DESIGN PARAMETERS IN A SYSTEM FOR REMOVING SURFACE MOISTURE FROM BLUEBERRIES

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ABSTRACT

DESIGN PARAMETERS IN A SYSTEM FOR REMOVING SURFACE MOISTURE FROM BLUEBERRIES

By

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Blueberries which are mechanically harvested are subjected to continuous deterioration prior to being packaged for the fresh market. Water handling could improve product quality by reducing detrimental effects. Cold water would rapidly cool the fruit. In addition, water would minimize bruising by cushioning the berries and would assist in removing extraneous material. Prior to packaging, the water must be removed from the blueberry surface since water on packaged blueberries decreases shelf-life.

The primary objective of the research presented was to investigate the influence of air velocity, water temperature, air temperature, and relative humidity on the rate of surface moisture removal from blueberries in air flow. The experiments were conducted such that a relationship between surface moisture removed and time could be determined. The ranges of the parameters investigated were: air velocity, 200-800 ft/min; water temperature, 45-75°F; air temperature, 62-87°F; and relative humidity, 16-50%.

The data obtained from these experiments were fit to least square-exponential curves from which surface moisture removal rate constants were obtained. The rate constants were also fit to least square-exponential curves to determine the influence of each parameter. An increase in air velocity or air temperature resulted in an exponential increase in the rate constant, while an increase in relative humidity exponentially decreased the rate constant. An increase in water temperature was assumed to exponentially increase the rate constant, although the relationship was insignificant at the 5% level.

A systems design equation for predicting the surface moisture removal rate constant was obtained by multiple linear regression. The increase of the predicted rate constant from the systems design equation, over the experimental range of each parameter, was greater than that predicted by respective exponential equations. This was very evident with water temperature and relative humidity variables and probably resulted from the influences of the parameter constants on the multiple linear regression.

In a commercial operation, the surface moisture would probably be removed from blueberries on a conveyor within a tunnel. Air temperature was found to be the most influential parameter on tunnel length. A 25% increase in air temperature resulted in a 41% decrease in tunnel length. Similar increases in air velocity and water temperature resulted in decreases of only 14 and 12%, respectively, in tunnel length. A 25% increase in relative humidity increased tunnel length by 40%.

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TABLE OF CONTENTS

	Page
LIST OF TABLES	iv
LIST OF FIGURES	v
LIST OF SYMBOLS	viii
INTRODUCTION	1
LITERATURE REVIEW	5
Historical Development of Mechanical Harvesting	5
Shelf-life and Quality of Blueberries	8
Effect of Mechanical Harvesting on Shelf-Life and Quality	9
Potential for Improving Quality of Mechanically Harvested Blueberries	12
Handling of Blueberries in Water	17
EXPERIMENTAL PROCEDURES	18
Laboratory Equipment	18
Measurement Systems	20
Experimental Procedures	22
RESULTS AND DISCUSSION	26
Data Analysis	26
Influence of Air Velocity	33
Influence of Water Temperature	36
Influence of Air Temperature	39
Influence of Relative Humidity	43
Systems Design Equation	45
Implementation of Design Equation	48
CONCLUSIONS	53
REFERENCES	55
APPENDIX A	58
APPENDIX B	75

LIST OF TABLES

TABLE		Page
1.	Parameter variables investigated with corresponding parameter constants	24
2.	Surface moisture removal rate constants obtained for experimental parameter variables	33
3.	Comparison of time, required to remove 90% of the surface moisture, obtained experimentally with that predicted by the corresponding exponential equation and by the design equation	47
4.	Tunnel lengths computed for given sets of parameters	50
A.1.	Fraction of water, r, vs time, t, obtained with varying air velocity	58
A.2.	Fraction of water, r, vs time, t, obtained with varying water temperature	59
A.3.	Fraction of water, r, vs time, t, obtained with varying air temperature	60
A.4.	Fraction of water, r, vs time, t, obtained with varying relative humidity	61

