EVAPORATION LOSSES IN SPRINKLER IRRIGATION

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ABSTRACT

EVAPORATION LOSSES IN SPRINKLER IRRIGATION

Water conservation, distribution of chemicals through irrigation water and the increasing popularity of low application rate irrigation systems are all important factors pointing up the need for more precision in irrigation management which in turn is dependent upon accurate estimates of expected evaporation losses. Data has been obtained to predict the independent effect of water application rate, air (wind) velocity, water temperature and dry bulb and dew point temperature of the ambient air on evaporation losses by water droplets and water droplets in combination with plant intercepted water. By far the most influential factor on evaporation losses is the rate of application. Results indicate evaporation losses are about 60% for low application rates (0.15 iph) with climatic conditions typical of Florida and when plant foliage is present to intercept most of the applied water. Evaporation losses by water droplets in motion is relatively insignificant in comparison to losses from extensive wetted surfaces afforded by dense vegetation. It is unlikely that evaporation by water droplets in transit could amount to more than 5% of a water application. The independent effect of water temperature and several important climatic factors on evaporation losses were determined and are presented in graphic form in this report.

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SUMMARY

The objectives of these studies were to evaluate independently the climatic factors of air temperature, dew point temperature and wind velocity, and the physical factors of water temperature and application rate in terms of evaporation losses for sprinkler irrigation. Evaporation losses were separated into two sources, that from the spray (water droplets) and that from the wetted surface of plant material. Supporting tests were conducted under controlled conditions in an environmental control chamber built in the laboratory of the Department of Agricultural Engineering at the University of Florida. The results of the study are not directly applicable to field conditions for sprinkler irrigation but the data in this report are interpreted so that it supplies a basis for making decisions concerning design and operational management of sprinkler irrigation systems.

The results of tests on evaporation losses for spray are consistent with those of several other investigators in that the losses are very small when compared to the total amount of water applied and also small when compared to evaporation losses from plant surfaces. Spray evaporation losses, expressed as a percentage of the amount applied, ranged from 0.20% to 1.13% while that from the plant intercepted water ranged from 3.5% to 60.3%. Based on laboratory tests and in consideration of adjustments for droplet size, time of exposure and relative velocity between droplets and air, it is estimated that evaporation from this source should not exceed 5% of the amount applied under typical field conditions in Florida. In past studies of evaporation the initial water temperature was not considered in most cases. However, the laboratory tests on this factor indicate that it is important even though the droplets approach the wet bulb temperature very rapidly. For field conditions where the droplet exposure time will be greater than that for the laboratory tests, the effect of initial water temperature on evaporation will be reduced. The influence of air (wind) velocity on evaporation from droplets appears to be more closely related to the movement of high-moisture-content-air from the general vicinity of the droplets rather than to the increase of the relative velocity between the air and the droplet. The effect of air temperature on evaporation losses is strictly related to the rate at which the droplet temperature changes and the equilibrium temperature (wet bulb) which is reached by the droplet. As the dew point of the air increases, both vapor pressure and wet bulb temperature of the air increases at increasing rates. The two occurrances have an opposing effect on the evaporation rate and it appears that the relationship is almost linear.

The relationships of the effect of air velocity, dry bulb temperature and dew point to evaporation losses from plant surfaces is similar to those found for water droplets, however, the order of magnitude of evaporation from plant surfaces is many times greater. Important factors contributing to these larger evaporation rates are the larger wetted areas and longer exposure time for plant intercepted water when compared to water droplets during transit. Evaporation losses from plant surfaces are primarily a function of the rate of application. Evaporation losses in terms of percent of the total application can vary from 10% for application rates of 5 iph to more than 60% for application rates of 0.15 iph for typical Florida climatic conditions.

Publications that have resulted from this project thus far are:

Baird, C.D. Measurement of Water Evaporation Rates Utilizing an Electrolytic Condensation Hygrometer. Unpublished. M.S. Thesis, University of Florida, Gainesville, Florida. 1967.

Baird, C.D., J.M. Myers and I.J. Ross. Precision Measurement of Dew Point Changes with Electrolytic Condensation Hygrometer. Transactions of the ASAE. 12(6): 849-853. 1969.

INTRODUCTION

Water losses by evaporation from sprinkler irrigation can vary from practically nothing to more than half the volume of water delivered to the sprinkler nozzle. It is believed that many users of irrigation have only a general appreciation of the magnitude of evaporation losses. In the management of irrigation, overall application efficiencies, i.e. the relative proportion of the water that is removed from the source and placed in the soil for crop use, of 70 to 80 percent are in standard usage in Florida.

Rule-of-thumb criteria for estimating irrigation efficiencies may not have affected significantly the economics of irrigation in the past, but, with anticipated new technological advancements and the increased awareness of the necessity for water conservation, the demand for more precise information on irrigation efficiency and evaporation losses will be required for the years ahead.

The potential is promising for effective and low cost application of chemicals through irrigation for plant growth regulation and insect and disease control. Evaporation from the foliage is a needed value in calculating the amount of chemical residues remaining on the plants after the cessation of the irrigation application. The concentration of chemical solutions at the moment of application is dependent upon evaporation losses from the water droplets as they move through the air. When plant foliages are sensitive to salt residues resulting from evaporation of saline irrigation water, the rate of evaporation with respect to rate of application becomes one of the important factors to consider in adjusting to this problem. At times, evaporation from irrigation spray is desirable as a medium for cooling plants and the surrounding air. Certainly there is a trend toward greater control of the micro-environment for growing agricultural crops. More knowledge about water evaporation losses associated with sprinkler irrigation is a significant entity towards coping with these situations.

Of course, any water that is removed from its source for irrigation purposes and does not reach the zone of intended application reflects unfavorably upon irrigation operating costs and is not in concert with the philosophy of water resource conservation.

Air temperature, dew point temperature and wind velocity are climatic factors that can greatly influence evaporation losses while irrigating. Water temperature, water droplet size, velocity of water droplet, time duration that the droplet is in transit between the sprinkler nozzle and the interception point and interception characteristics are other factors playing a part in this phenomenon. It was the object of the study reported herein to independently evaluate these factors in terms of their influence on evaporation losses from sprinkler irrigation.

REVIEW OF LITERATURE

Irrigation has been practiced in the United States for more than 100 years. Fortier (10) stressed the importance for increasing irrigation efficiency as early as 1915 when he stated that "measurements and experiments show that for every three gallons of water diverted from natural streams one gallon serves a useful purpose in nourishing plant life."

Irrigation principles and practices have advanced to the point that water application efficiency is primarily controlled by the amount of evaporation losses. Water application efficiency may be defined as the ratio of the quantity of water effectively put into the crop root zone and utilized by growing crops to the quantity delivered to the field (34).

Interest in evaporation and evapotranspiration is not of recent origin. Dalton (8) in 1798 showed that the rate of evaporation was proportional to the difference between the water vapor pressure at the evaporating surface and in the atmosphere. Essentially all vapor transport formulas since that time take this principle into account.

According to Frost (11) the operational factors which may influence the losses during sprinkling are droplet size, application rate, crop, crop height, soil moisture retention and water temperature. He also lists the following climatological factors as influencing evaporation losses during sprinkling: vapor pressure deficit, wind velocity and cloud cover. Evaporation spray losses by sprinklers have been studied by Frost and Schwalen (13). A test plot was set up for collecting the discharge from sprinklers by using collecting containers from which the total volume of water reaching the ground surface could be computed. The discharge from the sprinkler nozzles was measured through a calibrated meter and the spray loss was determined by the difference between the metered discharge and the computed amount of water reaching the ground surface. Using these tests as a basis a nomograph was developed which showed the relationship of relative humidity, air temperature, nozzle diameter, nozzle pressure and wind velocity to evaporation losses. The spray losses computed by using this nomograph include wind drift losses for small droplets that were blown out of the collecting area. Since this nomograph was computed for a single sprinkler and because wind drift losses might not be actual losses in a large area, Frost has suggested that a value approximately 25% of those computed from the nomograph could be used for a solid set system. Under extreme condidions this nomograph shows evaporation losses as high as 20%.

Results of studies with a single lateral by Krause (2) and with two laterals by Sternberg (31) at Davis California show that Frost and Schwalen's nomograph may result in low estimations of spray losses. Kraus' data show losses up to 20% higher than the nomograph and Sternberg's studies show losses up to three times greater than the nomograph. It should be noted that one would expect the greatest loss from the single lateral. In order to be consistent with Frost and Schwalen's interpretation of their nomograph, Kraus' and Sternberg's results should have shown less evaporation loss. On the other hand, Christiansen (5) in his work with sprinkler irrigation in California studied direct evaporation loss from the spray and concluded that this loss should be less than 2%.

The Sprinkler Irrigation Association (SIA) Proceedings (9) point out other apparent conflicts in the results of evaporation studies which are perplexing to the engineer. One of these is the amount of evapotranspiration during sprinkling. Sternberg (31) reported it was negligible for grass. On the other hand, Frost and others have found that evapotranspiration is approximately equal for sprinkling and nonsprinkling periods. SIA has also pointed out that many have concluded that the combination of evaporation, drift losses and interception by vegetation do not significantly reduce evapotranspiration from normal dry leaf values and that losses from wet leaves are equal to losses from dry leaves. Hence, interception of water by closely growing crops is not a loss. Paul and Burgy (27) on the other hand found that interception evaporation losses might approach 60% of the gross interception for widely spaced plants.

Wiser (33) tested the hypothesis that evaporation loss during sprinkling is approximately the same as evaporation from a free water surface under similar meteorological conditions, and found it to be true. He attempted to do this in field tests at Oxford, North Carolina, where he accounted for all the water applied except that lost due to evaporation, and took the difference to be equal to evaporation. Evidently there was no crop, so this evaporation was for spray losses, and soil surface evaporation but not evaporation and transpiration from plants.

In order to test his hypothesis, he compared his results with that of several other investigators who had developed equations for estimation of evaporation from free water surfaces. An equation by Leeper (23) showed a good overall relation to the test results.

$$E = 0.0207\ (e_a - e_d)\ X \qquad [1]$$

where E = evaporation, inches per day

e_a = saturation vapor pressure, millibars

e_d = water vapor pressure of the air, millibars

X = relative duration of daylight, hours of actual daylight/12

Weaver and Pearson (32) suggested a similar equation including the wind velocity

$$E = 0.011\ (e_a - e_d)\ X\ W^{0.76} \qquad [2]$$

where W = wind velocity at a four foot level in miles per hour

Wiser also compared these results with some equations by Penman (28) which were more complicated and harder to use.

Most designers of sprinkler irrigation systems are using a water application efficiency of approximately 70% which includes all water losses (1,15,34). Cannell (3) gave a summary of water application efficiencies obtained from sprinkler systems as reported by several investigators. These efficiencies range from 26 to 84% with a mean value of 55%.

The lack of uniformity in irrigation efficiency is partly due to disregard of rate of application. The use of any uniform figure for efficiency as a design criteria assumes that the total loss is proportional to the application amount but depends on no other factor. Published data do not bear this out. Several investigators, Christiansen (4), Mather (24), Hammilton and Schrunk (18) and Somerhalder (30) have pointed out that the efficiency is increased with higher application rates as long as the ilfiltration rate of the soil is not exceeded. For example, Mather got approximately the same rate of evaporation loss from two systems although one had a water application rate of 4 times the other.

Christiansen (5) developed an indirect method of estimating evaporation loss from the spray through the use of thermodynamic principals. Evaporation of water requires heat. Three sources of heat are available for evaporating water from a spray: (1) heat from the water, (2) heat absorbed from the air, and (3) radiant heat [principally from the sun]. If all the heat came from the water it would require a temperature drop of about 10.5 F to evaporate 1% of the water.

When the water is cooler than the air, which is normally the case in the daytime, the water will absorb heat from the air and the temperature drop will be less than 10.5 F for a loss of 1%. Absorption of radiant heat will increase the evaporation for the same temperature change, however, this has been shown to be negligible in most cases. When the initial water temperature is the same as the wet bulb temperature of the air an equilibrium temperature exists, in which case, all the heat required for evaporation comes from the air and the water remains at a constant temperature. When the initial temperature of the water is lower than the wet bulb temperature, the temperature of the water will increase even though some evaporation still takes place. The evaporation would be zero, however, if the water temperature was at the dew point; and if it were lower, condensation would occur and there would be a gain rather than a loss of water. Neglecting radiant heat, Christiansen developed the following expression for the evaporation loss from the spray.

$$E = \frac{100\ C\ \Delta t}{r}\left[\frac{P_w - P_a}{P_w - P_a - 0.00037B\ (t_a - t_w)}\right] \qquad [3]$$

where E = the evaporation of water from the spray expressed as a percentage of the amount discharged.

