed for energy savings using the box model approach of
5 Martsolf and Panofsky (2) and in some cases is being replaced by more
6 energy efficient frost protection techniques. In a study of orchard
7 heaters, Fritton and Martsolf (1) found that about two percent of the
8 energy used in an orchard heater was moving into the soil without
9 contributing to frost protection. Welles, et al. (4) have shown
10 that eliminating this loss is equivalent to an energy savings of
11 about four percent. Since much of the six million or more barrels of
12 oil used in frost protection in a typical year (5) is used in orchard
13 heating, this study was undertaken to find ways to reduce or eliminate
14 energy loss to the soil. Two possible energy conservation techniques
15 were studied experimentally and energy loss for each was compared
16 with that of bare soil under an orchard heater.

17 The experimental site and instrumentation were identical with
18 that used by Fritton and Martsolf (1). The study was located in an
19 experimental apple (Malus sylvestris L.) orchard on Hagerstown silt
20 loam (Typic Hapludalf) soil. A Scheu Auto-Clean-Stack orchard heater
21 was used with its base located 2-3 cm above the soil surface. Oil
22 was fed into the heater from a pipeline system through a nozzle
23 and ignited on the inside upper surface of the base of the heater.
24 The heater was lit and allowed to burn out and cool before each run
25 in the Spring of 1978 to guarantee that all old oil had been burned.
26 This precaution had not been taken in earlier runs. Fuel oil used
27 was measured with a flow meter.

1
2 The heat flux at the soil surface was measured at 0.0, 0.5,
3 and 1.0 m from the heater center. Heat flux plates buried at a 5-cm
4 depth were corrected for heat stored above 5 cm using soil temperature
5 data collected at depths of 0.0, 2.5, 5.0, 9.0, and 27.0 cm near each
6 heat flux plate. Temperature data was measured with four thermocouple
7 thermopiles with the reference junctions placed between iron plates
8 buried at the 30-cm depth. The reference junction temperature was
9 monitored with three thermocouples which were averaged. All heat
10 flux and temperature data were collected at three minute intervals.

11 Soil samples were taken near each concentration of instruments
12 for water content. These water content data were combined with pre-
13 viously taken bulk density data at this site and with specific heat
14 capacity values for this soil series (1) to calculate the heat
15 capacity of the 0 to 5-cm layer. The data analyses paralleled
16 similar analyses made by Fritton and Martsolf (1) resulting in a
17 surface soil heat flux at the 0.0, 0.5, and 1.0-m locations and a
18 spatially integrated surface soil heat flux.

19 Experimental data was collected with three surface soil
20 treatments: bare, gravel covered, and aluminum foil covered. The
(Fig. 1) 21 gravel treatment (Fig. 1) consisted of a one-layer thickness of a
22 white quartz landscaping gravel which covered about 80% of the soil
23 surface. The heater base was located 2 cm above the soil, gravel,
24 or aluminum foil surface during each run. The aluminum foil
25 treatment (Fig. 1) consisted of Heavy-duty Reynold's Wrap aluminum
26 foil placed on the soil surface for the Fall 1977 run and of 0.001-cm
27

1
2 aluminum foil laminated onto 0.01-cm black plastic (Stauffer
3 Chemical Company, Westport, Conn.) for the Spring 1978 run. The
4 aluminum foil proved to be inadequate immediately under the heater
5 in the Spring 1978 run and was replaced with the heavy-duty aluminum
6 foil a few minutes after starting the run. All materials covered an
7 area approximately 1.5 m in radius. Runs lasted approximately 0.6 hr
8 in the Fall of 1977 and 2.7 hr in Spring 1978. All runs were made
9 on radiation cooling nights and occurred in the very early morning
10 hours between midnight and dawn. All runs after 1976 used a constant
11 oil pressure of 80 PSI (0.54 megapascals).

(Fig. 2) 12 The two bare soil surface runs show the high temperature (Fig. 2) and
(Table 1) 13 large downward surface heat flux (Table 1) normally associated with an
14 orchard heater. The run of 1976 resulted in soil surface temperatures
15 of nearly 250°C while the 1978 run gave temperatures in the 150°C
16 vicinity. These temperatures are lower than the stack temperatures
17 measured on the orchard heater itself which ranged from 250-575°C (3).
18 Thus, the soil surface comes into an equilibrium with the high tem-
19 peratures on the bottom of the orchard heater.

20 The gravel treatment (Fig 2 of Table 1) had a delaying effect
21 on the rate at which heat crossed the soil surface but this effect
22 may be explained by the presence of the gravel. In this case, the
23 gravel heats up first and this energy is no more available for
24 heating the orchard than it is when it crosses the soil surface.
25 Thus, a gravel layer below the orchard heater is not effective in
26 eliminating downward energy flow into the soil.
27

1
2 The data (Fig. 2 and Table 1) show that for the aluminum foil
3 treatment nearly all energy flow across the soil surface is eliminated.
4 For the December 3, 1977 data, the soil surface temperature rose only
5 2°C after nearly 0.7 hr of heating and heat flowed upward across the
6 soil surface. The May 3, 1978 aluminum foil treatment data indicate
7 a 15-35°C rise in soil surface temperature. This temperature rise is
8 a result of using thin aluminum foil laminated on black plastic instead
9 of a heavier grade of aluminum foil. The use of this laminated alumi-
10 num foil looked promising from a practical viewpoint because the
11 December data showed so little temperature increase. The polyester
12 which formed the backing to the laminated aluminum foil has a service
13 temperature maximum between 121 and 204°C. This temperature was
14 apparently exceeded in one point at a hot spot under the heater
15 causing the aluminum material to tear. Once heavier aluminum foil was
16 placed below the heater on the laminated product, the soil surface
17 temperature dropped and stayed nearly constant throughout the remainder
18 of the fired period. It is concluded that aluminum foil placed below
19 an orchard heater with an air gap between the heater and the aluminum
20 foil will effectively cut off the downward flow of energy.
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Table 1. The heat flux at the soil surface averaged over a 100 - cm - radius circle around an orchard heater for the period of time during which the heater was lit.

Treatment	Date	Surface heat flux mw/cm ²
Bare soil	May 23, 1976	24.4
Bare soil	May 4, 1978	19.0
Gravel	April 29, 1978	10.0
Aluminum foil	May 3, 1978	3.8
Aluminum foil	December 3, 1977	-1.3

Figure 1. Photographs showing gravel (left) and aluminum foil (right) placed on the soil surface under an orchard heater to reduce downward energy loss.

Figure 2. Soil surface temperature under an orchard heater when the soil surface was bare and when gravel and aluminum foil were placed on the soil surface.