LIST OF FIGURES

Figure		Page
1.	Michigan Blueberry Growers Association grading and packing standards - fresh pack (Hansel, 1971)	10
2.	Plexiglass tunnel, with basket removed. .	19
3.	Schematic view of laboratory system for removing surface moisture from blueberries	21
4.	Determination of surface moisture removal rate constant, k, at air velocity variable of 800 ft/min (constants: $T_w=45^oF$, $T_a=76^oF$, RH=16%). . .	27
5.	Determination of surface moisture removal rate constant, k, at water temperature variable of 45^oF (constants: $\bar{u}=800$ ft/min, $T_a=76^oF$, RH=19%)	28
6.	Determination of surface moisture removal rate constant, k, at air temperature variable of 62^oF (constants: $\bar{u}=800$ ft/min, $T_w=45^oF$, RH=13%).	29
7.	Determination of surface moisture removal rate constant, k, at relative humidity variable of 26% (constants: $\bar{u}=800$ ft/min, $T_w=45^oF$, $T_a=76^oF$).	30
8.	Influence of air velocity, $\bar{u}$, on the surface moisture removal rate constant, k	34
9.	Influence of water temperature, T_w, on the surface moisture removal rate constant, k	37
10.	Influence of air temperature, T_a, on the surface moisture removal rate constant, k	40

LIST OF FIGURES (Continued . . .)

Figure | Page

11. Influence of air temperature on surface moisture removal rate constant, k, using an Arhenius-type plot 42

12. Influence of relative humidity, RH, on the surface moisture removal rate constant, k. 44

13. Influence of parameter increases on tunnel length 51

A.1. Determination of surface moisture removal rate constant, k, at air velocity variable of 200 ft/min (constants: T_w=45°F, T_a=76°F, RH=16%) 62

A.2. Determination of surface moisture removal rate constant, k, at air velocity variable of 400 ft/min (constants: T_w=45°F, T_a=76°F, RH=16%) 63

A.3. Determination of surface moisture removal rate constant, k, at air velocity variable of 600 ft/min (constants: T_w=45°F, T_a=76°F, RH=16%). 64

A.4. Determination of surface moisture removal rate constant, k, at water temperature variable of 55°F (constants: $\bar{u}$=800 ft/min, T_a=76°F, RH=19%) 65

A.5. Determination of surface moisture removal rate constant, k, at water temperature variable of 65°F (constants: $\bar{u}$=800 ft/min, T_a=76°F, RH=19%) 66

A.6. Determination of surface moisture removal rate constant, k, at water temperature variable of 75°F (constants: $\bar{u}$=800 ft/min, T_a=76°F, RH=19%) 67

A.7. Determination of surface moisture removal rate constant, k, at air temperature variable of 72°F (constants: $\bar{u}$=800 ft/min, T_w=45°F, RH=13%) 68

A.8. Determination of surface moisture removal rate constant, k, at air temperature variable of 82°F (constants: $\bar{u}$=800 ft/min, T_w=45°F, RH=13%) 69

LIST OF FIGURES (Continued . . .)

Figure		Page
A.9.	Determination of surface moisture removal rate constant, k, at air temperature variable of 87°F (constants: $\bar{u}$=800 ft/min, T_w=45°F, RH=13%)	70
A.10.	Determination of surface moisture removal rate constant, k, at relative humidity variable of 16% (constants: $\bar{u}$=800 ft/min, T_w=45°F, T_a=76°F).	71
A.11.	Determination of surface moisture removal rate constant, k, at relative humidity variable of 36% (constants: $\bar{u}$=800 ft/min, T_w=45°F, T_a=76°F)	72
A.12.	Determination of surface moisture removal rate constant, k, at relative humidity variable of 50% (constants: $\bar{u}$=800 ft/min, T_w=45°F, T_a=76°F)	73
A.13.	Unsteady-state temperature distributions in a sphere (Foust et al., 1960)	74

