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Development and Commercializatio Delivery System for Weather-Drive

The explosion within the last few years of application-oriented microprocessors has provided an ideal opportunity to make major advances in the design of equipment for disease prediction. The unique advantage of the microprocessor is that this pint-size computer can automatically observe the weather, analyze the data, and indicate disease risk directly to a farmer within his own field. Moreover, the unit is expandable to meet future needs because new information can be incorporated into the computer's memory.

This article describes the development and commercialization of a unit for disease prediction (Fig. 1). This case study is based on our experience with apple scab, but plant pathologists are rapidly adapting other disease models to the unit. For example, new models are currently being evaluated to aid in the control of black rot of grape, grape downy mildew, anthracnose on turf, fire blight on apple, and leaf spot on cherry. In addition, we have evaluated a simple apple phenology model and a degree-day model for estimating insect development on one of our prototypes.

In the early 1900s, timing of fungicide treatments to control apple scab, caused by *Venturia inaequalis* (Cke.) Wint., was based primarily on host development. Although early workers tried to relate the life history of the scab fungus to its control with fungicides, it was not until 1926 that Keitt and Jones (4) elucidated the life history of *V. inaequalis* and related infection to temperature and duration of wetting. Later, Mills (5) developed a graph and table (6) for predicting scab infection from the duration of wetting and the average temperature during wetting. In addition, the development of spray materials with curative properties was significant because it provided greater flexibility for the timing of fungicide applications, thus improving overall scab control. These developments provided the basis for making apple scab infection predictions and control information available to growers in many countries through radio, telephone, or postal warnings.

The need for environmental monitoring equipment in apple orchards dates to the early attempts to implement the Mills predictive system. The World Meteorological Organization (10) considered this problem at a conference in 1963, and interest in pest management research in the early 1970s has accounted for increased use of monitoring equipment, particularly in the United States. In the last 20 years, there have been many attempts to modify, simplify, or enhance existing environmental monitoring equipment for making Mills's predictions. With the emerging microprocessor technology, the time seemed right in 1978 to integrate a prediction function directly into these units.

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Design of Initial Units

Our initial objective was to predict apple scab infection periods and issue warnings to growers when sprays of curative fungicides were needed. To allow sufficient time for fungicide application, warnings were required within about 9–24 hours after the initiation of wet periods suitable for infection. Basically, the unit was designed to make weather observations and then predict infection periods by processing the observation through a computer model. This unit differs in concept from a data logger because its main function is to provide information to growers in an easy-to-understand format rather than to collect and store raw information for analysis sometime later.

Before the unit could be constructed, several questions regarding the design of the instrument had to be addressed. For example: How accurately must the time of day be maintained? How often must weather observations be made and with what accuracy? How detailed must the predictive model be? What information must be issued to the grower? How would the grower access the information? These are standard questions that are generally independent of the specific intended application.

To predict apple scab infection periods, air temperature, relative humidity, and leaf wetness data were required as input information for the model. We chose to make these weather observations once a minute and to pass 10-minute averages onto the predictive model for further data reduction. Dry-bulb and wet-bulb temperatures were measured to ± 1 F and leaf wetness, to ± 10 minutes. We chose to have the time of day accurate to 1 minute per month because timing errors are consistent and accumulate. A 1% error can mean as much as a 6-hour difference in 1 month.

The instrument was designed with a keypad for input and an eight-character display for outputting the current date and time; the dry-bulb air temperature, relative humidity, and leaf wetness; the prediction of infection (none, low, moderate, or high); and a listing of possible control fungicides. To help in validating the instrument, weather data collected by the unit were saved in memory. Later, these data were compared with similar information from hygro-

f an In-field Microcomputer
redictive Models

thermographs and leaf wetness recorders.

In developing software for the instrument, a modular design was used to increase the flexibility of the instrument and to ease debugging and modification of the software. When a modular design is used, similar functions are handled by identifiable units or modules within the program. For example, one module might control the functioning of the keyboard, another the display, and a third the collecting and formatting of the temperature data. Also, the instructions for predicting various diseases or insect pests would be contained in modules. In setting up an instrument, the programmer selects those modules needed to perform the desired functions.