C = the specific heat of water, caloriea per gram per degree F

r = the heat of vaporization, calories per gram

Δt = drop in temperature of the water from the time it leaves the nozzle until it reaches the ground

t_w = the mean water temperature, degrees F

t_a = the air temperature, degrees F

P_w = the vapor pressure at temperature t_w, in. Hg

P_a = the pressure of water vapor in the air, in. Hg

B = the barometric pressure, in. Hg

This equation fails to take into consideration the very small droplets which are completely evaporated or blown away by the wind and which do not contribute to the final temperature of the water as it reaches the ground. A study of the distribution of droplet size indicates that only a very small part of the water discharge is in the form of tiny droplets that are lost in this manner. Thus, it is believed that this loss would not cause an appreciable error in the determination of evaporation loss from irrigation spray. Tests have been conducted in which the change of water temperature as a result of evaporative cooling has been measured. Tests on rotating sprinklers with initial water temperature of 69.5 to 84 F and with air temperature ranging from 75 to 101 F show decreases of water temperature from 1 to 7 F corresponding to evaporation losses of 0.23 to 0.81%. Another test with the initial water of 98.7 F and an air temperature about 105 F resulted in a temperature drop of 20.7 F, corresponding to a loss of about 2%. Christiansen concludes that evaporation loss from the spray is negligible in comparison with subsequent losses from the wet soil and vegetation.

Mather (24) made a field investigation of evaporation from sprinklers by observing the actual increase in moisture content of the air moving through an irrigated spray area. His values were obtained from measurements of the dew point upstream and downstream of the air entering the irrigated area. He calculated the evaporation loss through the use of the absolute moisture gain of the air as it passed through the irrigated area. He either estimated the amount of moisture movement upward or assumed that it was negligible. His results show that as the distance downwind from the irrigated area increased the amount of evaporation into the air becomes less. For example, his data indicate that only within the first 40 meters is there much gain in the moisture content of the air. Thus, the percent of water lost would be minimized by making the size of the field to be irrigated as large as possible. The evaporation loss from the spray and moist soil ranged from 4 to 30% of the water applied. However, the application rate in some cases was less than 0.1 of an inch per hour. From actual observations and evaporation computations, Mather suggests that from a water conservation point of view the application of water by irrigation should occur as rapidly as is economically possible.

Ingebo (19), in his studies of vaporization rates of iso-octane sprays, developed a semiempirical equation for the prediction of spray losses during the initial period after atomization at the nozzle.

$$\frac{dm}{d\theta} = \frac{DK\pi\Delta t}{H_V}\left[2 + 0.4\left(\frac{\Delta VDW}{U}\right)^{0.5}\right] \qquad [4]$$

where m = mass of water

θ = time

D = diameter of droplet

K = coefficient of thermal conductivity

Δt = difference of temperature between the surface of the droplet and the surrounding gas atmosphere.

H_V = heat of vaporization of liquid

ΔV = the relative velocity between the droplet and the surrounding gas

W = density of surrounding gas atmosphere

U = viscosity of the surrounding gas atmosphere

This equation was derived by converting and simplifying a mass transfer equation.

Peters (29) studied the relative magnitude of evaporation from soil surfaces and the transpiration by plants. He concluded that in the midwest where frequent summer showers occur, as much of 50% of the total water loss in a season can be accounted for by evaporation from the soil surface. He used plastic covered plots in his experiments and determined that the amount of transpiration from a particular crop is within rather narrow limits. He pointed out that photosynthesis has been thought to be such a minor fraction of the total heat budget that it could be neglected and that the net radiation is used up principally in heating air and evaporating water.

Fortier and Beckett (10) conducted experiments to determine evaporation losses after an irrigation from undisturbed and cultivated soils at Davis, California. They found that one to two inches of water evaporated from a soil within three to four weeks after an irrigation, and that more than half of it occurred during the first five days. According to other experiments conducted by these men, the rate of evaporation from saturated soils is about the same as that from a free water surface or about 0.3 inches per day in the Sacramento Valley during the summer.

When relatively small amounts of water are applied to exposed soils at frequent intervals by sprinkling, much of the water can be lost by evaporation. In some instances, irrigation applications of about 1 inch are made at weekly intervals to aid in the germination and starting of a crop and to prevent the drying out and crusting of the surface soil. Most of this water may be lost directly from the soil by evaporation. It is estimated that if application rates of 0.25 to 0.5 inches per hour are used, more than 10% of the water may evaporate when it is applied during daylight hours.

When crops are sprinkled part of the water is intercepted by the foliage and later evaporated without reaching the soil. Clark (6) determined the maximum interception capacity of many plants and it appears, from his data, that few crops can attain more than 0.1 inches of water.

Kraus (21) reported spray evaporation losses as a function of vapor pressure deficit and separated the losses into evaporation loss and drift loss. He measured the drift losses by detecting and measuring impressions made by droplets falling on a layer of magnesium oxide which was smoked on a glass slide. This method is applicable for drops ranging from 10 to 200 microns in diameter.

Total losses ranged from 3.4 to 17.0% for vapor pressure deficits of 0.123 and 0.673 in. Hg, respectively. The average drift loss was 36% of the total. Through the use of lysimeters he determined that evapotranspiration in the drift zone, as compared to a dry control area, was increased under high wind speed conditions, and was decreased under low wind speed conditions.

George (14) studied spray evaporation losses by determining the salt content of the water in the lateral and in catchment bottles. Drift losses were not considered. The author reported a correlation between relative humidity and evaporation loss.

METHODS AND EXPERIMENTAL FACILITIES

Studies of irrigation evaporation have been conducted in the field under natural conditions and in the laboratory. Each of these locations has advantages and disadvantages. In the field, precision must be sacrificed in controlling and measuring the properties of the surrounding atmosphere, however, adequate space is available to operate irrigation sprinklers in the conventional manner. In the laboratory it is possible to control the properties of the atmosphere during the experiment and make precise measurements, however, it is costly to provide adequate space within an atmospheric control facility in which to operate a standard agricultural irrigation sprinkler. In either case, the experimental values that are obtained must be projected and related in order for them to provide practical information on irrigation evaporation. A climatic control chamber was used in conducting all the tests supporting this study.

Climatic Control Chamber

The climatic control chamber, shown in Figure 1 in cutaway perspective view, was built specially for conducting the experiments supporting this study. The chamber is equipped for control of a range of dry bulb temperatures, dew point temperatures, and air flow rates. Also, a water droplet generator with the capacity for controlling precipitation rates and water temperatures at different levels was constructed as an integral part of the chamber.

The approximate outside dimensions of the chamber are 50 feet long, 16 feet wide and 10 feet high. It was designed to minimize heat and vapor transfer between the surrounding atmosphere and the air inside the chamber. Typically, as shown in Figure 2, the exterior consisted of 4 inch thick panels of paper honey-comb insulation with sheet aluminum bonded to both sides and a 3 inch layer of polyurethane foam poured in place on the inside to assure a good air and vapor seal. Holes made through the exterior for water, electric and refrigeration conduits were sealed by pouring polyurethane foam around them. Nevertheless, there was some air leakage through small openings around the blower shafts, door seals, etc. However, the quantity of air transfer was determined for various operating conditions and taken into consideration for all data presented. The magnitude of the air transfer was estimated by operating the chamber with an inside dew point lower than outside and measuring the rate of moisture removal required to maintain a constant dew point temperature within the chamber. This value, along with the inside and outside dew points, was used to compute the quantity of air transfer. Air leakage under the most adverse conditions was approximately 125 cfm and this quantity was not considered significant except for tests where evaporation rates were low.

As indicated in Figure 1, air moves in a closed circuit from the blower discharges through the air conditioning section, airflow measurement section, air straighteners, test section

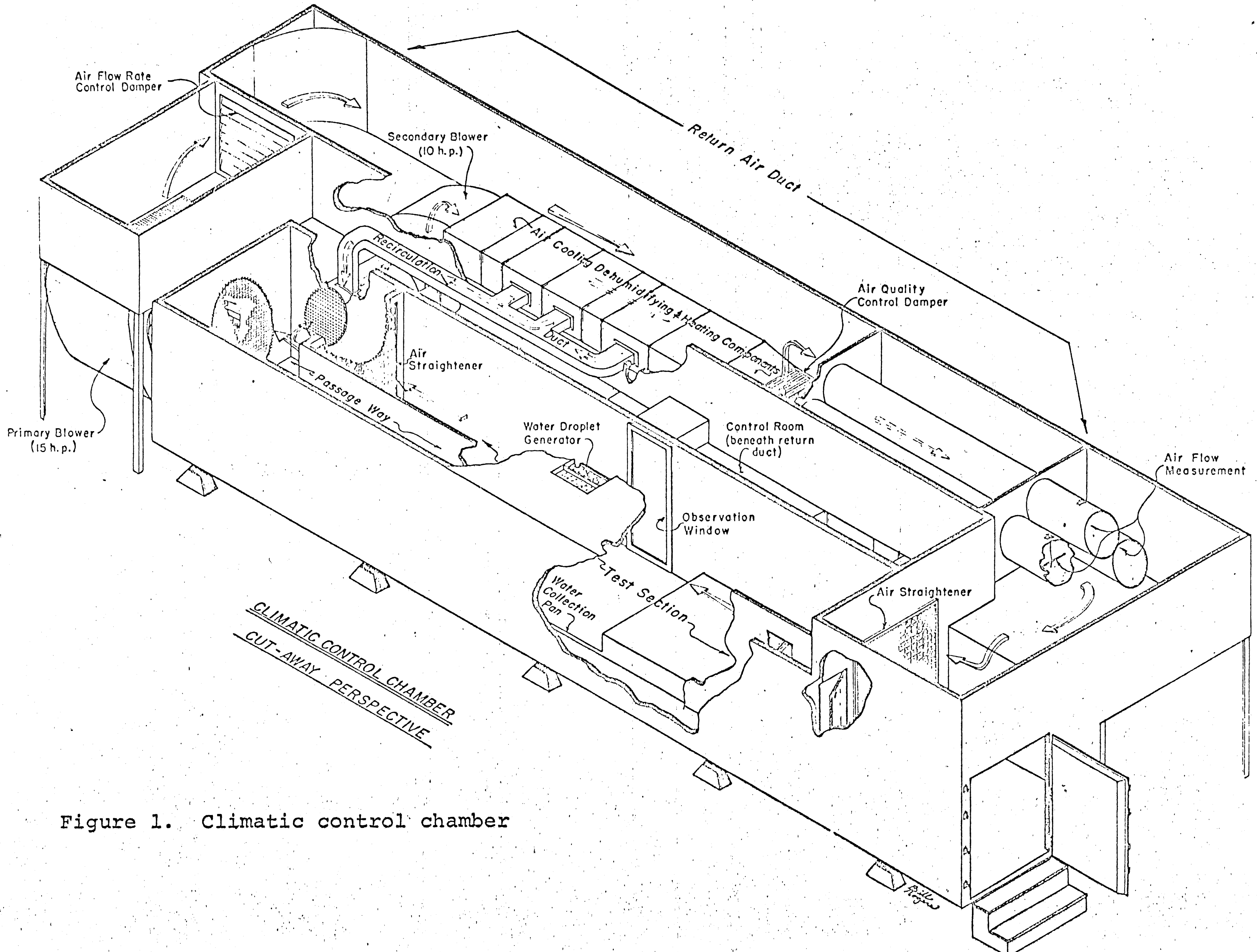
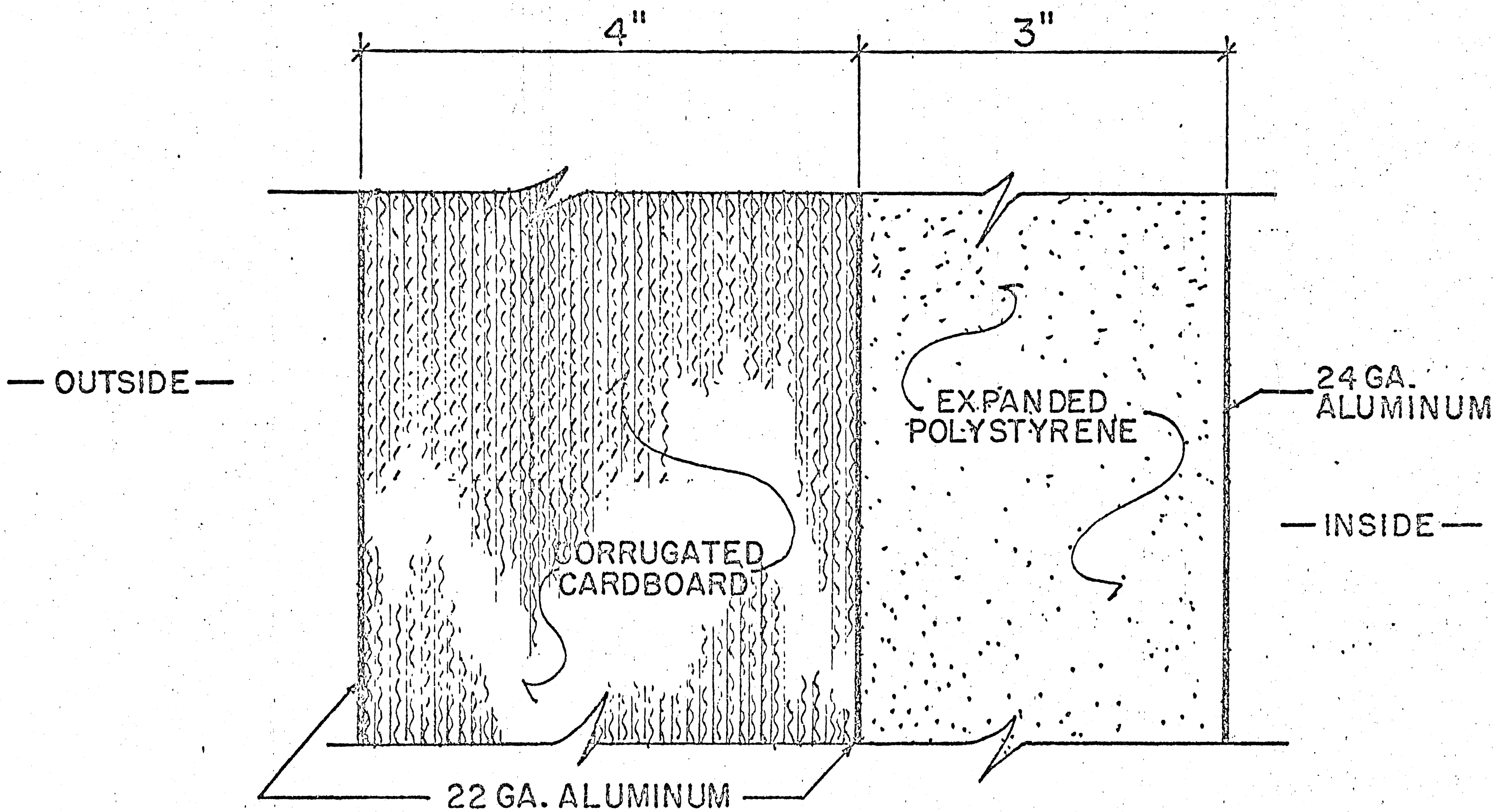