LIST OF SYMBOLS

a	computed water fraction at time, t=0
A	surface area, ft^2
B_w	conveyor belt width, ft
c	correlation coefficient
C_c	blueberry capacity of commercial system, pints
C_e	blueberry capacity of experimental system, pints
E	energy of activation, BTU/mole
h	surface heat transfer coefficient, BTU/hr-ft^2-^oF
k	surface moisture removal rate constant, 1/min
K_g	mass transfer coefficient, 1/hr
L	tunnel length, ft
M	rate of water vapor transfer, lb/hr
P_a	water vapor pressure in air, lb/ft^2
P_s	water vapor pressure at the surface, lb/ft^2
Q	rate of heat transfer, BTU/hr
r	fraction of water remaining on the basket + blueberries
R	universal gas constant, BTU/mole-^oR
RH	relative humidity, %
t	time, min
T_a	air temperature, ^oF
T_s	surface temperature, ^oF

LIST OF SYMBOLS (CONTINUED . . .)

T_w	water temperature, ^oF
$\bar{u}$	air velocity, ft/min
w_t	weight of the basket + blueberries at a given time interval
w_D	initial dry weight of the basket + blueberries where dry implies absence of surface moisture
w_0	initial wet weight of the basket + blueberries
T_a	absolute air temperature, ^oR
λ	latent heat of vaporization, BTU/lb

INTRODUCTION

In 1971, Michigan ranked first in the United States in the production of highbush blueberries, _Vaccinium corymbosum_, with an estimated value between 6 and 8 million dollars (Howell et al., 1971). Of the 31 million pounds harvested, about 32% was fresh marketed (anon., 1971). Approximately 75% of the highbush blueberries were harvested mechanically - either by straddle row harvesters (50%) or by hand held vibrators (25%) (Howell et al., 1971).

The advantage of mechanical harvesting over hand picking is that larger acreages are harvested more quickly with less expense. The mechanically harvested berries, however, are more bruised, vary more in maturity, lose more bloom (waxy surface coating), and require more cleaning than those that are manually picked. In addition to these problems, the blueberries must be manually sorted for removal of green, decayed, and overripe fruit. This could result in longer periods of exposure to heat in the packing house if adequate numbers of inspectors are not employed to handle the blueberries at the rate the fruit is being mechanically harvested. In the fresh market, these factors will probably decrease the product shelf-life and may reduce market appeal for the blueberries.

One approach suggested to minimize detrimental effects is a water handling system. The main advantage of such a system would be the rapid cooling of harvested blueberries, thereby retarding microbial and fungi growth, resulting in increased shelf-life. Cooling also decreases respiration to prevent rapid deterioration of the fruit (anon., 1971). Additional benefits may be derived from a water handling system. In addition, water should cushion the berries to decrease bruising. It could act as a lubricant to reduce loss of bloom normally caused by the blueberry rubbing against an object or other blueberries. Water would wash off exuded juice collected on blueberries from overripe fruit. In addition, water could be used to sort green berries, twigs, leaves, and other forms of trash collected in the mechanized harvest. Finally, a properly designed water sorting system should significantly reduce or even eliminate potentially long periods of heat exposure in the packing shed for the mechanically harvested blueberries.

The major obstacle preventing the use of a water handling system is the moisture to be removed prior to packaging for the fresh market. Stiles and Abdalla (1966) stated that surface moisture on picked blueberries enhanced mold growth. Heldman et al. (1971) reported that the shelf-life of blueberries increased as the amount of surface moisture removed increased, with blueberries which were not exposed to moisture displaying the longest shelf-life. Whether 100% of the surface moisture must be removed to attain maximum shelf-life has not been established, but if the surface moisture removal system is designed to be 100% efficient, maximum shelf-life should be obtained.

The implementation of a surface moisture removal system would not only allow fresh market blueberries to be handled in water, but would allow blueberries moistened by rain or dew to be harvested resulting in a uniform and uninterrupted harvest.