In the physical design of the unit, immunity from external electrical noise derived from farm machinery and storms and protection from dust, moisture, and chemicals in the orchard were given a high priority. Immunity from other electrical sources was important because stray electricity can cancel or reset the memory or damage electrical components in the unit.

Also, diagnostics were placed in read-only memory and access points were provided at key points throughout the circuit to facilitate calibrating the instrument, checking its accuracy, and identifying specific problems (Fig. 2). One very helpful feature incorporated in the instrument was a "fast-clock." In fast time, the instrument proceeds 60 times faster than normal. This shortened testing and debugging time significantly, eg, a test that normally required 3 days to conduct could be done in a little over 1 hour.

Two additional items were considered in the design of the unit. First, what features might be needed in future versions of the instruments? For example, the prototype had one type of output, an eight-character display, but was structured so that a printer, a magnetic recorder, or a phone line could be used to record or transmit output. Second, what other applications might the instrument be used for with little or no modification to its hardware? For example, adding sensors for monitoring rainfall (which we did), wind speed, wind direction, and solar radiation would immediately turn the instrument into a full-fledged weather station that might have broader application in and out of agriculture. Not only was the prototype structured to simplify addition of other sensors, but the function of the sensors was controlled by software that could be easily reprogrammed.

It took 3 years to design, construct, program, and field-test our first prototype disease predictor (3). Ultimately, five instruments were constructed representing three designs (1). The experience gained in this project was very useful when the unit was transferred to industry for commercialization.

Fig. 2. An apple scab predictor developed at Michigan State University being tested in the laboratory. The cover is removed and a hand-held calculator (lower left) and circuit board (upper right) are attached to the unit to test the circuitry and debug the program. The display and keypad on the cover (lower right) are connected to the unit with flexible cabling. A standard power supply (upper left), rather than a battery, is used to run the unit in the laboratory.

Fig. 1. A Reuter-Stokes apple scab predictor (left) in the field and (right) being checked to determine if infection has occurred.

Fig. 3. Removable circuit board with programmable memory increases flexibility and scope of the disease predictor.

Table 1. Control of apple scab in Michigan and New York experimental orchards with curative fungicides scheduled with an electronic scab predictor developed in Michigan

State Year	Timing technique	Fungicide applications per season (no.)	Terminal leaves with scab (%)[z]
Michigan			
1978	Protective schedule	11	2.0 a
	Curative schedule	8	4.7 a
	Control (no fungicide)	...	86.4 b
1979	Protective schedule	9	0.0 a
	Curative schedule	6	3.0 a
	Control (no fungicide)	...	55.0 b
1980	Protective schedule	10	3.5 a
	Curative schedule	6	3.0 a
	Control (no fungicide)	...	65.7 b
1981	Protective schedule	13	0.3 a
	Curative schedule	9	0.3 a
	Control (no fungicide)	...	86.0 b
1982	Protective schedule	12	3.9 a
	Curative schedule	9	1.8 a
	Control (no fungicide)	...	91.3 b
New York			
1979	Protective schedule	9	8.0 a
	Curative schedule	5	0.8 a
	Control (no fungicide)	...	41.0 b
1980	Protective schedule	8	2.4 b
	Curative schedule	5	0.2 a
	Control (no fungicide)	...	37.2 c
1981	Protective schedule	8	14.9 b
	Curative schedule	6	4.7 a
	Control (no fungicide)	...	49.3 c
Average (both states)	Protective schedule	10.0	
	Curative schedule	6.7	

[z]Numbers followed by the same letter within each year are not significantly different at $P = 0.05$ according to Duncan's multiple range test (Michigan data) or to Walter Duncan exact Bazesian K-ratio (New York data).

Characteristics of Model Used in Predictor

The software developed for the apple scab predictor incorporated our existing knowledge of apple scab prediction. It also addressed a number of problems that have made prediction of infection periods based on the Mills system difficult: effects of high humidity, split wetting periods, and duration of curative fungicide activity. Inclusion of these factors made the prediction system more robust, but the unit had to be validated before being made available to growers.