APPENDIX G

Solar Energy, Soil Management, and Frost Protection¹

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University Park, PA 16802

1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

1
2 Solar Energy, Soil Management, and Frost Protection 1/

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17 1/ Received for publication _____. Paper No. _____

18 of the Journal Series of The Pennsylvania Agricultural Experiment
19 Station. Supported by U. S. Department of Energy Research Contract
20 EC-77-S-02-4397, Northeast Regional Project NE-48, and Hatch
21 project 2207. Authorized for publication _____.

22 2/ Associate Professor of Soil Physics and Professor of Microclimatology,
23 respectively.

24 3/ We acknowledge the extensive technical assistance of Mr. John B.
25 Allison. The Stauffer Chemical Company of Westport, Connecticut
26 supplied the aluminum polyester laminate.
27

1
2 Additional index words. Plastic mulch, soil heat flux, soil temperature

3 Abstract. Management of the soil as a source of energy was investigated
4 to evaluate possibilities for the conservation of oil presently used
5 in frost protection. Two treatments involved the use of plastic and
6 aluminum foil covers to trap solar energy. Maximum benefit was
7 indicated for bare soil covered with plastic during the day and
8 uncovered just before critical temperatures are reached at night.
9 Bare soil and plastic covered mowed grass gave an intermediate benefit
10 while the mowed grass management scheme gave the least benefit to
11 frost protection

12 The soil is a major source of energy available to protect
13 vegetation against frost injury. While it is generally recommended
14 that the soil be kept bare, firm, and moist (6) to maximize this soil
15 energy source, few studies have measured the benefit of following
16 such a recommendation. Three studies which support the recommendation
17 are Gradwell (4) who concluded that the difference between a dense
18 and a loose soil could account for the reduced frost hazard on the
19 dense soil; Fritton, Martsolf, and Busscher (2) who showed that
20 50-80% of the nighttime net radiation loss from an orchard was derived
21 from the soil; and Cochran, Boersma, and Youngberg (1) who concluded
22 that soil properties caused a pumice area to have frequent radiation
23 frosts and therefore a different vegetation than the surrounding area.

24 Since over six million barrels of oil are used in protecting
25 orchards from frost in a typical year (8), the role of soil management
26 in frost protection deserves more attention. This paper discusses
27

1
2 the results of an experiment which compares bare soil with a soil
3 managed with a mowed grass cover crop and with both soil management
4 schemes when covered with plastic to trap solar energy during the
5 day to be later released when needed during the night. The overall
6 objective is to provide quantitative soil information and relation-
7 ships which can be used in models of the orchard foliage temperature
8 (7), and of orchard frost protection (5).

9 Eight plots (5 m x 5 m) arranged in two blocks of four plots
10 each were located in an experimental apple (Malus sylvestris L.)
11 orchard located on the Pennsylvania State University Agricultural
12 Research Center at Rock Springs. The soil in the area is a Hagerstown
13 silt loam (Typic Hapludalf). The four treatments consisted of bare
14 soil, grass covered soil, bare soil covered with plastic during the
15 day and plastic and aluminum foil during the late afternoon and
16 evening with both covers removed during the predawn hours when radiant
17 frosts are most likely to occur, and grass covered soil with plastic
18 covers managed the same way as the previous bare soil treatment.
19 All plots were originally managed as mowed grass. In order to prepare
20 the bare soil plots, all vegetation was cut at the mineral soil
21 surface and both the vegetation and a layer of organic residue were
22 removed. The plastic covers were constructed from transparent
23 (clear) plastic of 0.01-cm thickness. The aluminum foil covers
24 were constructed from aluminum polyester laminate which had a 0.001-cm-
25 thick layer of aluminum laminated onto a 0.01-cm-thick black polyester
26 plastic. All covers were weighed down at the edges to reduce
27 ventilation losses of energy and constructed so that they could

1
2 be rolled across a plot.

3 At the center of each plot, a set of instruments were buried to
4 measure the surface soil heat flux. The heat flux was measured at
5 the 5.0-cm depth using heat flux plates constructed in a manner
6 similar to Fuchs and Hadas (3). The heat flux was then corrected for
7 the heat stored in the top 5.0 cm of the soil using measurements of
8 soil temperature at the 0.0, 2.5, 5.0, 9.0, and 27.0-cm depths, water
9 content and bulk density of the 0 to 5.0-cm layer, and the specific
10 heat capacity using techniques similar to Fritton, et al. (2).

11 Soil temperatures were measured with four junction thermopiles with
12 the four reference junctions placed between two metal plates buried
13 at the approximately 30-cm depth and monitored with a thermocouple.
14 All sensors were placed in an undisturbed wall of a pit dug in the
15 center of each plot. The pits were then back filled and wet down to
16 reestablish a more normal compaction. All areas were allowed suffi-
17 cient time to return to moisture equilibrium before data collection.

18 Data were collected at five minute intervals at the end of the
19 afternoon of May 22, 1978 before and just after the plots were covered
20 with the plastic laminate cover on a near-frost night which had typical
21 radiation cooling. Plots had been covered with the clear plastic at
22 1028 true solar time (TST) and with the plastic laminate at 1605 TST.
23 Another set of data was collected before and just after the plots
24 were uncovered (0150 TST) during the early morning hours of May 23,
25 1978. Data analysis followed procedures developed by Fritton, et al.
26 (2) and resulted in a surface heat flux value for each plot for each
27 five minute interval.

1
2 The soil surface temperature (Fig. 1) at the end
3 (1605 TST) of the solar energy trapping treatment (clear plastic
4 covered) showed large differences between treatments. The grass plots
5 without plastic covers had the lowest temperature (19-25°C) at this
6 late afternoon time. The bare soil surface without covers was consid-
7 erably warmer with temperatures between 30 and 35° C. The grass plots
8 with plastic covers were somewhat warmer than the uncovered plots
9 ranging from 32 to 38 °C and the bare covered plots were the warmest
10 at 37 to 41°C. The surface soil temperature in all plots was decreasing
11 at 1600 TST and continued to decrease throughout the night. Vegetation
12 in the covered grass plots was severely injured by the high temperatures
13 during the day. In one of the plots this injury was more severe than
14 in the other. In this plot, the upwind side of the plot had less
15 injury probably indicating that some ventilation was taking place
16 during the day. Differences in vegetation also caused variation in
17 the soil surface temperatures of the grass plots whether covered or
18 uncovered.