Surface moisture could feasibly be removed from blueberries by an air flow system. The system, to be commercially feasible, must be designed to accommodate or improve upon present sorting rates and the blueberries leaving this system must be equal to or exceed present shelf-life expectancies. Therefore, the surface moisture removal rate must be known before the system can be designed. It is expected that this rate will be a function of air velocity, air temperature, relative humidity, and water temperature to which the blueberries are exposed.

The objectives of this investigation were:

1. To design and construct a laboratory apparatus for measuring surface moisture removal rates with independent regulation of air velocity, air temperature, relative humidity, and water temperature.

2. To evaluate the influence of each of the above parameters by obtaining and comparing moisture removal rate constants.
3. To derive an expression that describes the rate of change of the surface moisture removal rate constant for each parameter.
4. To derive a systems design equation which will incorporate the overall influence of air velocity, air temperature, relative humidity and water temperature on the surface moisture removal rate.
5. To illustrate the use of the systems design equation in construction of a commercial system to remove surface moisture from blueberries.

LITERATURE REVIEW

Historical Development of Mechanical Harvesting

The harvest season in Michigan for highbush blueberries extends from July through September with the dates of harvesting varying with variety and weather (Johnston, 1970). An acreage of one variety must be picked 3 to 7 times over a 6 to 8 week period to obtain maximum yield (Stiles and Abdalla, 1966).

Stiles and Abdalla (1966) reported that blueberries harvested manually were deposited either directly into the market container or into a pail. The advantage of the latter method was that the harvests could be examined for foreign material and green and overripe berries before filling the market containers. This procedure, however, resulted in increased handling of the fruit promoting increased loss of bloom. Stiles and Abdalla (1966) stated that mechanical harvesting was introduced to compensate for a decreasing supply of labor and an increase in wages.

In 1958, USDA engineers developed hand-held vibrators to aid in the harvesting of highbush blueberries (Monroe and Levin, 1966). The first units were powered by portable electrical generators driven by gasoline engines, but they could not be easily moved around. To alleviate this problem, an air compressor was used in place of the generator in 1960, but was very noisy resulting in battery powered vibrators in 1963 (Gaston, 1964). With a hand-held vibrating unit, 1 man could have harvested as many blueberries as 8 men could have picked by hand (Nelson, 1966).

Gaston (1964) discussed the need to mechanize the filling of lugs in the field and to reduce the need for qualified operators of the hand-held vibrators. Monroe and Levin (1966) reported that preliminary investigations on mechanical harvesters began in 1959. These investigations led to the conclusion that this harvester must remove, collect, and deposit ripe blueberries into lugs with minimum damage to the bushes.

The first mechanical harvester was towed by a tractor and subsequent models were self-propelled beginning in 1960 (Monroe and Levin, 1966). The initial blueberry removal structure was a vibrating angular unit, but this unit failed to remove the berries because of cane resiliency. Modifications to this system resulted in little improvement of the harvest. The next removal structure incorporated was a vertical rotating shaft with rubber flails. This unit failed because the flails damaged the bushes excessively. The third removal structure consisted of 2 rotating vertical spindles, each with a number of horizontal struts. The spindles revolved and vibrated horizontally and vertically with one spindle on each side of the bush. This over-the-row machine harvested 90% of the ripe berries with little damage done.

Over-the-row harvesters were used to harvest blueberries in Michigan beginning in 1965 (Howell et al., 1971). Monroe and Levin (1966) stated that labor costs were: 8¢/lb for manual picking, 3.5¢/lb for hand vibrator harvesting, and ½¢/lb for over-the-row harvesting. The over-the-row harvester, which required 3 men to operate, produced a daily harvest equal to that of about 120 manual pickers (anon., 1968). Nelson (1966) estimated the cost of an over-the-row harvester to be approximately $30,000.

Stiles and Abdalla (1966) reported that hand-held vibrators shook the branches detaching the blueberries which fell into canvas catchers positioned beneath the bush and then the fruit was transferred manually into field lugs. Over-the-row harvesters vibrated the whole bush removing the blueberries. The fruit then fell onto flexible baffles which closed in around the bush (Monroe and Levin, 1966). The berries then fell onto a conveyor which transported the fruit into field lugs.