The apple scab predictor measures the wetness duration and temperature in the orchard and determines the relative favorability of the weather for infection. Infection predictions above 8.3 C (47 F) were derived from the Mills table. Below this temperature, practical experience has indicated the Mills table sometimes fails to detect conditions suitable for infection. This problem was addressed in part by modifying the Mills table from 8.3 to 5.5 C (from 47 to 42 F) and extending the table to 0.6 C (33 F). The correctness of this modification was checked by experimentation.

How to predict scab when two wet periods occur close together but neither is long enough to result in infection has concerned most workers who have worked with the Mills system. The duration of the dry period between the wet periods appears to be the key factor for determining whether infection will or will not take place. Mills initially suggested that wetting periods separated by no more than 4 hours should be added together, but later this was changed to one-half day or more with sunny weather. The software for the apple scab predictor was programmed to wait for 8 hours of dry weather before the model was reset for the next wet period. This 8-hour figure is based primarily on the work of Roosje (9) in the Netherlands.

From the outset, determining relative humidity after wetting periods was considered important in detecting infection periods with our units. We included relative humidity for two reasons. First, grower experience with the Mills system indicated that short rain periods in the afternoon could result in infection even though a few hours of drying occur before dusk and no rain falls during the night. This suggested moisture periods from fog or dew or high humidity were favoring nighttime infection. Subsequently, we verified such infection periods in the field (3). Second, the electronic potential for the leaf wetness sensor was set relatively high to avoid "false starts" from minor showers that would not be expected to initiate ascospore discharge. Although the sensitivity of the wetness sensor was automatically increased by the microprocessor once wetness was detected, the wetness sensor may not be sensitive enough to detect the onset of dew formation. Therefore, relative humidity measurements were used for determining when leaf wetness periods had ended and for dealing with split wet periods when the second wet period was initiated by other sources of free moisture such as dew or fog. To reduce the complexity of the model, 90% relative humidity was chosen as a threshold level for separating wet and dry periods. This 90% value was used previously by Preece and Smith (8) for predicting apple scab.

Finally, Mills indicated one-third less time was required for infection by conidia, but the work of Roosje (9) and Moore (7) indicated the duration of wetting required for infection by conidia was as long as or longer than the duration required for infection by ascospores. Therefore, the same criteria were used to predict infection from both sources of inoculum.

Validation of the Prototype

The microprocessor-based units were constructed and programmed in Michigan and evaluated in experimental apple orchards in Michigan and New York. One method for verifying punitive infection periods was to place unsprayed apple trees in pots in the orchard before, and remove them after, each rain. In 1978, all infection periods predicted by an experimental unit at East Lansing, Michigan, were verified when apple scab developed on potted trees that had been placed in the orchard during wet periods (3). Similarly, during 1980 at Geneva, New York, all infections on potted trees were predicted by the unit with the exception of one split wetting period. That period marginally satisfied the criteria for a light infection period, although no infections developed on the trees in the pots.

Schedules of curative fungicides were applied when advised by the instrument. Tests were conducted during 5 years in Michigan and 3 years in New York in experimental orchards with high levels of inoculum (Table 1). Control obtained with these programs was compared with standard protective schedules common to Michigan and New York. The protective spray programs required an average of 10 sprays per season, whereas Michigan and New York growers normally sprayed about 12 times a season. Curative sprays timed according to output from the disease predictor averaged only 6.7 a year. Disease control was equivalent to the protective program in both light and severe disease years. An average of 3.3 sprays were saved each season when the disease predictor's curative spray program was substituted for a standard protective program.

The main function of the predictor is to provide growers with the basic information needed to carry out an effective scab control program. Most commercial apple growers follow a protective spray schedule to control scab. Fungicides are applied on a set spray interval or according to the stage of bud development. This includes the alternate middle concept of spraying, a protective program made up of a series of half sprays. In practice, protective spray programs can be disrupted when the weather is too wet or windy. There is also the temptation to allow the interval between sprays to fluctuate, particularly in dry years, which jeopardizes the success of the program if the weather changes for the worse. The grower who has information from a predictor, however, can judge whether to continue with a protectant fungicide or switch to a curative fungicide if the weather suddenly changes.