19 Soil surface temperatures were again monitored for an hour
20 starting at 0053 TST before the surface plastic covers were removed.
21 All plots were still cooling and temperature differences between
22 treatments had narrowed. The grass plots were at about 10°C, the
23 bare soil between 10 and 12°C, the covered grass at about 13°C,
24 and the bare covered plots at about 17°C. Upon removal of the covers,
25 the bare soil which had been covered showed an immediate response
26 and cooled quickly to below 12°C. The grass plot which had been
27

1
2 covered showed some acceleration in cooling but at a much reduced
3 level. The bare and grass plots which had never been covered con-
4 tinued the cooling trend observed earlier in the evening.

5 The average heat flux at the soil surface for each of the four
6 treatments is shown in (Fig. 2). Considerable scatter is shown in
7 the individual data points and only the trend lines are drawn in
8 Fig. 2. The bare soil which had not been covered released energy
9 at a rate twice that of the grass plot (-6.5 versus -3.5 mw/cm^2).
10 The grass plot which had been covered released heat at the same or at
11 a greater rate than the bare soil for a short period of time and then
12 dropped below the bare soil rate after about one hour. The bare
13 soil which had been covered, on the other hand, released a large
14 quantity of heat reaching the equivalent of one-half of full sunlight
15 for a very short period of time and staying above -10 mw/cm^2 for the
16 whole two-hour cooling period. This represents a greater than doubling
17 of energy output when compared to the bare soil which had not been
18 covered.

19 It is concluded that bare soil gives off more energy than a grass
20 covered soil at least when the radiant cooling night follows a bright
21 sunny day. It is also evident that covering a bare soil results in a
22 large increase in energy available for frost protection while covering
23 a grass surface results in an amount of energy available for frost
24 protection approximately equivalent to maintaining a bare soil plot
25 uncovered.
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8. Wynn, N. A. 1977. A guide to energy savings for the orchard grower. Commodity Economics Division, Economics Research Service, United States Department of Agriculture and Federal Energy Administration Report. 49 pp.

1
2 Figure 1. Soil surface temperature for a radiation cooling night for
3 bare and grass covered plots some of which were covered with
4 plastic during the daylight hours.
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14 Figure 2. Soil surface heat flux for a radiation cooling night just
15 before and after plastic covers were removed from bare and
16 grass covered plots.
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APPENDIX I

Sprinkler Distribution Versus Leaf Development
During Frost Protection¹

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University Park, PA 16802

1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

SPRINKLER DISTRIBUTION VERSUS LEAF DEVELOPMENT
DURING FROST PROTECTION

by

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For presentation at the 1979 Summer Meeting
of ASAE and CSAE

University of Manitoba
Winnipeg, Canada
June 24-27, 1979

SUMMARY: Three-dimensional sprinkler distributions were obtained for an apple orchard. Uniformity coefficients (UC) were computed for three locations within the trees and for the whole tree at six stages of blossom development. The dispersion caused by the foliage improved the UC values with depth downward through the canopy for sprinklers with poor distributions but the foliage disrupted water movement, thus decreasing the UC values for well designed sprinklers.

Joint Meeting of
American Society of Agricultural Engineers
and
Canadian Society of Agricultural Engineering

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Sprinkler Distribution Versus Leaf Development¹ During Frost Protection

by

A.R. Jarrett, C.T. Morrow, K.B. Perry, J.D. Martsolf²

INTRODUCTION

Overtree irrigation water has been applied to fruit trees in the early Spring for cooling to achieve bloom delay during the "post rest" period and for warming to achieve frost protection if necessary during late Spring frosts. Irrigation water has also been applied to apples and other fruit to provide cooling during warm periods when fruit are maturing. In most cases, cooling water is applied with conventional kicker-type irrigation sprinklers, most of which are designed to distribute water on the soil surface.

Little effort has been devoted to determining how well conventional sprinklers distribute water throughout a fruit tree where water is required for the irrigation activities just discussed. Karmeli and Walker (1976) determined the impact of foliage at various heights above the soil surface by collecting water in catch cans placed on the orchard floor. Buds and fruit, however, are distributed throughout the tree canopy and not on the orchard floor.

The objective of this experiment was to determine how well water applied from overtree sprinklers was distributed to various locations within an apple tree canopy as a function of bud and leaf development. The uniformity coefficient (UC) developed by Christiansen (1942) and defined by

$$UC = 100 \cdot \left(1 - \frac{d}{m}\right)$$

and

$$d = \frac{1}{n} \sum_{i=1}^n |x_i - m|,$$

¹This research was supported in part by ERDA (DOE) Grant NO. EC-77-S-02-4397, by a grant on Calcium Nutrition of Pome Fruits from the Pennsylvania Department of Agriculture and by the Agricultural Experiment Station, The Pennsylvania State University, University Park, PA 16802.

²Assistant Professor, Department of Agricultural Engineering; Associate Professor, Department of Agricultural Engineering; Graduate Student, Department of Horticulture; and Professor, Department of Horticulture, The Pennsylvania State University, University Park, PA, respectively.

where x_i = the depth in each sampling container
 n = the number of sampling containers
 m = the mean depth in all sampling containers

was used as a measure of the uniformity of water distribution. The uniformity coefficient is equal to 100 percent when all sampling containers have the same depth of water after a run. As the UC decreases, the uniformity of distribution also decreases. A UC of 70 percent is usually the minimum accepted value for agricultural field crop irrigation, (Karmeli and Peri, 1977).

EXPERIMENTAL PROCEDURE

Six apple trees in each of two experimental blocks were instrumented with twenty five 10.0-cm long by 1.27-cm diameter vertical sided test tubes spaced on a five by five horizontal square grid with 0.61 m between test tubes in each direction. The center of each grid was located at the center of a tree. Two trees in each block were instrumented 0.91, 1.52 and 2.13 m above the orchard floor, respectively. Separate trees were used for each replication and treatment to prevent changes in catch volumes at lower elevations caused by experimental apparatus located higher in the tree. Both blocks contained 2.5-m high trees spaced 3.0 m apart along each row and 5.5 m between rows, Fig. 1.

Water applied to trees in the South Block was distributed by Reed Irrigation Systems Inc., Browning sprinkler with one #07 nozzle per sprinkler operating at 140 kPa pressure. One sprinkler was centered above each tree at a height of 3.0 m. Each Browning sprinkler discharged 1.32 l/min over an 8.0-m diameter circular area. This sprinkler arrangement produced overlapping coverage in the rows but no double coverage of water between rows. The average distribution of water applied to the 2.13-m height of each tree in the South Block is shown in Fig. 2. This distribution has a UC of 76.1 percent and an average application rate of 1.20 cm/hr.

Sprinkler distribution tests were run simultaneously on all trees in the South Block on April 25 and 30 and on May 2, 9, 11 and 22, 1979. During this period the leaves and blossoms developed from nearly no leaves and small buds on April 25th to fruit set and full leaf development on May 22nd. The South Block is normally used for a frost protection experiment. Distribution data were collected during a frost protection run during the early morning of May 2nd, but water dripping into test tubes from above during the melt period produced depths of application which were much larger than were applied by the sprinklers.