Blueberries harvested from either the hand-held vibrator or the over-the-row harvester required more cleaning than those harvested manually because of excessive foreign material, green berries, and damaged and overripe fruit (Stiles and Abdalla, 1966). A pneumatic winnower, incorporating an air stream, removed the foreign material and green berries, but the damaged and overripe fruit had to be removed manually. (Nelson (1966) stated that one pneumatic cleaner could efficiently handle the harvest from 8 hand-held vibrators (600 lb/hr), but that 4 of these cleaners were needed for each over-the-row harvester.) The inspected fruit was conveyed to a filling tray where the blueberries dropped into containers for the fresh market.

Shelf-life and Quality of Blueberries

Hruschka and Kushman (1963) reported that the shelf-life of blueberries was one week, or less, and that this shelf-life was very short compared with other fresh products. Stiles and Abdalla (1966) stated that blueberries, high in quality, could be stored for 2 days at 75°F (no relative humidity given) and 1 week at 40°F, 85% RH. The shelf-life could be extended from 2 to 4 weeks if these berries were stored at 32°F, 85% RH, in pints placed in plastic lined lugs (Hruschka and Kushman, 1963). At 4 weeks, some loss in quality could develop. Stiles and Abdalla (1966) reported that the shelf-life was increased to 6 weeks by storing the blueberries at 32°F, 85% RH in sealed polyethylene bags. Turgidity, flavor, weight, and appearance were maintained, but after 6 weeks, off-flavors and off-odors became apparent.

Quality was defined by Kushman (1970) as cleaned fruit that looks and tastes good and will remain in this state for a few days. A more complete definition as it applies to blueberries is given in the grading standards of the Michigan Blueberry Association, Figure 1.

Ballinger and Kushman (1971) employed storage tests to evaluate quality. The blueberries were placed in pint containers and covered with cellophane. The packaged fruit was then stored for 7 days at 70^{o}F and 85% RH. At the end of this period the blueberries were individually sorted into marketable (ripe) and not marketable (decayed, damaged, etc.) fruit and counted to determine % decayed. Galletta and Mainland (1971) used similar procedures to obtain the amount of decayed fruit.

Bowers (1960) discovered that controlled harvesting and storage produced sugar-acid ratios that correlated linearly to the deterioration and shelf-life of blueberries. Increased sugar-acid ratios increased deterioration and decreased shelf-life. Bowers (1960) stated that this ratio was not a function of ripening alone. The sugar-acid ratio may also be affected by the amount of sunshine, berry size, nutritional status, amount of irrigation, size of yield, pruning practices and, especially, by variety. If the harvest was not controlled, the sugar-acid ratio may also be influenced by the source of the fruit, handling and picking methods, and elapsed time between harvesting and testing.

Effect of Mechanical Harvesting on Shelf-life and Quality

Galletta and Mainland (1971) compared blueberries harvested mechanically with those harvested manually and

MICHIGAN BLUEBERRY GROWERS ASSOCIATION

Grading & Packing Standards — Fresh Pack

GREAT LAKES BRAND

GENERAL: All berries packed in 12 pint and 8 quart crates, and bulk cartons shall conform to the following requirements:

A. All blueberries accepted by the Association must conform to the general requirements set forth in the Federal Food, Drug and Cosmetic Act. Failure to meet these requirements will be basis for rejection.

B. The following defects shall result in rejection, regardless of the overall condition and character of the fruit:
  1. The fruit must have "normal flavor and odor" meaning that the product is free from objectionable flavors and objectional odors of any kind.
  2. Excessive insect fragments and blueberry fly infestation.
  3. Any form of adulteration or contamination, including chemical residues, foreign material, or unclean fruit.

C. Marking: — Each crate or carton must be stamped with Grower's stamp on one end.

D. Inspection: In addition to the Field Men, the General Manager (or any appointed employee of the general manager) of the Michigan Blueberry Growers Association has authority to open packages and inspect the pack of any member of the Association at any time or place.