Another way growers can use the predictor is to wait until the unit predicts an infection period, then spray with a curative fungicide. Once infection is predicted, the fungicide must be applied promptly, even at night or on weekends, and the grower must be able to cover the orchard quickly. Because only a few hours may be available to apply the fungicide, large growers who use this kind of program should do so on only a portion of their acreage. In years with average or below-average rainfall, the number of sprays in a curative schedule should be three to five fewer than in a protective program. Any potential monetary saving from fewer sprays could be offset by the fact that curative fungicides are generally more expensive than protective compounds. As more curative-type fungicides are introduced, however, their cost may be reduced.

Commercialization of the Unit

The acquisition of the apple scab predictor as a new product by Reuter-Stokes is an example of industry and university cooperation. The initial contact with the developers of the apple scab predictor was established at an Instrumentation Society of America meeting in Seattle, Washington, in May 1980. A staff member of the Reuter-Stokes research group attended a talk on "Psychrometric Measurements with Microprocessors" presented by P.D. Fisher of Michigan State University (2). The apple scab disease predictor was used as an example of an instrument that incorporated temperature and humidity sensors, interfaced to a microprocessor.

Reuter-Stokes (18530 South Miles Parkway, Cleveland, OH 44128) is a well-established manufacturer of radiation and temperature sensors and of electronic instrumentation. After several in-house reviews, Michigan State University was contacted formally in December 1980 by Reuter-Stokes. The selection criteria set by Michigan State University to be met by a manufacturer were, briefly, technical competence, willingness to make a significant commitment to the project, and availability of the necessary resources to develop and market the instrument.

Generally speaking, the relationship developed rather smoothly. The proximity of Reuter-Stokes in Cleveland to Michigan State University in East Lansing certainly aided the technology transfer process. The technology transfer agreement was signed in August 1981, some 8 months after the initial contact by Reuter-Stokes. With the agreement in place, the university's documentation package— mechanical drawings, electrical schematics, bill of material, flow charts, and a software program listing—could be formally transferred.

At Reuter-Stokes, developing the prototype unit to a precommercial unit consisted of redesigning the hardware to

Fig. 4. Apple scab predictor with plug-in printer for obtaining permanent copies of predictions and weather data.