Figure 1. Climatic control chamber



TYPICAL WALL SECTION

Figure 2. Typical wall section indicating construction materials and dimensions

and back to the blower intakes. The reason for using two blowers was primarily for convenience in manipulating air flow velocities through the heating and cooling coils with minimal interference with air flow rates through the test section.

Air Straighteners

Air straighteners and resistance layers were installed at both ends of the test section as shown in Figure 3. They consisted of stacks of 3 inch diameter by 12 inch long sheet metal tubes, layers of aluminum honey-comb type material and 10-mesh screen wire. Trial and error techniques were used to attain the desired degree of uniformity of air velocity through the test section. The technique used required that air velocity measurements, obtained with a hot wire type velocity meter, be made at each intersection of an imaginary 12 inch square grid across the test section in the vicinity of the water droplet generator. On a basis of these values, unsatisfactory air flow patterns were altered by adjusting the location, size and number of layers of screen wire patches that were placed on the leading air side of the air straighteners. The level of uniformity of air flow was considered satisfactory when none of the individual velocity measurements varied by more than 25% from the mean.

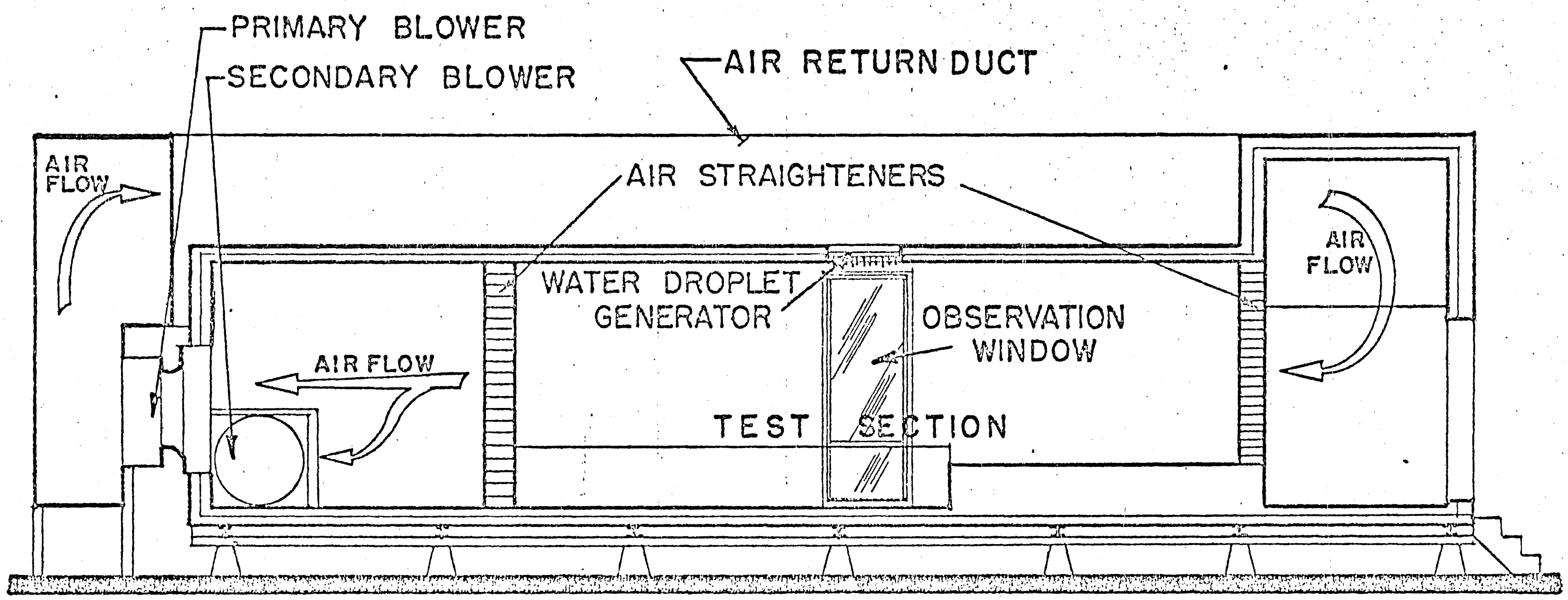
Test Section of Chamber

The test section is approximately 24 feet long, 8 feet high and 5.5 feet wide. Figures 3, 4 and 5 are section drawings of the climatic control chamber on which the location and relative size of the test section is indicated.

Ten "viburnum" plants were placed in the test section immediately beneath the water droplet generator to provide vegetative material for tests involving evaporation losses from intercepted water. Individual plants were approximately 3 feet high and 2 1/2 feet in diameter and conformed generally to an ellipsoidal shape. In elevation, shown schematically in Figure 5, they were located at three levels so as to fully occupy the volumetric space beneath the generator. On each plant there were approximately 500 leaves, each with a surface area of about three square inches. Leaf density appeared to be about the same as that found in a mature citrus grove. During test, it appeared that 80 -90% of the droplets were intercepted by the plants.

Water Droplet Generator

A special apparatus was developed to generate water droplets that could be used to simulate irrigation spray. Figure 6 shows



SECTION THRU CLIMATIC CONTROL CHAMBER

Figure 3. Section through climatic control chamber indicating relative position of air straighteners and test section