Water applied to trees in the North Block was distributed by Weathertec 10-10 kicker-type sprinklers with 1.984-cm (5/64-in) diameter nozzles operating at 280 kPa pressure. Each sprinkler discharged 4.24 l/min over a 12.2-m diameter circular area. Sprinklers were located 3.0 m above the orchard floor with 12.2 m between sprinklers in the rows and 11.0 m between rows. This rectangular layout, shown in Fig. 1, applied

water at 0.190 cm/hr. A second identical sprinkler system was placed in alternate orchard rows and staggered two trees, or 6.1 m. This permitted the flexibility of applying water for bloom delay at 0.190 or 0.380 cm/hr depending on weather conditions. The average distribution of water applied to the 2.13-m height of each tree in the North Block is shown in Fig. 3. This distribution has a UC of 81.9 percent and an average application rate of 0.35 cm/hr.

Sprinkler distribution tests were run simultaneously on all trees in the North Block on May 2, 9, 18 and 22, 1979. During this period the leaves and buds developed from no leaves and no buds on May 2nd, to full leaf development on May 22nd. None of the tests were run during frost conditions.

RESULTS AND DISCUSSION

The results will be presented and interpreted as if the data at each instrumented tree were combined to form a single tree with two replications at each of three heights above the orchard floor as shown in Fig. 4. The uniformity coefficients defined earlier and the application rates were computed for each height instrumented within the tree and for the whole tree on each date of testing.

South Block

Uniformity coefficients (UC) computed for each of three heights above the orchard floor and for the three heights combined (whole tree) are presented in graphical form in Fig. 5 for each date. Sprinklers in this block distributed water to the 2.13-m height with a UC of 76 percent when no interference was present from the tree. When the tree branches were present, the UC at the 2.13-m height was only 65 percent throughout the early stages of bud development. After the "tight cluster" stage, however, the UC at the 2.13-m height started to increase, due to dispersion from the tree limbs and buds, to a UC of 76 percent at the "full-bloom" stage. After "full bloom" on May 11, the UC decreased rapidly to a value of 61 percent on May 22nd.

While the UC at the 2.13-m height started low and increased before decreasing after "full bloom", the UC at the 0.91- and 1.52-m heights started at about 80 percent and decreased slowly to 72 percent at "full bloom". These relatively high values of UC indicate that as water passed downward through the tree during this period the poorer distribution at the tree top was improved as it penetrated the tree. After "full bloom" on May 11, the UC at both heights decreased rapidly to a UC of 50 percent by May 22. This shows that after "full bloom", the dispersion within the tree actually reduced the evenness of distribution at lower levels.

The UC for the whole tree followed a decreasing pattern during the first stages of bud development. It then increased to about 70 percent at "full bloom" followed by a rapid decrease as was also shown by the UC at all other heights. It should be noted, that whole tree UC reflect the greatest variability present in the individual height data.

The average application rates observed at each instrumented height are plotted in Fig. 6. The application rates at the 2.13-m height increase throughout the early spring from a low of 0.8 cm/hr to a high of 1.4 cm/hr. This increase shows that foliage developing near the tree top served to deflect greater quantities of water to the 2.13-m height. The depth of water reaching lower levels of the tree decreased sharply in the region between 1.52 and 2.13 m. At the 1.52-m height the average application rate, again started low, when bud development was minimal, at about 0.6 cm/hr and increased at the same rate as reported for the 2.13-m height to 0.96 cm/hr. The difference between the application rates at 1.52- and 2.13-m height averaged about 0.33 cm/hr and was due to water being intercepted and/or diverted in this region of the tree. There was approximately the same amount of water reaching the 0.91-m height as reached the 1.52-m level. The application rate values also followed the same general increasing pattern as observed at the 1.52-m height during the leaf and bud development. The only exception occurred after the "full bloom" stage, when there was an additional loss as the water penetrated the 1.52-m to 0.91-m heights. This decrease can probably be attributed to the more highly developed leaves in the tree during this period.

Most of the variability shown throughout the test period in the South Block can not be correlated to weather conditions, Table 1. The flat sections shown at all heights as a result of the May 2nd data, however, may be caused by the very low relative humidity conditions present on May 2nd. Otherwise, the application rates may have increased through that period also.

The whole tree data shown was the average of the data presented at all three tree heights. It also shows a generally increasing application rate with the possible exception of a slight decrease between April 25th and 30th.

North Block

Uniformity coefficients computed for each of three heights above the orchard floor and for the three heights combined are presented in Fig. 7 as a function of time. Sprinklers in the North Block distributed water to the 2.13-m height at an average UC of 82 percent when there was no interference from foliage. This high UC at the 2.13-m height was maintained throughout the experimental period until the buds reached the "full-bloom" stage. At this point, there was a decrease to 77 percent at the "post-bloom" stage.

As the water penetrated the tree to the 1.52-m height, the UC values remained high, in fact higher than at the 2.13-m height, for the "1/2-inch-green-tip" to "tight-cluster" stages. After the "tight-cluster" stage, the UC values started to decrease, reaching 70 percent at "full bloom" and only 45 percent at the "post bloom" stage. This trend indicates that dispersion resulting from water contacting the developing leaves and buds, exerted a beneficial influence during the May 2nd to May 9th period, but served to severely disrupt the water movement as the buds approached "full bloom" and then causing very poor distribution after "full bloom".

The uniformity of distribution at the 0.91-m height followed a pattern similar to that observed at the 1.52-m height until the "full-bloom" stage, except the UC values were about six percent less than at the 1.52-m height. Additional dispersion in the lower region of the trees can easily explain this poorer distribution. At the 0.91-m height, there was no severe reduction in UC values after the full bloom stage. The whole tree UC values followed about the same trend as was observed at the 1.52-m height.

The application rates observed at the 2.13-m height followed the same trend as recorded for the UC values, Fig. 8. An application rate of about 0.35 cm/hr occurred until the "full bloom" stage when the dispersion in the upper tree region caused the application rate to decrease to 0.26 cm/hr. The application rate at the 1.52-m height was 0.36 cm/hr at the "1/2-inch-green-tip" stage. It decreased to 0.30 cm/hr at the "tight-cluster" stage and then remained about constant until "full bloom" when it decreased to 0.27 cm/hr. These data would indicate that nearly all of the water reaching the 2.13-m height was penetrating to the 1.52-m height. At the 0.91-m height, the application rate was 0.51 cm/hr at the "1/2-inch-green-tip" stage. This extremely high value may be subject to error or it may be that after water reached the 1.52-m height, the intensity of application was concentrated to give increased application rates. The application rate by the "tight-cluster" stage, had decreased to 0.33 cm/hr, a value approximately equal to that observed at the other heights during that particular stage of development. At the 0.91-m height, the application rate continued to decrease as the buds reached "full-bloom" and the "post-bloom" stages. The average application rate observed for the whole tree decreased as the buds developed during the period when frost protection is commonly required.