When berries fail to meet the established standards in grade, quality, or fullness of pack, if they have not left the grower's premises, the grower shall repack the berries, so that they will meet the standards. If the inspection is made after the shipment has left the grower's premises, a) the shipment shall be excluded from the pool and sold as a separate item, returns being made separately and directly to the grower, or, b) the grower will be notified to pick up shipment for re-packing.

QUALITY: Berries shall be mature, firm, well colored, well developed, and not over-ripe; which are free from stems, mold and decay; and from damage caused by dirt or other foreign matter, shriveling, moisture, disease, insects, mechanical or other means. There shall not be more than eight (8) defects per pint; of which not more than two may be soft berries. Soft is defined as not bleeding or moldy. Red berries are not counted as a defect.

SIZE: — Count shall be made on the basis of a standard measuring cup stroked level full and shall not be more than 175 BERRIES PER CUP. If more than 2 pints in any crate are below grade, the crate shall be considered below grade.

PACK: — Fruit destined for the fresh market shall be packed as follows:

A. 12 Pint Crate
  1. All pints shall be tightly packed, corners well filled, and well rounded in the center.
  2. Filled cups should be settled down on vibrators and/or other mechanical devices or means to insure full pack.
  3. Cellophane should be secured tightly with rubber bands.
  4. Minimum *net* weight of berries per 12 pint crate is 11-1/2 pounds (that is, 11-1/2 pounds after deducting weight of crate, cups and other packing material).

B. 8 Quart Crate
  1. Items 1 — 3 for 12 pint crate also applies to this pack.
  2. Minimum *net* weight of berries per 8 quart crate is 15 pounds (that is, 15 pounds after deducting weight of crate, cups and other packing material).

C. Bulk Carton ("10 Pound" Carton)
  1. Minimum *net* weight of berries per carton is 11 pounds (that is, 11 pounds after deducting the weight of the carton).
  2. The quality and size requirements for this pack are the same as for crates.
  3. The center divider and/or other carton modifications must be put in each carton. Failure to do so will be basis for rejection (unless the item was not available at the warehouse).

LAKE STATE BRAND

Prior permission is necessary before the Lake State Brand is packed.

Berries shall meet the requirements and be graded in conformity with the GREAT LAKES BRAND except as to size, count shall not be more than 250 BERRIES PER CUP. All Berries smaller in size than 250 count per cup — Special arrangements must be made — not to be packed under cellophane — will be excluded from pool.

DEFINITION OF TERMS

AS USED IN THESE GRADES:

"Well Colored" means that the whole surface of the berry shall be of good blue color.

"Well Developed" means that the berries shall not be misshapen owing to frost injury, lack of pollination, insect injury or other causes.

"Over-ripe" means dead ripe, over mature, past commercial utility.

"Damage" means any injury from the causes mentioned which materially affects the appearance, edible or shipping quality.

1970 Revision

Figure 1. Michigan Blueberry Growers Association grading and packing standards - fresh pack (Hansel, 1971).

found that after 7 days at 70°F, 85% RH, the mechanically harvested fruit was 15% more decayed on the average. The leading cause for the higher incidence of decay was believed to be bruising of the fruit during mechanical harvesting and subsequent handling. Galletta and Mainland (1971) also found that blueberries harvested mechanically were on the average 11% darker in color than those harvested manually, due to loss of bloom.

Ballinger and Kushman (1971) also reported increased levels of decay with mechanically harvested blueberries. Mechanically harvested fruit stored at 70°F, 85% RH, that had not been sorted was 12 to 26% more decayed than manually harvested samples. Mechanical sorting and packaging operations increased the incidence of decayed mechanically harvested fruit an additional 4 to 13%. Ballinger and Kushman (1971) found significantly more bruised berries from mechanical harvesting than with hand harvesting, confirming the observations of Galletta and Mainland (1971). These investigators also discovered that mechanically harvested berries were covered with juice that had dried and become sticky, resulting in a less appealing appearance of the blueberries.