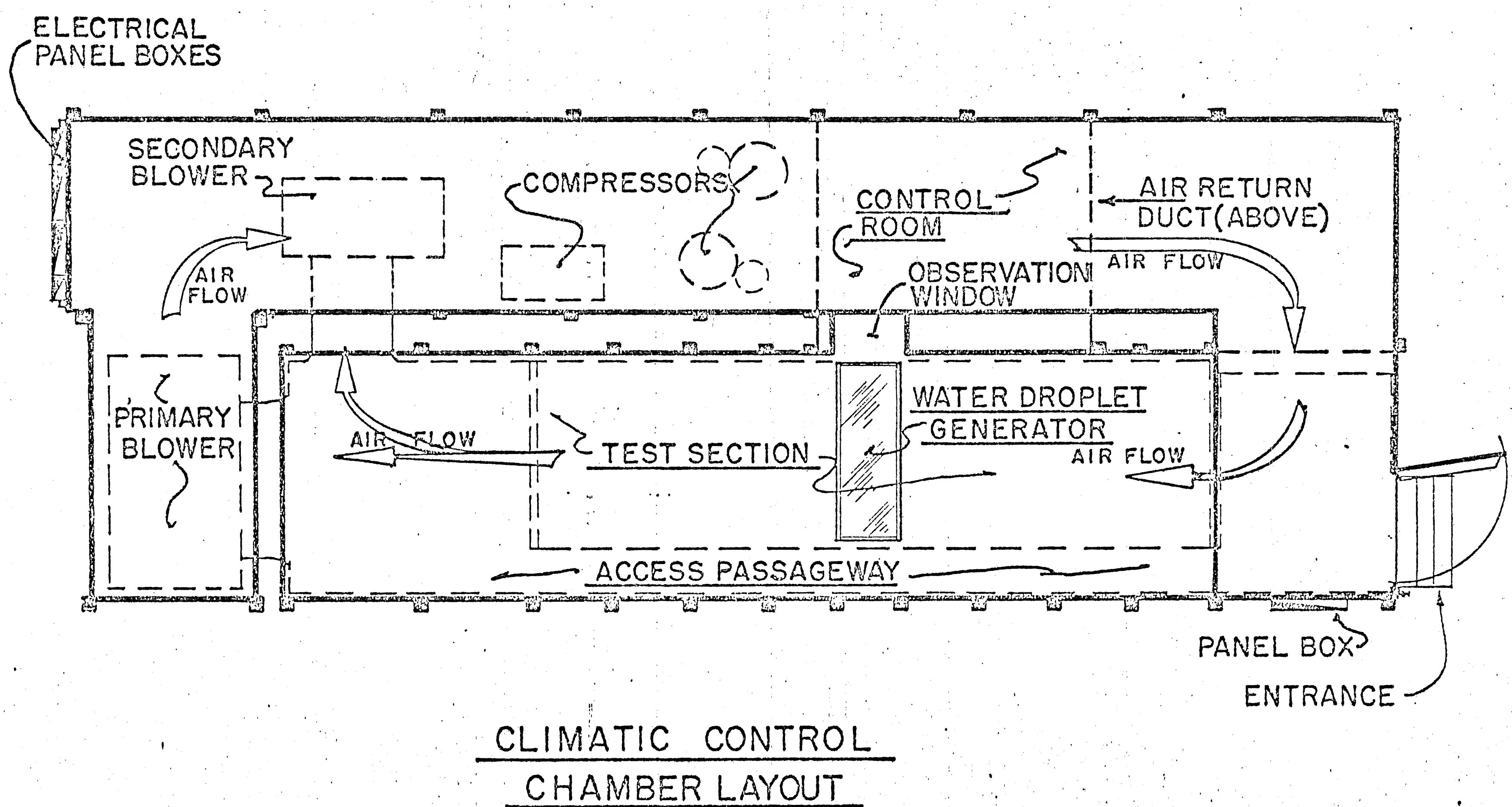
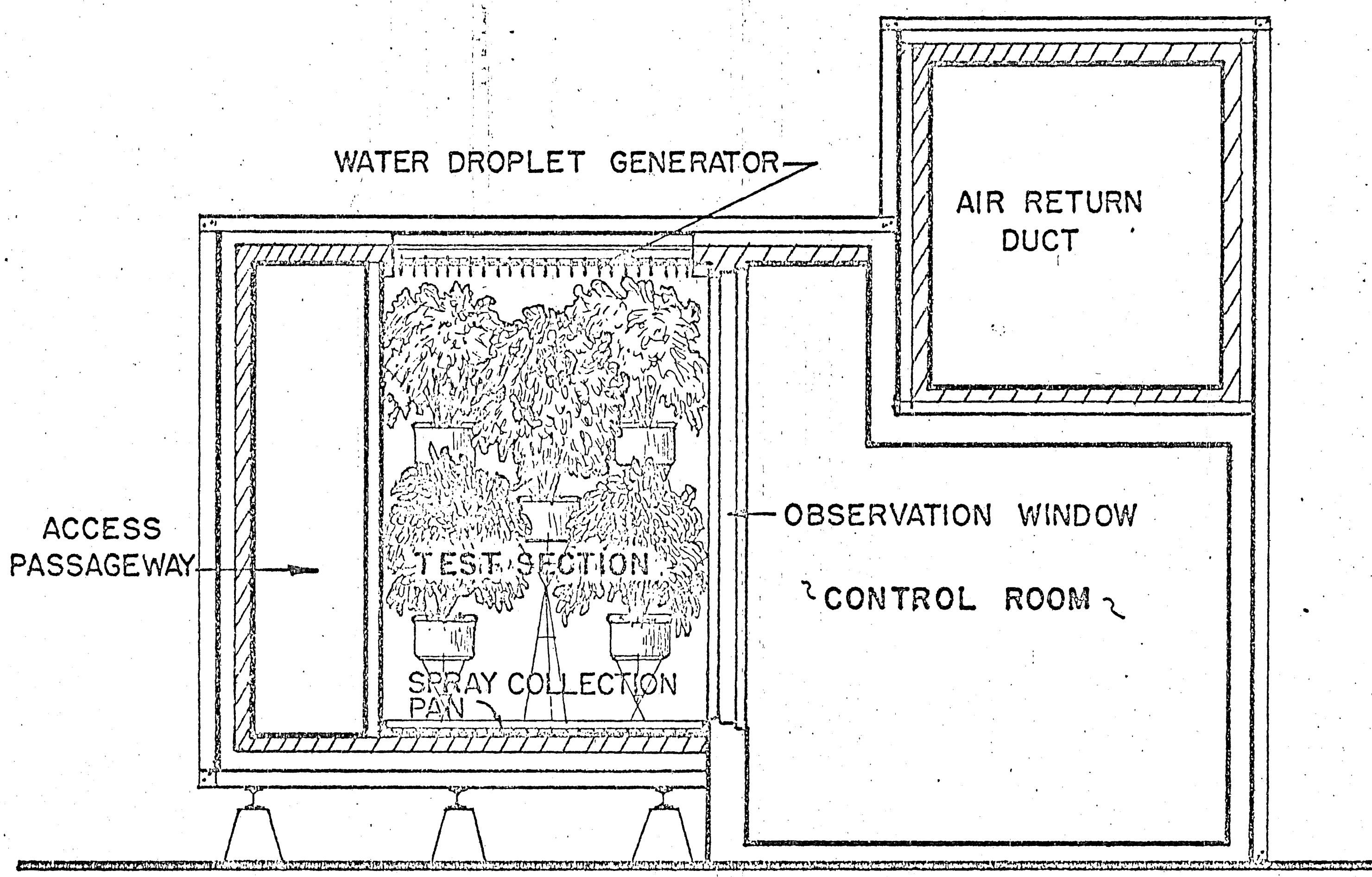


Figure 4. Layout drawing through the climatic control chamber indicating relative position of the component parts of the chamber



SECTION THRU

CLIMATIC CONTROL CHAMBER AT CONTROL ROOM

Figure 5. Section view through the climatic control chamber at the test section indicating the positioning of plants

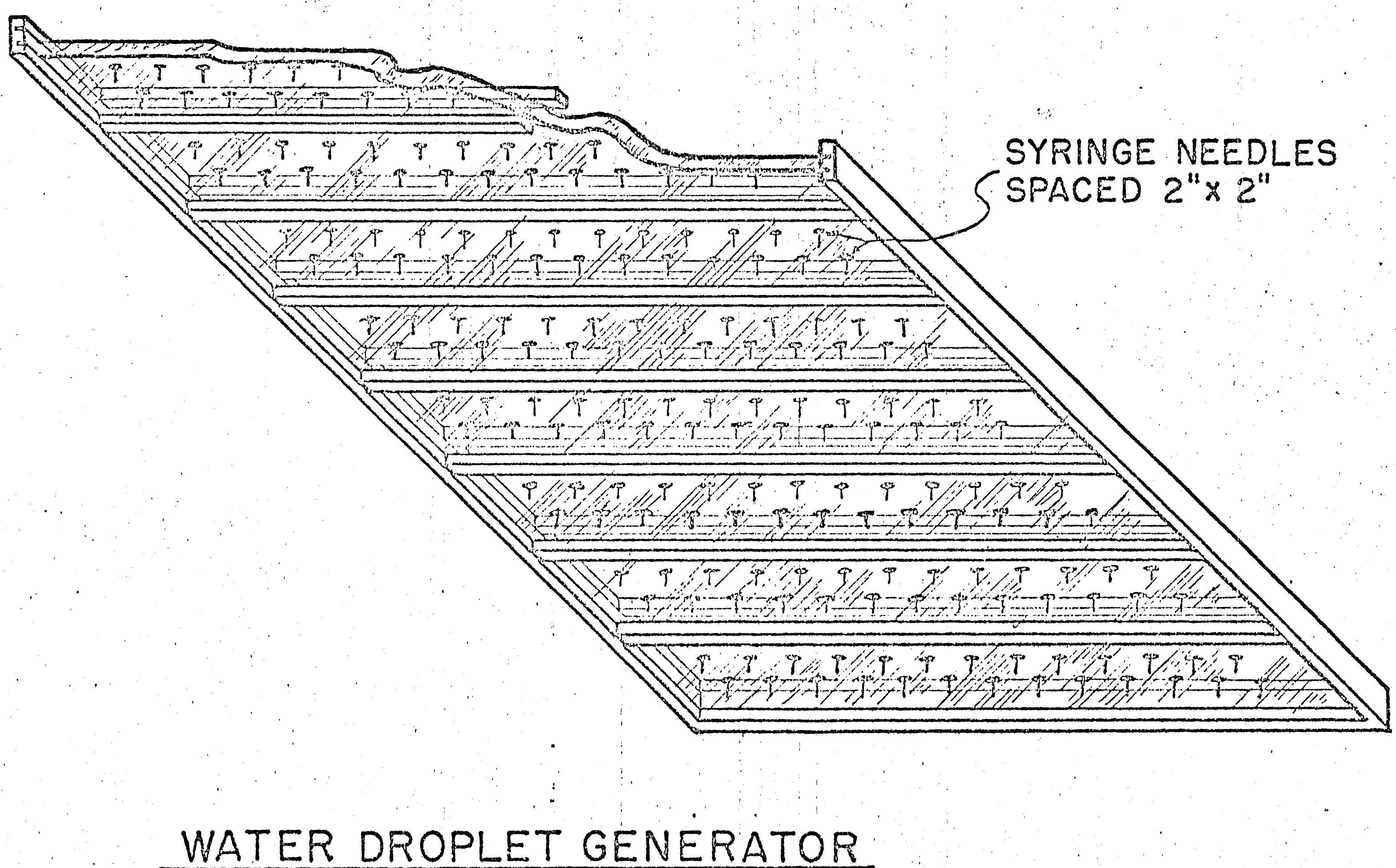


Figure 6. Schematic of water droplet generator

a view of this apparatus. The reservoir with disposable type syringe needles projecting through the bottom, was recessed into the ceiling of the test section of the climatic control chamber so that the tips of the needles were flush with the ceiling. It was constructed of plexiglass panels fastened into a fabricated aluminum framework. Four hundred and three needles spaced on two inch centers in a square pattern were required to dispense droplets uniformly over an area 62 inches wide and 26 inches long. When in operation the reservoir was vented to the atmosphere through a stand pipe. The rate of flow was controlled by adjusting the rpm of the paristaltic type pump until the desired water pressure head was obtained over the needles.

Number 20 gage X 1 inch syringe needles were used for all tests. Preliminary tests had revealed that this size needle produced droplets that were approximately 3 mm in diameter which is also approximately the same average diameter as water droplets produced by many irrigation sprinklers (13,17). Flow rates equivalent to precipitation depths of 0.1 to 5.4 inches per hour could be obtained by adjusting the water pressure head between 0.1 and 6.0 inches.

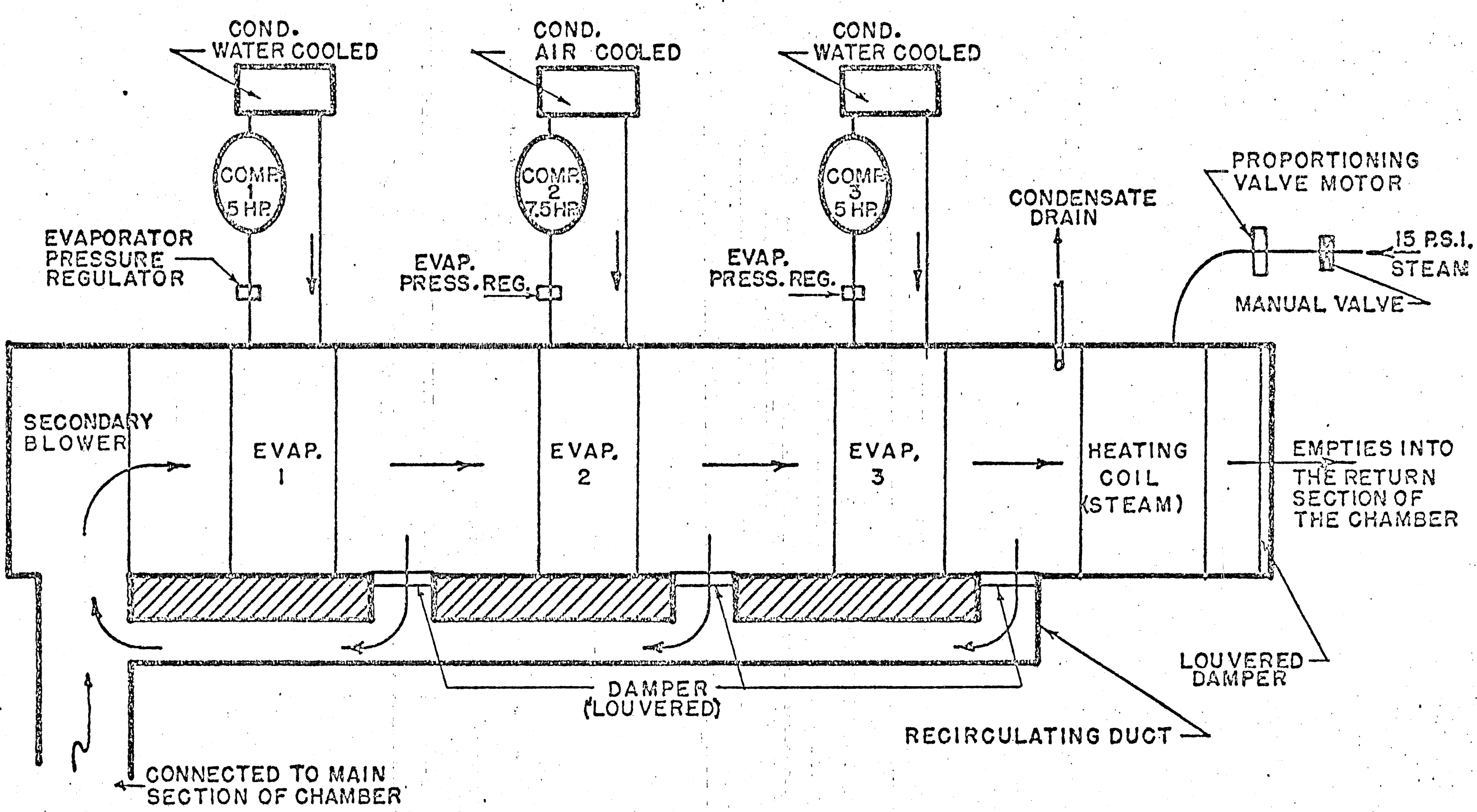
In order to have instant shut off of flow from the needles it was necessary to install solenoid valves in the standpipe and inlet water lines. The valves were electrically wired in series with the pump motor and thus were open or closed when the pump was on or off. It was necessary for the entire water droplet generating system to be purged of air in order to obtain sudden shut off of flow from the needles.