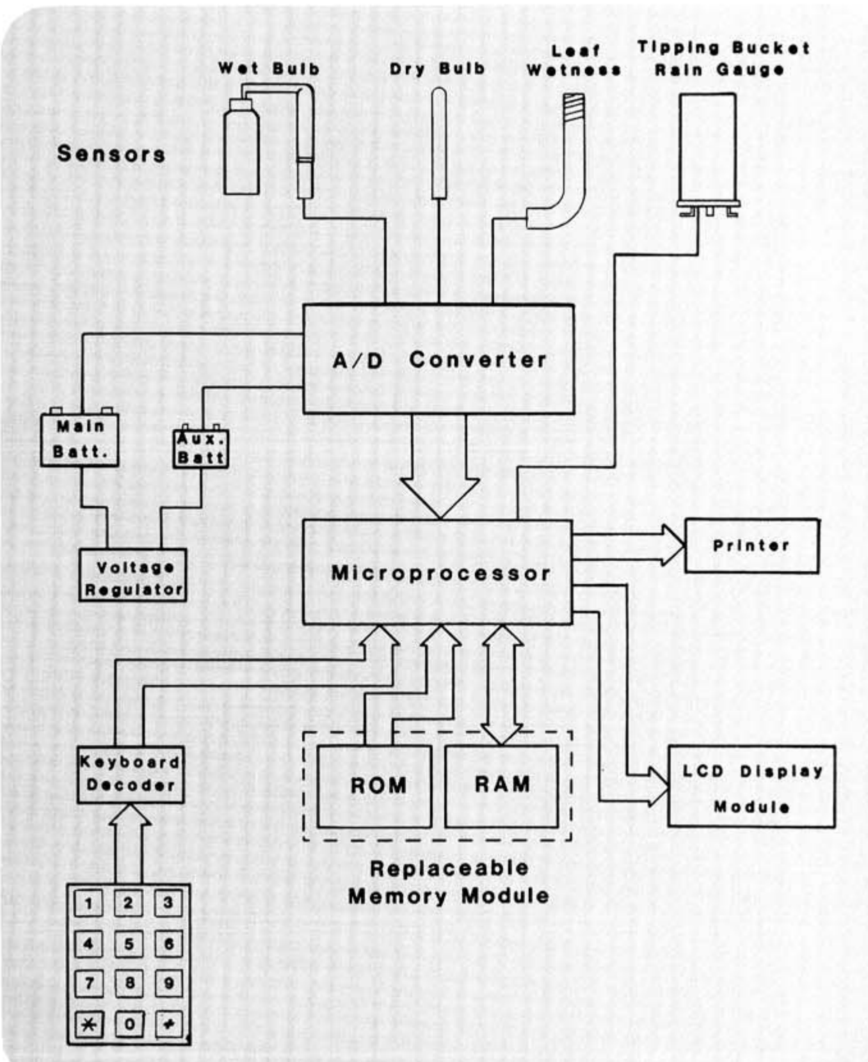

Fig. 5. Block diagram of the Reuter-Stokes apple scab predictor, showing organization of the sensors, keyboard, and display with the microprocessor.

be consistent with technology available at Reuter-Stokes, writing software for the new hardware design without changing the unit's functionality, adding features to facilitate manufacture and testing, and building two prototype units by 1 December 1981. A market analysis was also begun, since the instrument clearly represented new technology to apple growers and Reuter-Stokes was already in a "pioneering" mode.

The target date of prototype completion was met and two units were exhibited at the Michigan Horticultural Society annual meeting in December 1981. Because of the instrument's novelty, several trade journals and Michigan newspapers carried feature articles describing the "electronic" apple scab predictor. In fact, subsequent display at several different state horticultural shows became the primary promotion vehicle.

By 31 December 1981, the decision was made to manufacture 30 instruments for lease or sale in Canada and the United States. By March 1982, all units were placed. Ten were loaned to experiment stations, universities, and government agencies for evaluation. Because these organizations provide an important advisory service to growers, their opinion on this "new" instrument was crucial for future product acceptance. One instrument was evaluated in West Germany, and the remaining were used by growers in the United States and Canada.

The main purpose of this phase of the program, the evaluation phase, was to establish credibility of the concept with progressive growers in the industry and to validate on a large scale some of the earlier findings obtained in the research at Michigan State University. On the whole, the results of the evaluation phase were sufficiently encouraging to proceed to the next phase, the commercial phase, consisting of the manufacture of 100 instruments. This decision was reached in September 1982.

The evaluation phase proved to be an important test of instrument performance and reliability as an in-orchard real-time environmental data acquisition system. Several changes were introduced in the commercial unit based on the evaluation phase: 1) improving readability of the liquid crystal display by increasing the number of characters from eight to 16; 2) minimizing the number of parts by packaging the sensor interface and electronics in *one* electronic housing; 3) correcting the minor software deficiencies encountered during the evaluation phase; 4) mounting the unit program memory in a removable module called the "personality module" (Fig. 3), so that the instrument could be easily changed to predict other diseases such as fire blight and black rot in grapes; 5) equipping units with a printer option for permanent recordkeeping (Fig. 4); and 6) adding switches to display temperature as either °F or °C and time on either a 12- or a 24-hour system. The final unit is diagrammed in Figure 5.

During the 1983 growing season, approximately 60 units were in use by growers in the United States and Canada, distributed geographically from east to west. In addition, growers and research organizations from Southern Hemisphere countries have bought 25 instruments for the 1983–1984 growing season. Hence, there are encouraging signs the instrument could be both a domestic and an international success.

Developing Software

The software for the commercial version of the apple scab predictor was written and developed for use with the INTEL 8031 microcomputer. The apple scab predictor incorporates a unique interrupt-driven multitasking operating system developed by Reuter-Stokes for all of their instruments. This operating system makes efficient use of the processor by scheduling tasks on a priority basis.