Weather data, presented in Table 2, do not correlate well with the variability observed in the application rates. Evaporation during dry warm days was obviously higher, but the experimental procedure was not sophisticated enough to show these variations. The temperature and relative humidity changes from day to day were not widely varied, leading to the lack of correlation observed.

SUMMARY AND CONCLUSIONS

Sprinkler distribution tests were conducted in two experimental apple orchard blocks. Water was collected in test tubes located 0.91, 1.52 and 2.13 m above the orchard floor. Christiansen uniformity coefficients and application rates were computed for each instrumented height on selected days during the period when the buds developed from the "1/2-inch-green-tip" stage to the "post-bloom" or "fruit-set" stages.

The uniformity coefficients computed at the 0.91- and 1.52-m heights showed a decreasing trend ranging from about 80 percent at the "1/2-inch-green-tip" stage to 55 percent at the "post-bloom" stage. Uniformity coefficients near the tree tops remained nearly constant in

the block with conventional kicker-type sprinklers, averaging about 82 percent throughout the period. In the block with Browning spinner sprinklers over each tree, the UC values near the tree top increased from 65 percent at the "1/2-inch-green-tip" stage to a peak value at "full bloom" of 76 percent, then decreased to 62 percent after "full bloom".

Average application rates observed in the block with conventional sprinklers showed a slight trend toward decreasing application rates at all instrumented heights ranging from 0.40 cm/hr at the "1/2-inch-green-tip" to 0.24 cm/hr at the "post-bloom" stage. Application rates measured in the block with Browning spinner sprinklers showed a general trend toward increasing application rates, ranging from 0.65 cm/hr in the early stages of bud development to 1.0 cm/hr at "fruit set".

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Table 1. Weather conditions and stage of bud development existing on data collection days in the South Block.

Date	Dry Bulb Temperature	Relative Humidity	Bud Development
	°C	%	
4/25/79	25	42	1/2-in green tip
4/30/79	19	44	tight cluster
5/2/79	19	22	tight cluster
5/9/79	31	61	first bloom
5/11/79	28	51	full bloom
5/22/79	25	40	fruit set

Table 2. Weather conditions and stage of bud development existing on data collection days in the North Block.

Date	Dry Bulb Temperature	Relative Humidity	Bud Development
	°C	%	
5/2/79	25	22	1/2-in green tip
5/9/79	31	61	tight cluster
5/18/79	21	40	full bloom
5/22/79	19	40	post bloom

Fig. 1. Position of trees instrumented for sprinkler distribution tests.

Fig. 2. Average application rate in cm/hr. applied to the 2.13-m height at each instrumented tree in the South Block.

Fig. 3. Average application rate in cm/hr applied to the 2.13-m height of each instrumented tree in the North Block.

Fig. 4. Conceptualization of tree instrumented at three heights.

Fig. 5. Uniformity coefficients at three heights within an apple tree in the South Block.

Fig. 6. Average application rate for three heights within an apple tree in the South Block.

Fig. 7. Uniformity coefficients at three heights within an apple tree in the North Block.

Fig. 8. Average application rate for three heights within an apple tree in the North Block.

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APPENDIX K

Sprinkling for Bloom Delay in a Humid Climate¹

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1979

¹Appendix to final report to Department of Energy under contract No.
EC-77-S-02-4397

INTRODUCTION

Conventional methods of frost protection, using oil-fired orchard heaters, have become more costly as fuel prices have continued to increase. Thus, more energy-efficient and economical frost protection techniques must be developed.

Sprinkling for bloom delay offers one method of reducing energy required for frost protection. Blossom and fruit loss may be avoided by delaying bloom; a later bloom period would reduce the probability of experiencing severe frost during bloom.

Two temperature-based models, formulated at Utah State University in 1972, have been used to predict phenological development. The Chill Unit and Growing Degree Hour Models were developed to relate accumulation of chill units and growing degree hours with the end of rest and the initiation of sprinkling for bloom delay.

Since these models were developed under Utah conditions, the objectives of this research were to determine if bloom delay was feasible under conditions of high relative humidity in central Pennsylvania, and to provide a test for the Chill Unit and Growing Degree Hour Models.

LITERATURE REVIEW

Sprinkling for bloom delay was first investigated at Utah State University in 1972. From the Utah research, two predictive models were formulated (1,2,28,29). Within the Chill Unit Model, one chill unit equals one hour of exposure to a temperature of 6°C . As temperatures rise and fall about the optimum temperature of 6°C , temperature effects are reduced (Fig. 1). Negative chill units accumulate when temperatures exceed 15°C , and no chill units are accumulated when subfreezing temperatures occur. Positive chill units begin to accumulate the day after the maximum negative chill unit accumulation occurs in late summer or early fall (16). A mathematical technique was developed to estimate the number of chill units necessary to complete rest for a specific cultivar (3). From applications of this technique, an accumulation of 1234 chill units was reported to be necessary to complete the chilling requirement for 'Delicious' apples (1,2,3,16).

The Chill Unit Model is based solely on temperature (1,2,16,28,29). The model gives little indication of the physiological processes occurring during the time interval between the initiation of dormancy, a period in which endogenous factors prohibit growth (18), and termination of rest in early spring. In late summer or early fall, dormancy may be induced by short day length, senescent

Figure 1. Conversion of air temperature to Chill Units
Richardson et al. (1975)

foliage, exposure to lower temperatures, or by a combination of these factors (32,33). However, temperature has been recognized as the most significant factor in triggering the onset of dormancy (13,33). Periodic exposure to low temperatures is necessary in apple and many other woody perennials for the resumption of normal growth (8). The intensity and duration of chilling has been reported to significantly influence the number of days required to reach full bloom (26,27). Failure to experience lower temperatures of adequate duration, necessary to satisfy the chilling requirement, has been shown to delay flowering (27,30). Additional chilling, beyond the chilling requirement, has been shown to reduce the number of days needed for plants to reach full bloom (25).

The concept of the growing degree hour was developed when the conventional growing degree day was recognized as being too large an energy unit for use in modeling plant growth (3,16). The growing degree hour Celcius (GDH) was defined as one hour of exposure at one degree above a base temperature of 4.4°C (16); and in Figure 2, $\text{GDH}^{\circ}\text{C}$ are calculated by subtracting 4.4°C from each hourly temperature between 4.4° and 25°C .