Water that was not evaporated was collected in a pan recessed into the floor of the test section of the chamber. A trap was installed in the pan drain pipe line so that the depth of water in the pan was maintained at a constant level of about three inches above the bottom. In order to minimize evaporation from the water collected in the pan, a layer of type I hydraulic fluid (oil), 3/8 inch in depth, was maintained over the water surface during all tests.

A small electrical resistance type emersion water heater, equipped with rheostat, was used to maintain the water temperature in the reservoir at the desired temperature.

Air Conditioning and Heating

Air leaving the test section of the climatic control chamber is divided so that part of it goes through the air conditioning-heating system and the remainder is recirculated. The quality of air passing through the air conditioning-heating system is dehumidified, cooled or heated to a level so that when it is mixed with the recirculated air, the two will combine to produce air with the desired physical properties for a particular test. Figures 1 and 7 show the relative location of



DEHUMIDIFYING — COOLING AND HEATING COMPONENTS
(Located in the return section of the CHAMBER)

Figure 7. Schematic indicating layout of mechanical components of the dehumidifying, cooling and heating section of the climatic control chamber

the components of the air heating, cooling and dehumidification system as well as the distribution and direction of air flow.

If the dew point of the air coming in contact with the water droplets is less than the temperature of the water droplets, some of the water is evaporated from the droplets and becomes water vapor in the air stream. In order to keep the dew point of the air within the chamber from increasing it becomes necessary to remove water from the chamber at the same rate that it is evaporating. Water is removed from the chamber as condensation on refrigeration coils. This condensation is collected and weight measurements made with respect to time to determine the rate. Since the only significant source of moisture added to the system comes from the water droplets, the rate of condensation is also the rate of evaporation. This measurement is the primary criteria for evaluating treatment responses presented in this report. Two precautionary measures had to be taken to assure accuracy. First, instrumentation had to be monitored to assure that the chamber had been operated for a sufficient length of time, during each test, for all systems to be in equilibrium and second, that none of the condensation coils were permitted to become cold enough for the condensated moisture to freeze.

Dew Point Temperature Control

Normally, dew point levels were obtained by controlling the temperature of the evaporator coils at the desired level. This was usually accomplished by manual adjustment of the evaporator pressure regulating valves, however, for several of the lower dew points, it was necessary to manipulate the dampers of the recirculating duct to attain the desired levels.

Dry Bulb Temperature Control

Air within the climatic control chamber was heated by a steam coil equipped for automatic dry bulb temperature control. The essential components of this control system were as follows: motorized proportional control steam valve, electronic proportional controller with reset and rate action and thermopile temperature sensing element.

Air Flow Rate Control

As indicated in Figure 1, two centrifugal blowers with backwardly inclined impeller blades were used to obtain the desired air velocity through the test section of the climatic control chamber. It has been stated earlier that the secondary (10 hp) blower was used primarily to facilitate ease of controlling air velocities over the heating and cooling coils, however it did furnish varying amounts of air (depending on dew point level) for the test section. A motorized damper was installed in the discharge duct of each blower to regulate the

PROCEDURE

Air velocity, dry bulb temperature, dew point temperature, water temperature and rate of precipitation were factors tested at different levels to measure their independent effect on rate of evaporation. Levels at which these factors were tested is given in Table 1. The influence of these factors on evaporation was considered in terms of losses from water droplets (spray) and from water intercepted by plants.

All tests were conducted in the climatic control chamber that has been described in the "Methods and Experimental Facilities" section of this report. Evaporation rates are expressed as a percentage of the discharge rate of the water droplet generator (precipitation rate) and presented in graphical form.

TABLE 1. The factors Tested and Levels of Treatment.

Water Droplets (Spray)

Factor	Level of treatment (nominal)
Air velocity, mph	2, 3, 4, 5, 6
Dry bulb temperature, F	75, 80, 85, 90, 95, 100
Dew point temperature, F	50, 55, 60, 65, 70, 75
Water temperature, F	75, 80, 85, 90, 95, 100
Precipitation rate, iph	5.4

Plant Intercepted Water

Factor	Level of treatment
Air velocity, mph	2, 3, 4, 5, 6
Dry bulb temperature, F	75, 80, 85, 90, 95
Dew point temperature, F	60, 65, 70, 75
Water temperature, F	82
Precipitation rate, iph	0.15, .50, 1.0, 2.0, 5.4

discharge rate for each blower. Unless prohibited by a test requiring a low dew point treatment level, the damper for the secondary blower was completely open at all times. The damper for the primary blower would then be adjusted to attain the desired air velocities through the test section. Air velocities through the test section could be controlled at levels up to 6 miles per hour.

Instrumentation

Instrumentation systems were required for dry bulb air temperature control and measurement, dew point temperature measurement and air velocity measurement.

An adjustable zero-adjustable range, proportioning band potentiometric controller with reset and rate action was used in conjunction with a motorized proportioning steam valve to sense the dry bulb air temperature and regulate the rate of steam flow into the air heating coil. The sensing element for the controller was a 5 junction thermopile located at the approximate centroid of the cross section of the test section of the chamber and about 3 feet up the air stream with respect to the water droplet generator. Dry bulb temperature measurements were made with a dual-element quartz thermometer. Both elements were located at the approximate centroid of the cross section of the test section with one element being located about 3 feet up the air stream and the other about 3 feet down the air stream with respect to the water droplet generator. The thermometer elements were connected to a digital read-out indicating the nearest 0.001 degree Celsius.

Dew point temperature measurements were made at two locations. One was in the air stream at approximately the same location as that of the up-stream dry bulb air temperature sensing element and the other was outside the climate control chamber. A direct reading dew point indicator equipped with dual miniaturized "Heated Salt" thermistorized probes was used to measure dew point temperatures. Meter readout was scaled so that dew point temperatures could be read to the nearest 0.1 F.

Air flow rate measurements were made in a section of the return air duct of the climatic control chamber as indicated in Figure 1. All the air was channeled through three 21 inch diameter pipes, each equipped with a calibrated annular ring type velocity probe. An electronic pressure meter was used to measure the pressure output of the probes. Readout accuracy of the electronic pressure meter was to the nearest 0.001 mm Hg. Based on manufacturers claims for accuracy for the two primary components of the air flow rate measuring system, it is believed that air velocity measurements are accurate to within 2.0 percent of the values presented in this report.

DISCUSSION AND RESULTS

All the data given in this report were taken under controlled conditions in an environmental control chamber. The exact duplication of field conditions for sprinkler irrigation systems was sacrificed for conditions which could be adequately controlled and described.

Therefore, the results of these tests should not be taken as directly applicable to field conditions for sprinkler irrigation, but as a basis for making decisions concerning the design and operation of sprinkler irrigation systems and the long range advantages and limitations of sprinkler irrigation.

The data taken were for two separate sources of evaporation, that from the spray and that from the plant intercepted water. Since the configuration of the water applicator is quite different from most field conditions, the spray losses require considerable interpretation before applying to field conditions. However, that from the plant intercepted water, which also included some spray losses, should be closely related to field conditions if the variations due to different crop configurations are taken into account.

Evaporation is directly proportional to the difference between the saturation vapor pressure corresponding to the temperature of the water surface and the vapor pressure of the air (8). Therefore, the mean temperature of the water surface directly affects the evaporation rate.

In most of the previous evaporation studies, evaporation rate has been reported as a function of air quality only without regard to the initial water temperature or application rate. One term commonly used in evaporation studies is vapor pressure deficit, which is the difference between the saturation vapor pressure of the air and the actual vapor pressure of the air. When considering evaporation of water droplets in air, the vapor pressure deficit is the vapor pressure difference between the air and the droplet only for a mean water temperature equal to the air temperature. Another similar term which has been reported as being directly proportional to evaporation rate is wet bulb depression. These terms, of course, are useful and very practical since they do not envolve the mean water temperature, which is hard to determine. However, the evaporation rate should not be expected to be directly proportional to these terms.

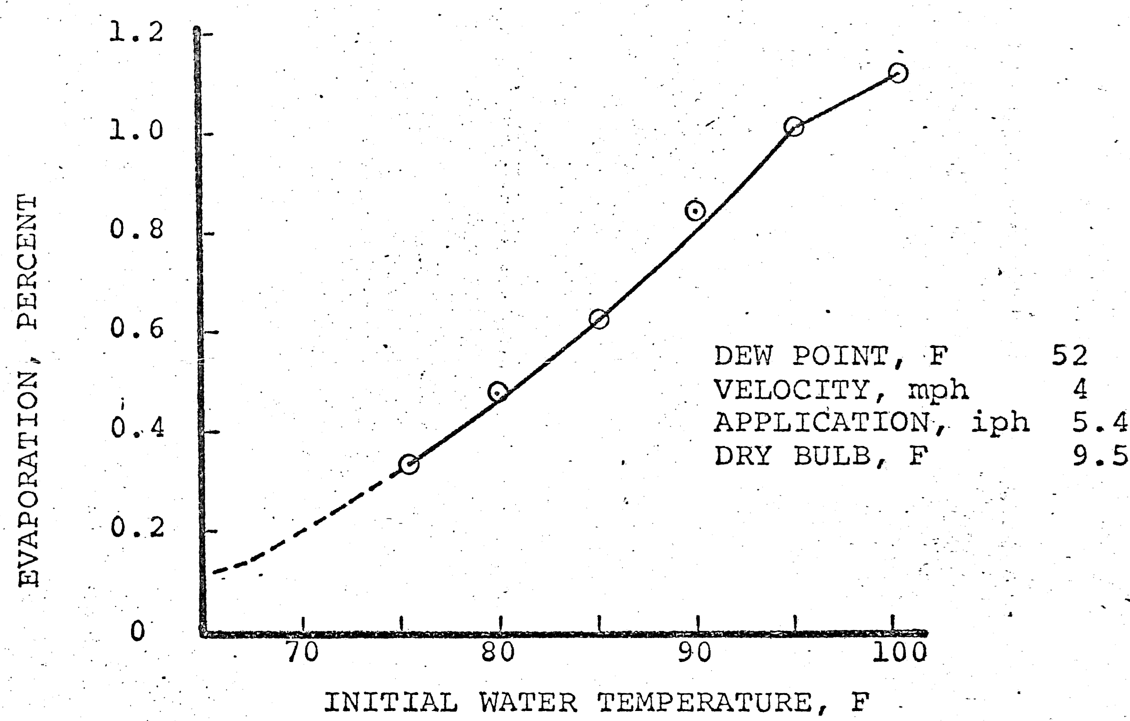


Figure 8. Evaporation of water droplets as a function of initial water temperature. Dashed lines are not an extrapolation of experimental results and are presented only to support discussion.