Different tasks were defined, including data acquisition, timekeeping, data interpretation, and keyboard and display


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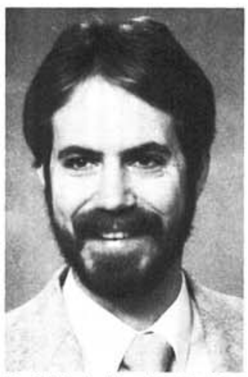
Patrick J. Van DeMotter

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functions. A separate software module was written for each individual task. Using this modular concept simplified the design and increased program flexibility. For instance, changing the prediction module can readily change the instrument's mission. This has been beneficial for quick instrument adaptation to cherry leaf spot, black rot and downy mildew in grapes, and anthracnose in annual bluegrass.

Code for disease-predicting algorithms was prepared by Reuter-Stokes on their special development system. After being tested and debugged, the program was permanently transferred to EPROMs (erasable programmable read-only memories), which were then plugged into the unit. All memory for the instrument, both EPROMs and RAM (random-access memory), resides on a separate printed circuit board that plugs into the main printed circuit board containing the microprocessor and other circuitry. This allows for quick, easy addition of new predictive models (or updates of existing models) and extends the useful life of the instrument.

Expanding Applications

Based on our experience over 5 years, it is apparent the predictor can do more than simply predict scab and assist in the timing of fungicides. Already programming has been added to the predictor to provide information on daily temperature and rainfall in a grower's orchard and for making degree-day accumulation from selected dates and for various base temperatures. Degree-day accumulations can then be utilized for estimating insect development, ascospore development, and harvest dates.

Several plant pathologists are adapting the unit to predict other diseases. For example, the unit has performed well in predicting black rot of grapes and in timing fungicide controls in Ohio. A model to predict fire blight and a second to predict cherry leaf spot are currently being developed in Michigan by the senior author. Recently, a graduate student at Michigan State validated a model for predicting anthracnose on turf. Although many other applications and adaptations of this instrument remain to be explored, it is already clear predictors can play an important advisory role in disease control programs.

Literature Cited

1. Fisher, P. D., Jones, A. L., and Neuder, D. L. 1979. Microprocessors improve pest management practices. Pages 89-102 in: Microprocessor Applications: International Survey of Practice and Experience. J. Hosier, ed. Infoltech. International Ltd., Berkshire, England.
2. Fisher, P. D., Lillevik, S. L., and Jones, A. L. 1981. Microprocessors simplify humidity measurements. IEEE Trans. Instrum. Meas. IM-30:57-60.
3. Jones, A. L., Lillevik, S. L., Fisher, P. D., and Stebbins, T. C. 1980. A microcomputer-based instrument to predict primary apple scab infection periods. Plant Dis. 64:69-72.
4. Keitt, G. W., and Jones, L. K. 1926. Studies of the epidemiology and control of apple scab. Wis. Agric. Exp. Stn. Res. Bull. 73. 104 pp.
5. Mills, W. D. 1944. Efficient use of sulfur dusts and sprays during rain to control apple scab. N.Y. Agric. Exp. Stn. Ithaca Bull. 630. 4 pp.
6. Mills, W. D., and LaPlante, A. A. 1951. Control of diseases and insects in the orchard. Pages 18-22 in: N.Y. Agric. Exp. Stn. Ithaca Bull. 711. 96 pp.
7. Moore, M. H. 1964. Glasshouse experiments on apple scab. I. Foliage infection in relation to wet and dry periods. Ann. Appl. Biol. 53:423-435.
8. Preece, T. F., and Smith, L. P. 1961. Apple scab infection weather in England and Wales, 1956–60. Plant Pathol. 10:43-51.
9. Roosje, G. S. 1963. Research on apple and pear scab in the Netherlands from 1938 until 1961. Neth. J. Plant Pathol. 69:132-137.
10. World Meteorological Organization. 1963. The influence of weather conditions on the occurrence of apple scab. Report of a working group. J. J. Post, C. C. Allison, H. Burchhardt, and T. F. Preece, eds. World Meteorol. Organ. Geneva Tech. Note 55.