A number of assumptions have been incorporated into the Utah model. Temperatures below 4.4°C or above 25°C are assumed to contribute to the completion of chilling like 4.4° or 25°C . It is assumed that no growth may occur below

Figure 2. Conversion of bud temperature to growing degree hours °C
Griffin (1976).

the base temperature of 4.4°C . In the Utah Model, rootstock is assumed to exert no influence upon the date of bloom; and the range, from 4.4°C to 25°C , is assumed to be valid for all fruit tree species (15,16).

The influence exerted by rootstock upon the chilling requirements and the growing degree hours needed to reach full bloom has not been assessed for apples. However, for pear cultivars, rootstock had no effect on the date of full bloom (14). Young and Olcott-Reid (40), using Siberian C peach seedlings as rootstocks, reported later development and a consistent five-day delay of full bloom of peach scions possessing Siberian C rootstocks.

The number of growing degree hours necessary for 'Delicious' apple and several other species to attain various phenological stages has been established (3). Using the Chill Unit Model, the end of rest can be predicted. Upon the completion of rest, sprinkling should be initiated to be most effective in the promotion of bloom delay (6,15,20). When rest ends, the accumulation of growing degree hours begins; through accumulation of heat units in sprinkled and nonsprinkled orchards, the models have been used to predict differences in date of bloom for each block with varying degrees of success (1,2,3,5,16,19,34). Predictions accurate to within three or more days between the predicted and observed dates of full bloom have been reported (1,2,3,5,16,34). Sprinkling for bloom delay has

yielded varying levels of delay; generally, greater delays have been achieved in regions experiencing low relative humidity levels during the period in which sprinkling was done (2). Humid regions, such as Ohio, have achieved delays of only eight or nine days (11,34). Bloom delay has also been reported to reduce fruit set and yield (5,7,11,34). Reduced fruit set has been attributed to reduced boron levels in misted trees; there are indications that foliar sprays of boron significantly increased fruit set in sprinkled plants (11). Pollinator activity is also a significant factor in determining fruit set (24). It has been postulated that continuing to sprinkle up to the date of full bloom interferes with the activity of pollinators (6,34). Damage to pollen from misting may occur (5).

Reduction in yield has also been observed in sprinkled blocks. Fewer fruit per meter and fruit of smaller size have been reported in sprinkled orchard blocks (5,7,34). Buchanan et al. (7) reported sprinkled peach and nectarine blocks produced 22% fewer fruits than did nonsprinkled blocks. Ohio researchers reported smaller fruit in sprinkled blocks than in nonsprinkled blocks (34). Delays in maturity of a week or more have also been reported (7,34). Other workers have reported no difference in maturity (1,2,3,19).

Increased soil moisture levels have been reported in sprinkled treatments (11). Waterlogging of the soil has

been used as an explanation for tree losses in sprinkled blocks (11,34).

MATERIALS AND METHODS

A 0.7 Ha orchard, composed of eleven-year-old 'Golden Delicious', 'Delicious', and 'Rome Beauty' scions on MM 104, MM 111, MM 106, and seedling rootstocks was utilized. The block, shown in Figure 3, was separated by a farm road into northern and southern halves. Each half was composed of 18 rows. A row, in each half block, consisted of 11 trees spaced 10 feet apart. The southern block served as a control plot. The northern half of the orchard, shown in Figure 4, was equipped with an overhead sprinkling system. Each low-angle Weather-Tec 5/64 nozzle, mounted on three-meter polyvinyl chloride risers, covered an area having a radius of approximately 13 m. Lateral pipelines, also composed of polyvinyl chloride, were placed upon the surface of the ground at the base of trees. The sprinkling system consisted of two independent sets of lateral pipelines. This permitted operation of one or both sets of lateral pipelines. A set of lateral pipelines supplied water to every other row of trees. The overhead sprinkling system was manually activated when bud temperatures at a height of 1.4 m above the ground exceeded 10°C . Water was applied at a pressure of approximately 13 to 14 kg per cm^2 , giving an application rate of 0.38 cm per hour. Total water application for the 0.35 Ha block was 3.6×10^6 liters, or approximately 10^8 liters per Ha.

Tree/Row	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	
1	1	1	L	4	3	3	1	1	4	4	3	3	3	3	2	2	1	1	
2	1	1	L	4	3	3	1	1	4	4	3	3	3	3	2	2	1	1	
3	4	4	1	1	2	2	2	2	1	1	4	4	4	4	3	3	2	2	
4	3	3	2	2	1	1	3	3	2	2	2	2	1	1	4	4	3	3	<u>Rootstock</u>
5	2	2	3	3	4	4	4	4	3	3	1	1	2	2	1	1	4	4	1 = Seedling
6	4	4	2	2	1	1	1	1	4	4	2	2	3	3	2	2	1	1	2 = MM 106
7	4	4	3	2	1	1	1	1	4	4	2	2	3	3	2	2	1	1	3 = MM 104
8	1	1	4	4	3	3	4	4	3	3	4	4	2	2	1	1	4	4	4 = MM 111
9	2	2	3	3	4	4	2	2	1	1	3	3	4	4	3	3	2	2	<u>Variety</u>
10	3	3	1	1	2	2	3	3	2	2	1	1	1	1	4	4	3	3	Rome Beauty
11	3	3	1	1	2	2	3	3	2	2	1	1	1	1	4	4	3	3	Rows A,B,I,J,O,P
12	4	4	2	2	1	1	4	4	1	1	2	2	4	4	3	3	2	2	Goldspur Golden Delicious
13	4	4	2	2	1	1	4	4	1	1	2	2	4	4	3	3	2	2	Rows D,G,Q
14	3	3	1	1	2	2	3	3	2	2	4	4	1	1	4	4	3	3	Regular Golden Delicious
15	1	1	4	4	3	3	1	1	4	4	3	3	2	2	1	1	4	4	Rows C,H,R
16	2	2	3	3	4	4	2	2	3	3	1	1	3	3	2	2	1	1	Topred Delicious
17	4	4	4	4	3	3	3	3	2	2	4	4	4	4	3	3	2	2	Rows E,K,N
18	4	4	4	4	3	3	3	3	2	2	4	4	4	4	3	3	2	2	Redspur Delicious
19	3	3	2	2	1	1	1	1	4	4	1	1	3	3	2	2	1	1	Rows F,L,M
20	1	1	1	1	2	2	4	4	3	3	2	2	1	1	4	4	3	3	
21	2	2	3	3	4	4	2	2	1	1	3	3	2	2	1	1	4	4	
22	2	2	3	3	4	4	2	2	1	1	3	3	2	2	1	1	4	4