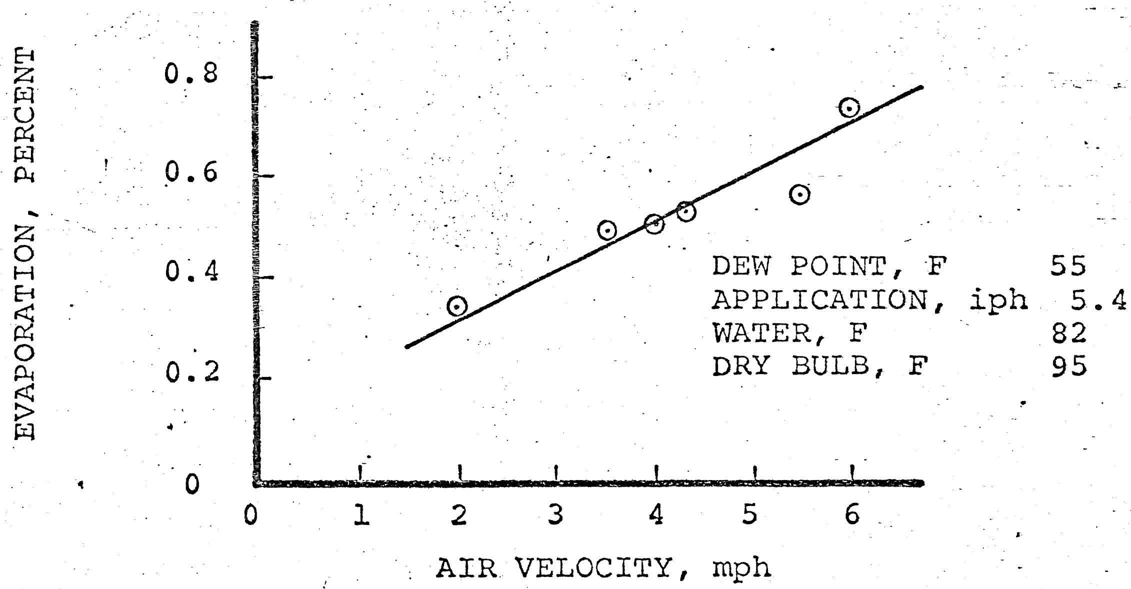


Figure 9. Evaporation of water droplets as a function of air velocity

Since the independent air quality variables such as dew point, dry bulb, wet bulb and relative humidity are not directly proportional to the actual water vapor pressure difference; one should not expect them to be directly proportional to the evaporation rate. However, in many cases, for the ranges indicated, an approximately linear relationship does exist, but it should not necessarily be expected to hold for other values of the independent variables.

The results of the tests for spray evaporation losses are consistent with those of other investigators (5, 13, 33) in that the losses are very small compared to the total amount applied and also small compared to evaporation losses from the plant and soil surface. The evaporation loss from droplets expressed as a percentage of the amount applied ranged from 0.20% to 1.13%, while that from the plant intercepted water ranged from 3.5% to 60.3%. The effect of each independent variable on evaporation, as indicated by Table 1, will be discussed separately. Theoretical reasoning, as well as recorded data, was used in discussing the characteristics of the curves that follow.

Evaporation from Water Droplets

Initial Water Temperature (Figure 8)--Figure 8 indicates the percentage evaporation as a function of initial water temperature. When the temperature of the droplet is equal to the dew point temperature of the air, no evaporation will occur. However, for an initial droplet temperature equal to the dew point (52 F) or even lower, heat from the air will be transferred to the droplet as it moves through the air and evaporation will occur. The droplet will be heated until the wet bulb temperature (67.7 F) is reached, provided the exposure time is sufficient. There will be an abrupt change in the slope of the curve where the initial water temperature is equal to the wet bulb temperature with the slope immediately above the wet bulb temperature being greater than that immediately below it. The evaporation rate will increase at an increasing rate up to the dry bulb air temperature (95 F) at which point another abrupt change will occur with the slope immediately above 95 F being less than that immediately below it. The evaporation rate increases at an increasing rate since the saturation water vapor pressure increases at an increasing rate with respect to water temperature.

The abrupt changes in the slope of the curve occur due to the change in the relative amount of heat which is used for evaporation in comparison with that used as sensible heat. Below the wet bulb temperature some of the heat transferred from the air must go to increase the temperature of the droplet;

between the wet bulb temperature and the dry bulb temperature heat for evaporation comes from both the air and the droplet; and above the dry bulb temperature heat is transferred from the droplet to the air.

In past studies of evaporation the initial water temperature has not been considered in most cases. However, as can be seen from these results, the initial water temperature is an important factor even though the droplets rapidly approach the wet bulb temperature of the air. For field conditions where the droplet exposure time is greater than that for the laboratory tests, the effect of initial water temperature on evaporation is reduced.

Air Velocity (Figure 9)--The effect of air velocity on evaporation appears to be more closely related to the movement of high-moisture-content air from the general vicinity of the droplets rather than to the increase of the relative velocity between the air and the droplet. This is substantuated by results presented in Figure 9 where evaporation is directly proportional to air velocity rather than proportional to a lower power of the air velocity as would have been the case if the change in relative velocity was the only contributing factor (19).

Dry Bulb Temperature (Figure 10)--Since a change in dry bulb temperature, in itself, does not affect the vapor pressure of the air, the effect of dry bulb temperature on evaporation is related only through the rate at which the droplet temperature changes and the equilibrium temperature (wet bulb) attained by the droplet. As the dry bulb increases the wet bulb increases at a slightly decreasing rate. Thus the mean droplet temperature during flight also increases at a slightly decreasing rate, causing evaporation to have a similar relationship. There is an abrupt change in the slope of the curve where the air temperature is equal to the initial droplet temperature (82 F). The slope immediately below the droplet temperature (82 F) is less than the slope immediately above it. There is another abrupt change in the slope where the air temperature is equal to the dew point. Note that the evaporation at this point is not zero since the droplet will heat the air; thus allowing further moisture transfer to the air.

Dew Point (Figure 11)--As the dew point of the air increases, both the vapor pressure and the wet bulb temperature increase at increasing rates. These two occurrances have an opposing effect on the evaporation rate and it appears from the curve of Figure 11 that the relationship is linear. There will be an abrupt change in the slope where the dew point equals the initial water temperature (82 F). The dew point at which zero net evaporation occurs will depend upon the time of exposure for the droplet. For a dew point above the initial water temperature and below the dry bulb, the droplet will gain moisture from the air until the droplet is heated to the dew point. At this point evaporation will begin when the droplet is heated above the dew point.

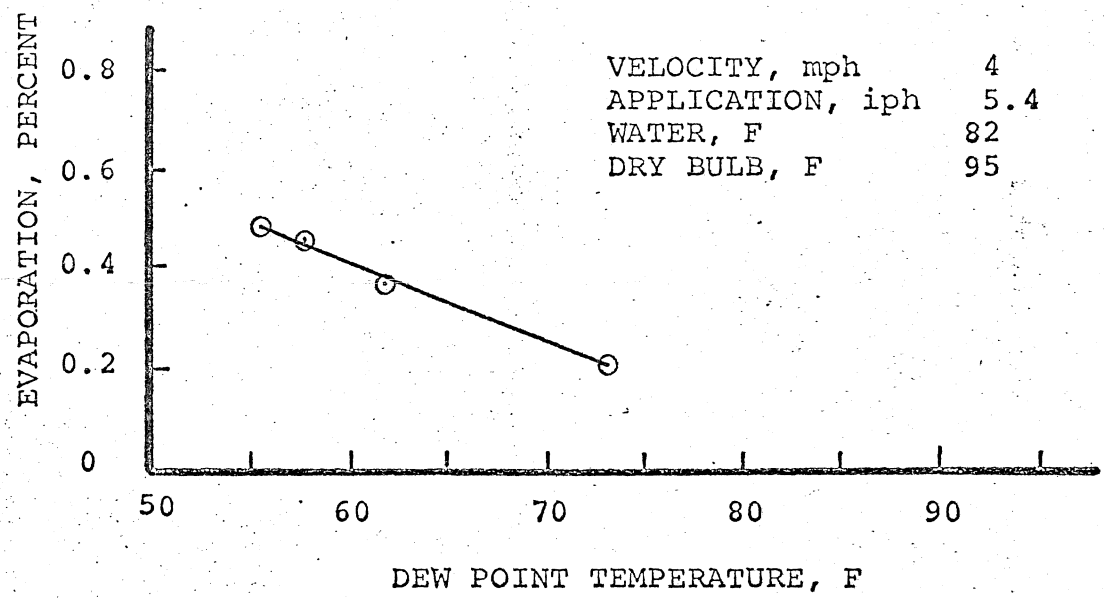


Figure 11. Evaporation of water droplets as a function of Dew point temperature.

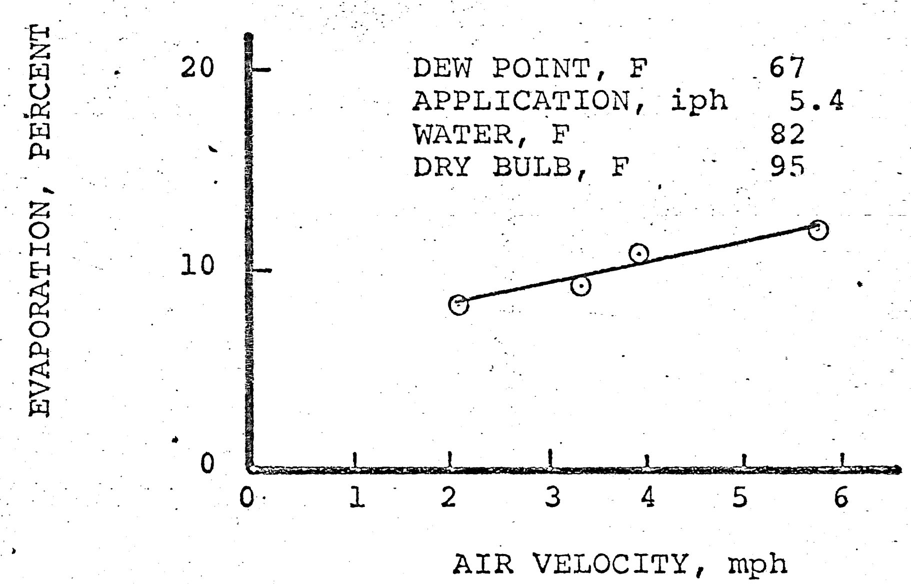


Figure 12. Evaporation of plant intercepted water as a function of air velocity.

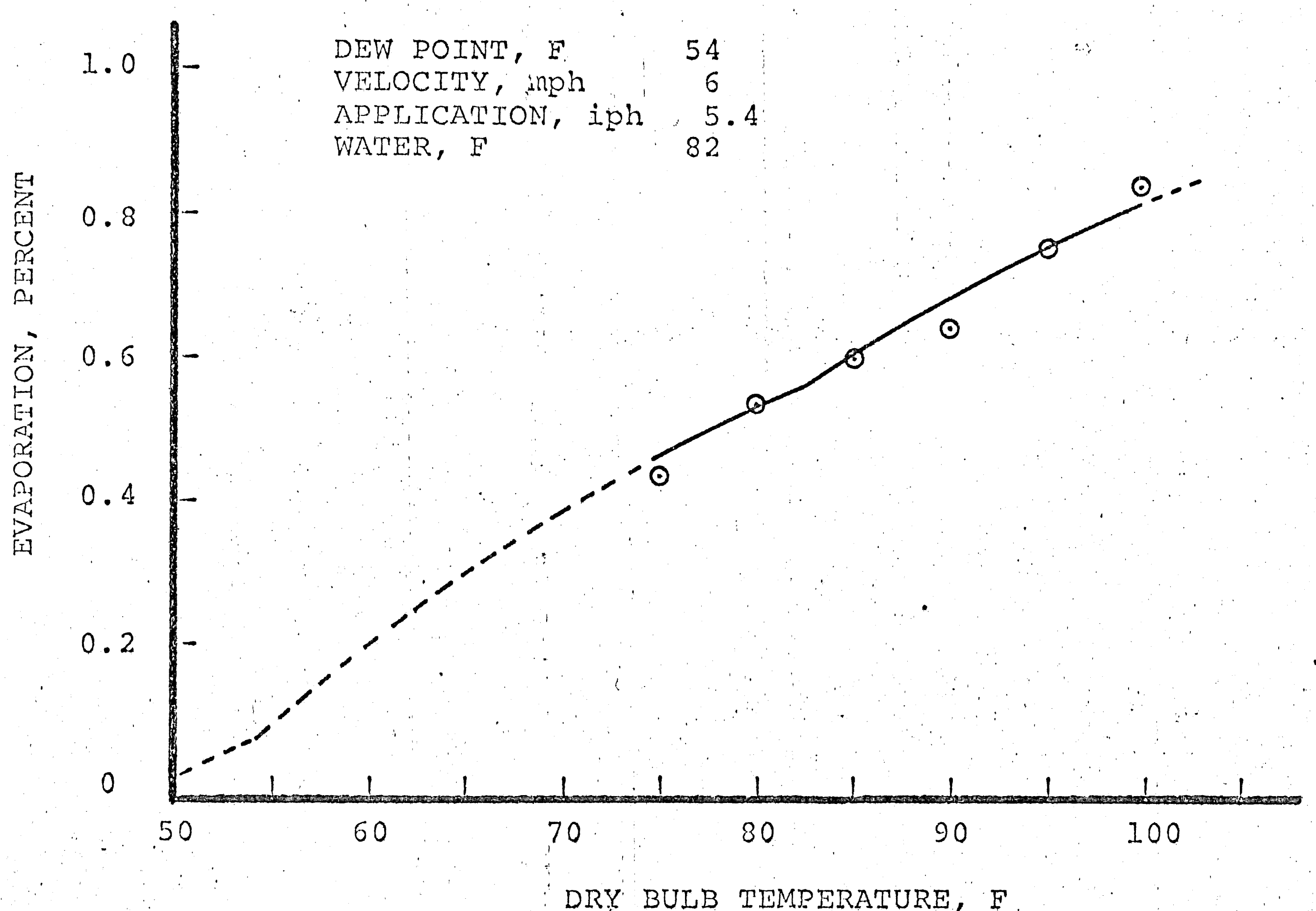


Figure 10. Evaporation of water droplets as a function of dry bulb temperature. Dashed lines are not an extrapolation of experimental results and are presented only to support discussion.

Evaporation from Plant Intercepted Water

The curves for evaporation (Figures 12-15) from plant intercepted water appear to be similar in shape to those for evaporation from the spray, with the main difference being the magnitude of the evaporations. It is more difficult to determine the slope of the curves for the plant intercepted water because heat is transferred between the water and the plant as well as between the air and the water. The curves should still possess abrupt changes in slope corresponding to the dew point and initial water temperature on the appropriate curves.

Because of the much longer exposure time for the plant intercepted water, the effect of initial water temperature should be much less than for the spray. This means that all of the curves for plant intercepted water would have been changed only slightly if a different water temperature had been used.

As has been discussed in the review of literature, all of the evaporation from plant intercepted water should not be considered as a loss charged to irrigation since some evapotranspiration would have occurred without irrigation. The evapotranspiration rate was measured before the plants were wet, for 95 F dry bulb temperature, 60 F dew point and 4 miles per hour and was found to be 30 grams per minute or 0.066 inches per hour. This indicates that, for most of the tests, more than 90% of the evaporation would be considered a loss.

It should be noted that solar radiation which was eliminated in these tests, would have increased the amount of evaporation.

In the following discussion of each variable, only the important differences between the curves for evaporation from plant intercepted water and for spray evaporation will be given.

Air Velocity (Figure 12)--Percent evaporation appears to be directly proportional to air velocity for the range of values used in this test. The discussion in the section on spray evaporation with respect to air velocity is applicable here.

Application Rate (Figure 13)--This curve indicates that the percent evaporation increases very rapidly for application rates below 1 inch per hour. Since all of the water that was discharged was not intercepted by the plants, it is believed that most of the intercepted water is evaporated for application rates below 0.1 inch per hour. It should be noted that this test was for a particular crop configuration and that these values would vary according to the plant surface area and the kind of plant.

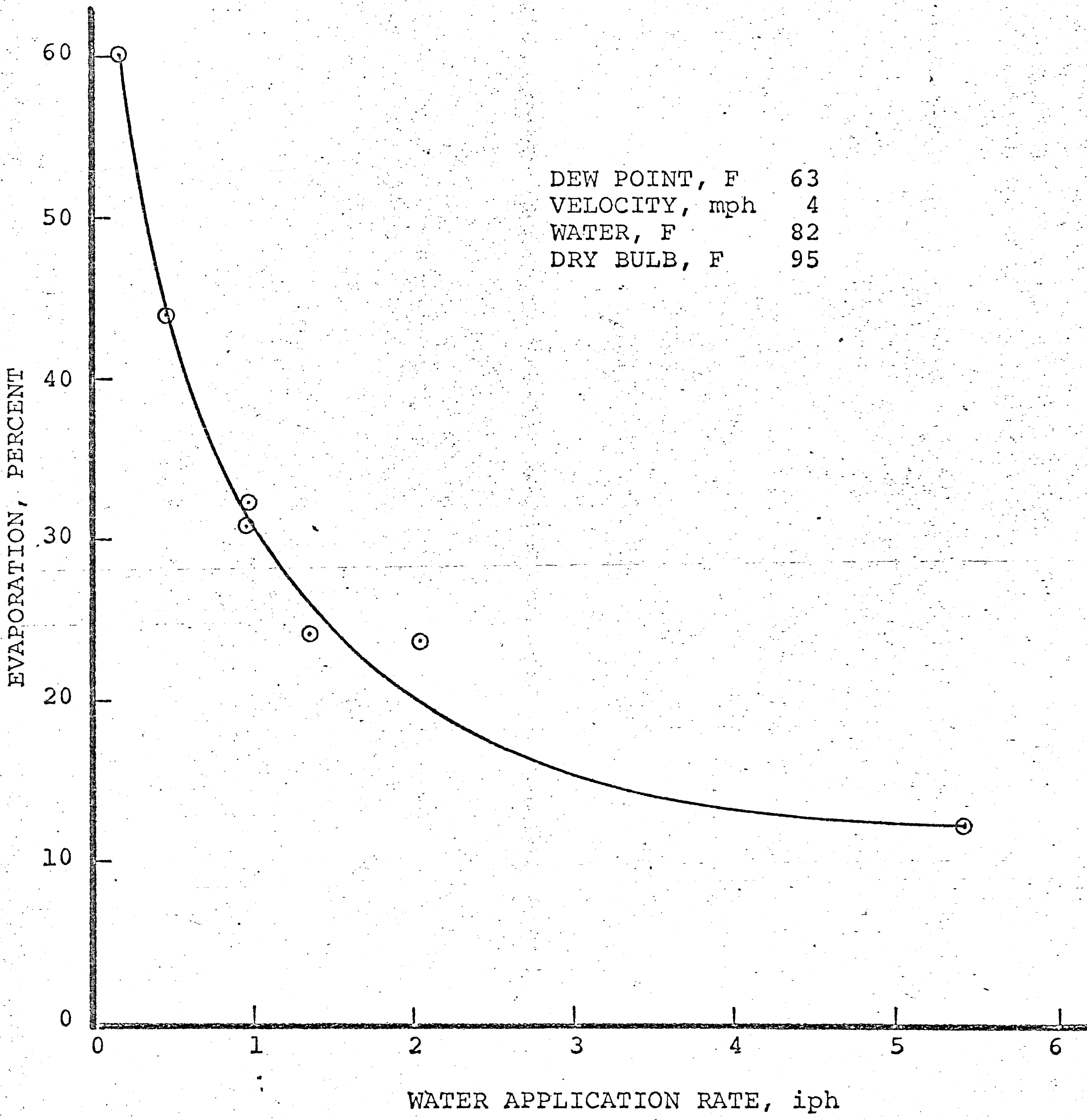


Figure 13. Evaporation of intercepted water as a function of application rate.

Dry Bulb Temperature (Figure 14)--Here again, as was discussed for spray losses, a change in dry bulb temperature does not affect the vapor pressure of the air but only the rate at which the water changes temperature and the equilibrium temperature attained. But in the case of plant intercepted water the equilibrium temperature is not the wet bulb temperature, but slightly higher, because heat is conducted from the plant.

Dew Point (Figure 15)--The curve for evaporation from plant intercepted water indicates a definite curvature with the evaporation decreasing at an increasing rate with respect to dew point while the curve for spray evaporation was approximately linear.

Interpretation of Results

The values indicated for spray losses are not directly applicable to field conditions for sprinkler irrigation systems since they were obtained from uniform size droplets (3mm) falling a distance of 8 feet with a zero initial velocity. The factors which would significantly contribute to a different value for field sprinkler systems are the droplet size, time of exposure and relative velocity between droplet and air.

In addition to correcting for these factors, one must measure the climatic conditions in the immediate vicinity of the spray, such as was done by Mather (24) and referred to in the review of literature section of this report.

In order to show how the results of these tests might be applied to field conditions, consider a sprinkler with a 7/32 inch diameter nozzle operating at 40 psig on a 10 foot riser. Assume the climatic conditions are 95F dry bulb, 54 F dew point and 4 mph wind. The water leaves the nozzle at 82 F.

According to studies by Frost and Schwalen (13) the average size droplet under these conditions would be approximately 3mm in diameter. Thus no correction is needed for droplet size. It is realized that the use of the average size droplet does not give the correct value for the total surface area since the area is proportional to the square of the diameter. However, it is a good approximation for a properly designed and operated sprinkler where a very small percent of the distributed water would be in the form of a mist.

If the total exposed surface area per volume is different than that for 3 mm diameter droplets, the percent evaporation can be considered inversely proportional to the diameter (D) of the droplets (evaporation is proportional to D^2 while total amount applied is proportional to D^3).

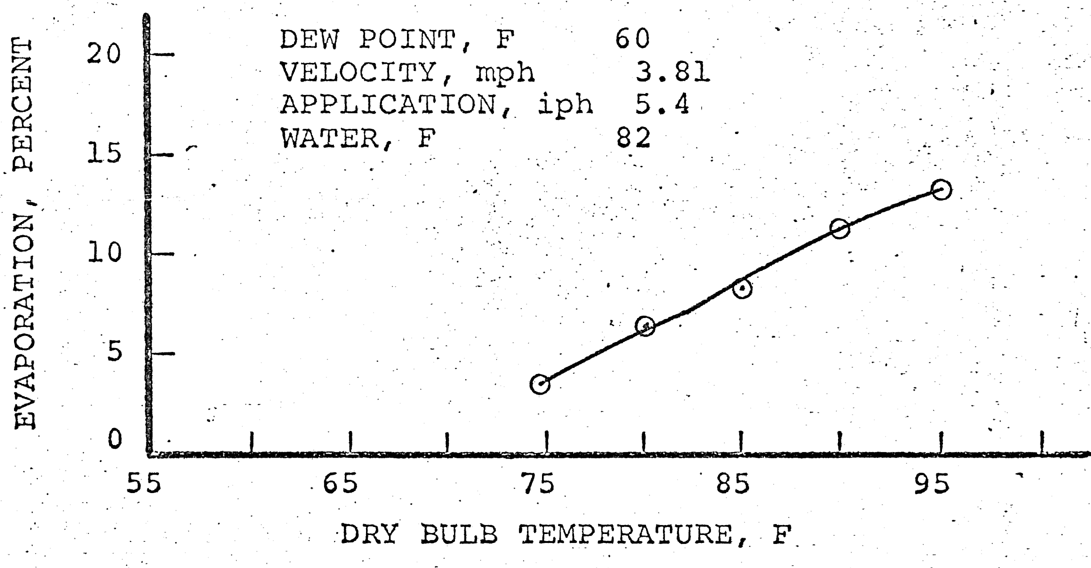


Figure 14. Evaporation of plant intercepted water as a function of dry bulb temperature

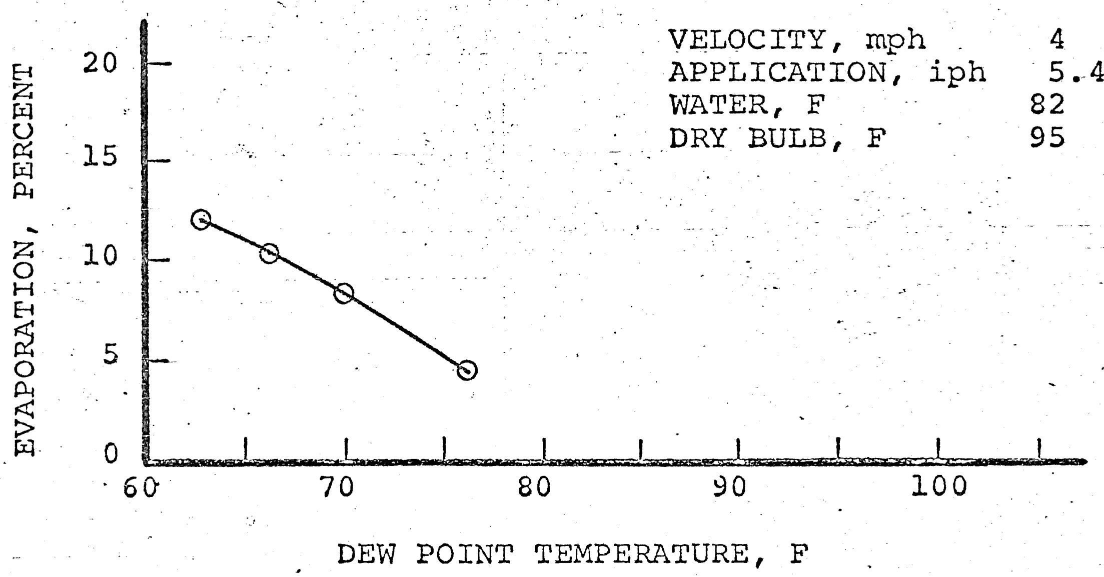


Figure 15. Evaporation of plant intercepted water as a function of dew point temperature

If a large portion of the water is in the form of small droplets significantly different in size from the average, the average size droplet should not be used to calculate the total surface area.