Figure 3. Nonsprinkled and sprinkled orchard blocks

Row	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
	4	4	2	2	1	1	4	4	1	1	2	2	4	4	3	3	2	2
	4	4	2	2	1	1	4	4	1	1	2	2	4	4	3	3	2	2
	3	3	1	1	2	2	3	3	2	2	4	4	1	1	4	4	3	3
	1	1	4	4	3	3	1	1	4	4	3	3	2	2	1	1	4	4
	2	2	3	3	4	4	2	2	3	3	1	1	3	3	2	2	1	1
	4	4	4	4	3	3	3	3	2	2	4	4	4	4	3	3	2	2
	4	4	4	4	3	3	3	3	2	2	4	4	4	4	3	3	2	2
	3	3	2	2	1	1	1	1	4	4	1	1	3	3	2	2	1	1
	1	1	1	1	2	2	4	4	3	3	2	2	1	1	4	4	3	3
	2	2	3	3	4	4	2	2	1	1	3	3	2	2	1	1	4	4
	2	2	3	3	4	4	2	2	1	1	3	3	2	2	1	1	4	4

Figure 4. Sprinkled orchard block

Rootstock

- 1 = Seedling
- 2 = MM 106
- 3 = MM 104
- 4 = MM 111

Variety

- Rows A,B,I,J,O,P = Rome Beauty
- Rows C,H,R = Regular Golden Delicious
- Rows D,G,Q = Goldspur Golden Delicious
- Rows E,K,N = Topred Delicious
- Rows F,L,M = Redspur Delicious

+ = Sprinkler site K11

Initially, 36 gauge copper-constantan thermocouples, hand-coated with polystyrene, were threaded into buds. Later, precoated 40 gauge copper-constantan thermocouples were found to be more satisfactory and were used. Also, instead of threading thermocouples into bud tissues, buds were punctured with a large dull needle, and thermocouple beads, lightly coated with hydrated lanolin, were inserted into the wound. The wound area was then sealed with a small quantity of lanolin to minimize moisture loss from damaged cells and prevent entry of microorganisms into the wound. Thermocouple leads were then secured three to four cm below the bud to prevent the thermocouple from being accidentally removed.

Sprinkled and nonsprinkled blocks were each equipped with four thermocouples, placed at a height of 1.4 m above ground level. Two thermocouples were positioned in the southwestern portion of the tree, and the other two were placed in the northeastern portion of the tree. Aspirated air temperature at a height of one meter above ground level was monitored in mid-block. Wind speed, wind direction, wind peak, bud temperature, quantum sensor, and pyranometer readings were monitored on an hourly basis from early fall over winter to the post-bloom period. Data was accumulated and recorded by an Esterline-Angus PD 2064 data acquisition system.

A computer program was written to read and convert hourly temperatures to chill units, according to the methods described by Richardson et al. (). Hourly chill units were accumulated beginning in late August to determine the date of the maximum negative chill unit accumulation. On September 22, 1979, positive chill units began to accumulate.

After 980 chill units accumulated, buds of Golden Delicious and Delicious trees were collected. Chilling was considered to be complete if buds reached anthesis when conditions favorable for growth to occur were provided. Collection of 50 buds from each variety began on January 20, 1979. Branches, 10 to 30 cm in length, were collected every other day. They were placed in plastic bags, brought immediately into a greenhouse, held in distilled water, and observed daily. Collection ceased on February 6, 1979, when buds collected on January 20, 1979, reached anthesis. It was assumed that the end of rest, as previously defined (18), had been reached. This definition of rest differs from the Utah definition which used the terms rest and dormancy synonymously. The response of buds to conditions favorable for the resumption of growth was documented photographically.

On March 7, 1979, sprinkling began. After manual activation of the system, one lateral set was controlled by an automatic timer. The automatic timer was capable of

producing a variable on-time and reducing water consumption. As the season progressed and ambient air temperature rose, bud temperatures were difficult to maintain near 10°C using one set of laterals. To obtain maximum cooling and maximum bloom delay, low bud temperatures were maintained by application of additional water. On March 28, 1979, the second set of continuously-sprinkling laterals was activated and used in conjunction with the lateral set controlled by an automatic timer. To obtain maximum cooling, without complete drying of buds, both sets of laterals were operated continuously beginning April 13, 1979. To conserve water, sprinklers were turned off at night because evaporative cooling during this time has been observed to be minimal (34).

A second computer program was written to compute growing degree hour (GDH) units from the hourly bud temperatures. Temperatures less than 4.4°C were assumed to equal 4.4°C . Temperatures greater than 25°C were assumed to be equivalent to a temperature of 25°C . For each hourly temperature, the base temperature of 4.4°C was subtracted to obtain growing degree hour units. Growing degree hours required to reach various phenological stages were summarized by Griffin (16).

On March 28, 1979, bud swell was observed in the unsprinkled half of the orchard. To document phenological changes, 100 flower buds were randomly selected and observed

in sprinkled and nonsprinkled Delicious and Golden Delicious trees. Trees at the ends of rows were excluded from the evaluation. The canopy was divided into eight sections. Buds were observed at heights of 1, 1.5, and 2 m from the ground. Three radii were selected; distances of 0.25, 1.0, and 1.5 m from the main trunk were used. Using the previously described scheme, a table of randomized five-digit numbers was generated. Using the five-digit numbers, determination of the tree, canopy section, height, and radius for the 100 buds was done. Counts were taken every six days or when the majority of buds appeared to have reached another stage of development. Photography was also used to document phenological changes in sprinkled and nonsprinkled blocks.

The possible reduction of pollen viability by sprinkling was also examined. Although apples possess 30 or more stamens, rarely do more than four anthers dehiscence per blossom at any one time. Therefore, whole anthers from seven different blossoms of Golden Delicious and Rome Beauty cultivars were collected during the bloom period from sprinkled and nonsprinkled blocks. Anthers were held in gelatin capsules and refrigerated for 24 hours. Pollen viability was evaluated using Cotton Blue stain (9). Two slides were made for each cultivar and 200 pollen grains per slide were examined at 1000x under a phase-contrast microscope. Only viable pollen appeared plump, rounded, and retained a deep blue stain.

Leaching of nutrients from tissues during sprinkling has not been investigated. On June 13, 1979, after sprinkling had ceased, three samples consisting of seven 15-cm-sections of new vegetative growth were collected from each block. Samples of leaves were also collected on June 13. All samples were oven dried at 70°C for two weeks, ground to pass thru a 40-mesh screen in a Wiley mill, ashed at 400°C, and dissolved in concentrated HCl. Samples were analyzed using a radio frequency spectrometer. Elements of interest to this study included: nitrogen, potassium, phosphorus, calcium, boron, iron, zinc, and magnesium.