The time of exposure for the droplets, for the laboratory tests and for the sprinkler being considered was estimated by assuming that the force due to air resistance is proportional to the velocity. The constants were evaluated from the results reported by Green (16) on the evaluation of air resistance to freely falling drops of water. The time of exposure for the laboratory tests was determined as 0.80 seconds while that for the sprinkler was 2.00 seconds.

The average relative velocity was calculated to be 10.3 fps for the laboratory tests and 45 fps for the sprinkler. These velocities were determined through the use of equations of motion similar to those described by Green (16). Although normal wind velocities did affect the relative velocities for the laboratory tests, they do not significantly affect relative velocities for sprinklers due to the higher velocities of the droplets.

The effect of relative velocity on evaporation can be determined from equation [4] as approximately proportional to the square root of the relative velocity. Thus considering the relative velocities used in this example, the evaporation for the sprinkler would be 2.1 times that for the laboratory tests.

The percent evaporation is not directly proportional to the exposure time for the droplet since the temperature of the droplet is approaching the wet bulb temperature of the air (Figure 16). However, as shown in Figure 17 the percent evaporation is almost directly proportional to exposure time for this example. This is a typical relationship as long as the difference between the initial water temperature and the wet bulb temperature is not large compared to the difference between the wet bulb temperature and the dew point temperature. If this is not the case, the curve becomes more non-linear.

The curve in Figure 16 was generated by the equation:

$$t_{droplet} = (t_{di} - t_{wb}) \; e^{-A\theta} + t_{wb} \qquad [5]$$

where

$t_{droplet}$ = temperature of droplet at time θ, F

t_{di} = initial temperature of droplet, F

t_{wb} = wet bulb temperature of the air, F

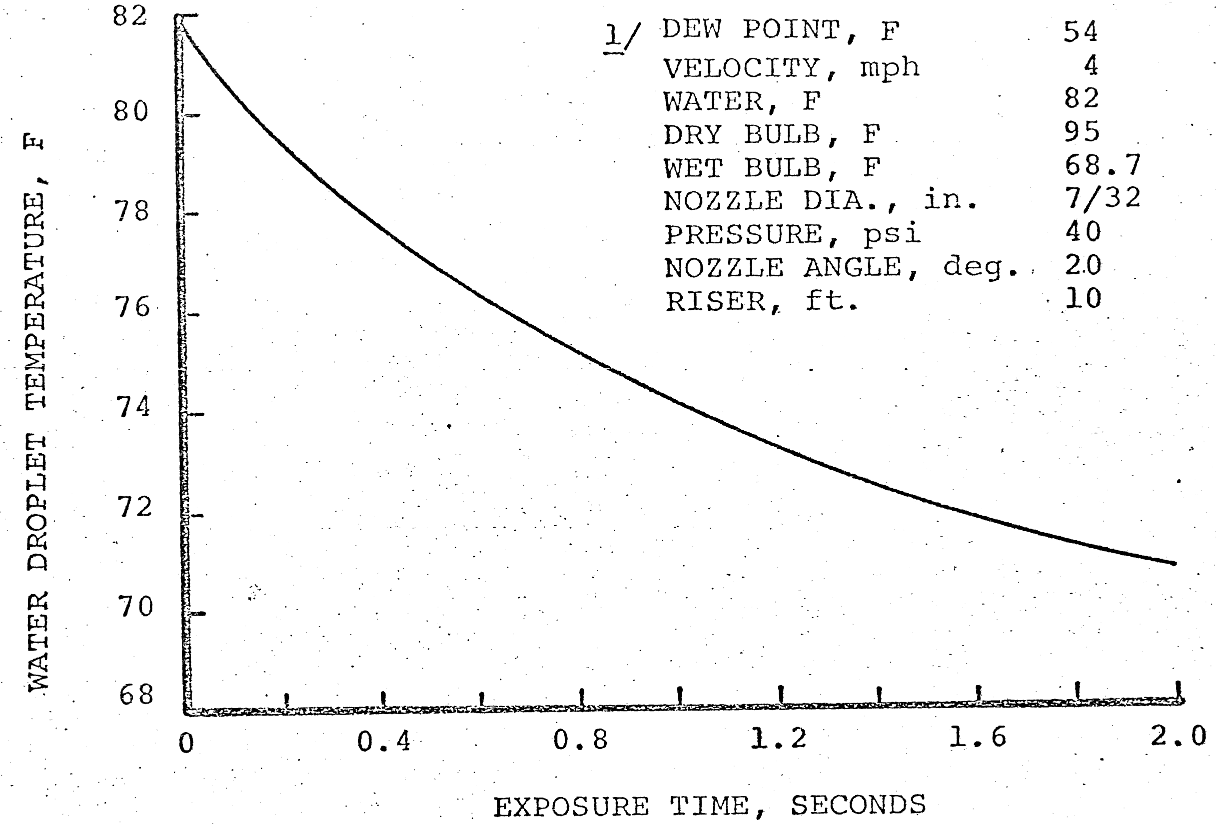


Figure 16. Effect of exposure time on water droplet temperature

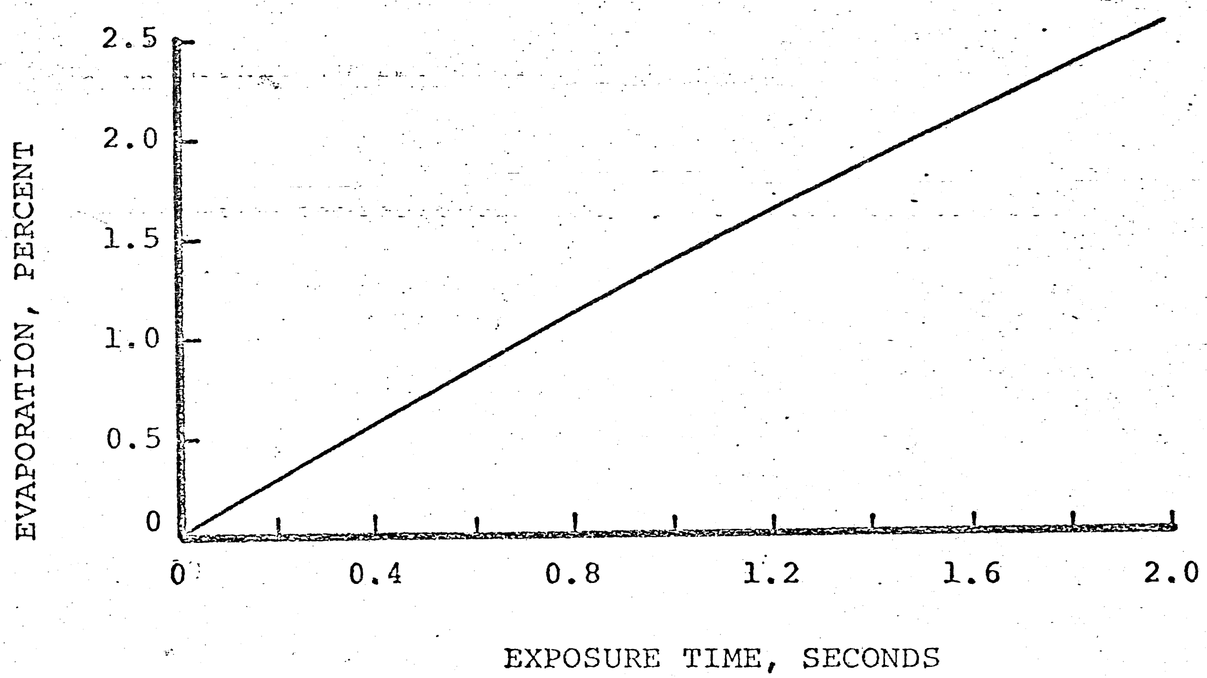


Figure 17. Exposure time of water droplets as a function of evaporation

1/ Values are applicable for figures 16 and 17.

A = a constant for this example, but a function of droplet size and relative velocity.

θ = time of exposure, sec.

Equation [5] was derived by assuming that the droplet temperature can be described by the following differential equation:

$$\frac{dt_{droplet}}{d\theta} = A\ (t_{droplet} - t_{wb}) \qquad [6]$$

with conditions: $t_{droplet} = t_{di}$ when $\theta = \infty$

$t_{droplet} = t_{wb}$ when $\theta = \infty$

The constant "A" was evaluated through the use of equation [3] (review of literature) in conjunction with laboratory tests for percent evaporation. A limited number of measurements were made on the initial and final temperatures of the water droplets, to check equation [3]. "A" was determined to be 0.447 for the laboratory tests and 2.1 (0.447) for the sprinkler. The factor 2.1 was determined from the ratio of the relative velocities.

The curve in Figure 17 was generated by the following equation:

$$m = 0.146\ \frac{B}{A}\ (\ 1 - e^{-A\theta}) + B\theta\ (0.011\ t_{wb} - P_a) \qquad [7]$$

where m = total evaporation expressed as percentage for a droplet exposure time of θ.

B = constant for this example, but a function of droplet size and relative velocity.

A = the constant in equation [6]

P_a = water vapor pressure of the air, in. Hg

Equation [7] was derived assuming that the water mass transfer rate to air could be described by the following differential equation:

$$\frac{dm}{d\theta} = B\ (P_{droplet} - P_a) \approx B\ (0.011\ t_{droplet} - P_a) \qquad [8]$$

This equation assumes a linear relationship between the water vapor pressure of the droplet and the droplet temperature which is a "poor fit" but gives reasonable accuracy for the range of temperatures used in this example. For higher accuracy a different model should be used, for example, a polynominal expression. The constant "B" was evaluated from test results and

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The authors hereby express their sincere appreciation to both of these gentlemen for their contribution to the project.

the assumed relationship between relative velocity and evaporation and was found to have a value of 3.0

This example indicates that a value of 2.5% evaporation should be used for a sprinkler in comparison to 0.52% obtained from laboratory tests for the same climatic conditions. A factor of 5 could be used as a "rough" value for most of the tests.

The application of laboratory results for plant intercepted water should be directly applicable to field conditions if the climatic conditions are measured in the vicinity of the sprinklers and the plant surface area and configuration are taken into account.

CONCLUSIONS

This study has resulted in the following conclusions:

1) Rate of application is the most significant factor influencing evaporation losses where a large proportion of the applied water is intercepted by vegetative material. It should be optimized with respect to economical system design and limited by maximum infiltration rate.

2) Evaporation losses from water droplets while in transit in air should not exceed 5% of the total water application under typical climatic conditions in Florida. The amount is relatively insignificant when compared to the larger losses that can occur after the water droplets have been intercepted by plant surfaces.

3) The effect of the climatic factors of wind, air temperature and air dew point on evaporation losses from irrigation are approximately linear within the ranges tested in this study.

4) The effect of initial water temperature on evaporation losses from irrigation does not appear to be significant in the realm of general irrigation practice. The contribution of this factor to evaporation losses is approximately linear for climatic conditions and natural water temperatures prevailing in Florida.

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