Fruit set was also examined in sprinkled and nonsprinkled blocks. Fruit was counted on each Rome Beauty tree in sprinkled and nonsprinkled blocks to determine if sprinkling has reduced fruit set. Fruit size in each block was also examined. Using the previous described five-digit, randomized table, 50 apples were examined in sprinkled and nonsprinkled blocks. Length and diameter of fruit were measured in sprinkled and nonsprinkled blocks to determine if a delay in maturity had occurred in Golden Delicious trees.

RESULTS AND DISCUSSION

The end of rest for Delicious apples was predicted by the Chill Unit model to be March 17, 1979, after 1234 chill units had accumulated. Bud forcing indicated buds were capable of resuming growth and flowering after 980 chill units had accumulated. The Chill Unit model has not been used in the northeastern states. Additional work is needed to accurately calibrate the Chill Unit model for a more accurate prediction of the end of rest.

In Figure 3, the number of growing degree hours accumulated by the nonsprinkled block in attaining various stages of development are compared with growing degree hour requirements reported in Utah (1,2,29). From the silvertip to tight cluster stage, the heat units needed to attain each phenological stage were similar. Variations from the Utah model occurred after the first pink stage. The number of growing degree hours accumulated to reach later stages of development were different from those reported in Utah (1,2,29). Variations in the number of growing degree hour units from those reported in Utah were also reported in other geographic regions where bloom delay has been investigated (34). Van Huyster, Weiser, and Li (37) reported the phenological responses of Cornus stolonifera clones, grown in different geographic areas, were different even when provided with identical environmental conditions.

Figure 3. Comparison of Pennsylvania and Utah growing degree hours (nonsprinkled block)

Table 1. A comparison of predicted and observed phenology in the nonsprinkled block.

Stage	Date Predicted	Date Observed
Silvertip	April 14	April 13
Greentip	April 21	April 20
Half-inch green	April 23	April 23
Tight cluster	April 26	April 25
First pink	April 31	April 30
First bloom	May 6	May 8
Full Bloom	May 8	May 10

The observed dates on which the orchard reached a specific phenological stage of development are compared with dates predicted by the Growing Degree Hour Model (Table 1). The predictions made by the model differed slightly from actual orchard conditions; approximately one day separated predicted and observed dates in the nonsprinkled block. For the nonsprinkled block, the predicted dates of phenological stages approximated actual orchard conditions. Further refinement, using additional phenological and climatological data, should produce a more accurate, predictive model.

In Figure 4, the growing degree hours accumulated by the sprinkled block are compared with observations reported in Utah (1,2,29). The number of growing degree hour units needed to reach the silvertip and greentip stage are similar. However, after the greentip stage, the sprinkled block required more growing degree hours to reach later stages of development than was predicted by the Utah model (1,2,29). Sprinkling delays development through evaporative cooling of the aerial portion of the plant (6,20).

Within the Growing Degree hour it is assumed that both sprinkled and nonsprinkled blocks required equivalent growing degree hour accumulations to reach a specific stage of development (1,2,29). This may not necessarily be a valid assumption. In some instances, modification of environmental conditions may result in a marked change in plant response (31). Sprinkling for bloom delay not only

modifies the aerial environment of the plant, but the large amounts of water applied (100-150 cm) modifies the soil environment. Even with typical orchard drainage, long periods of total soil saturation may have resulted. Saturation reduces gas exchange between the soil and atmosphere (38). Over a period of weeks, saturated soils may have altered plant response to temperature. The changes in plant response to modified environmental stimuli, such as sprinkling, has the potential to change and amplify energy requirements of the plant (38). The sprinkled block required approximately 2000 more growing degree hours, or 20% more energy, than did the nonsprinkled block to reach full bloom. The additional energy requirement may be the result of changes in plant response to modifications of the aerial and soil environment.

Sprinkling for bloom delay may result in the generation of unusual soil conditions. Saturated soil may have resulted in plant stress and different plant responses to temperatures within the sprinkled block.

A comparison between dates predicted by the Growing Degree Hour model and the dates the sprinkled block was observed to reach specific phenological stages is given in Table 2. Notice that the model predicted a difference of only two days, rather than ten days, between the sprinkled and nonsprinkled blocks. This is another indication that sprinkled plants may have had different responses to the

UTAH

PENNSYLVANIA

Figure 4. Comparison of Pennsylvania and Utah growing degree hours for sprinkled block

Table 2. A comparison of predicted and observed phenology in the sprinkled block.

Stage	Date Predicted	Date Observed
Silvertip	April 21	April 19
Greentip	April 24	April 23
Half-inch green	April 26	April 29
Tight cluster	April 31	May 5
First pink	May 4	May 9
First bloom	May 8	May 15
Full bloom	May 10	May 20

modifications of environment and consequently responded more slowly to temperature than did the nonsprinkled plants.

Pollen examination indicated that pollen viability was reduced in the sprinkled block. For Golden Delicious, 96 percent of the pollen was viable in nonsprinkled trees. For sprinkled trees, however, the pollen viability was determined to be 89 percent. Viability was reduced by seven percent for the Golden Delicious trees in the sprinkled block. For Rome Beauty, 95 percent of the pollen was viable in nonsprinkled trees. Pollen examination, for sprinkled plants, indicate viability to be 93 percent. For Rome Beauty, pollen viability was reduced by two percent in the sprinkled block. Changes in the pollen viability indicate that there may be changes in plant response within the sprinkled block.

Foliar analysis, after sprinkling had ended, indicated leaching of nutrients had occurred in the sprinkled block. For the sprinkled block, levels of nitrogen, iron, and aluminum were higher than those in the nonsprinkled block. Nitrogen was probably carried more quickly to the root regions in the sprinkled block than the nonsprinkled block. Higher levels of iron and aluminum can probably be attributed to the dissolved metallic ions within the water which had been obtained from a reservoir. In the nonsprinkled block, levels of potassium, calcium, and boron were higher than the sprinkled block. Leaching of nutrients

was also reported, in 1979, by researchers in Ohio (11). Foliar analysis indicated that sprinkling for bloom delay modified the availability of nutrients necessary for normal plant growth.

Fruit set has been modified in some instances by sprinkling for bloom delay (5,11,34). Counts of the fruit set on Rome Beauty trees showed an equal number of fruit present in the sprinkled and nonsprinkled blocks. The size of fruit, length and diameter, in sprinkled and nonsprinkled blocks were different. On July 8, 1979, the average fruit diameter and length within the nonsprinkled block was .25 cm greater than fruit examined in the sprinkled block. In Ohio, similar observations concerning a delay in maturity were reported (34).

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