Ballinger and Kushman (1971) conducted a detailed study on the causes of bruising when blueberries were harvested with an over-the-row machine. Once detached, the blueberries fell as much as 6 feet, striking branches and harvester parts. The fruit was then conveyed to the rear of the harvester where the berries fell 10 to 18 in. into a lug hitting the bottom or other fruit, bruising these berries also. Bruising also occurred when these lugs were roughly loaded onto the vehicle for transporting the fruit to the packing house. The lugs may also have bounced around, depending upon the terrain over which the vehicle traveled, causing additional bruising. In the packing house, the blueberries were dumped onto conveyor belts, falling 10 to 15 in. The fruit was then transported to the pneumatic cleaner where the berries were bounced around by the force of the air causing secondary bruising of other berries. When the fruit left the air cleaner, the berries rolled onto the sorting table striking other berries already present. In the mechanized packaging system, the blueberries rolled into the emptying chute where the fruit fell up to 15 in. into pint containers hitting the container bottom or other berries, bruising this fruit also.

Potential for Improving Quality of Mechanically Harvested Blueberries

To improve the quality of blueberries harvested mechanically, several areas of research were undertaken. One approach was to improve the blueberry through breeding. Moore (1966) stated that specific characteristics were strived for in obtaining new varieties. One was large berry size which not only harvested easier, but also had a greater market appeal. Another was firmness which was desired for handling and shipping. Other desirable characteristics included resistance to disease and uniform ripening, especially for mechanical harvesting.

Eck (1970) conducted research to determine if Ethrel (2-chloroethylphosphoric acid) could increase the rate at which blueberries ripen to obtain more ripe fruit in the mechanical harvest. When Ethrel was applied 2 weeks prior to the expected harvest date, the ripe fruit obtained on the first harvest increased 28% with the variety, Weymouth, and 22% with Blueray. The amount of ripe fruit obtained on the second harvest decreased 27 and 22%, for Weymouth and Blueray respectively, compared with the second harvest where Ethrel was not applied. There were no significant differences in the percentages of ripe berries in succeeding harvests. Ethrel treated acreages produced significantly smaller fruit in the first 2 harvests except in the first harvest of Blueray. Also, with Ethrel treated varieties, the pH increased while tritratable acidity decreased. Eck (1970) cited the need for further research on the concentration of Ethrel needed for other varieties (the 2 varieties tested here did not respond the same with identical concentrations of Ethrel), when to apply, how often to apply, and on the effects of multiple applications.

Ballinger and Kushman (1970) have suggested that varieties high in acid be developed for longer shelf-life. These investigators found that acid was more effective than sugar in controlling <u>Alternaria</u> and <u>Botrytis</u>, which were reported to be the most common producers of decay in the storage of blueberries. Culture solutions with the same concentration of sugar and acid as found in various stages of ripening in blueberries were used. Ballinger and Kushman (1970) also used blueberry samples, with the berry interior uniformly exposed. In these samples, decay increased from 12% with the small dark green berries to 99% with the overripe. These results were obtained from an average of samples held for 10 days at 75-80^{o}F and of samples held at 32^{o}F for 21 days followed by storage at 60^{o}F for 6 days.

Ballinger and Kushman (1970) verified that the sugar-acid ratio increased as the blueberries ripened from small green to overripe. These investigators also reported that the anthocyanin content highly correlated with the sugar-acid ratio. The anthocyanin content increased 12 times from the stage where the blueberry was ½ red-½ green to the overripe stage. Ballinger and Kushman (1970) concluded from these results that there was a potential for sorting by light transmittance, thus automating the inspection table.

Ballinger and Kushman (1971) discovered that light transmittancy was a feasible method for sorting blueberries while sizing was not. The berries were separated into light classes corresponding to the anthocyanin content using a light transmittance difference meter. These berries were then stored at 70^{o}F, 85% RH for 7 days.

The incidence of decay was found to increase as the anthocyanin content increased. These same tests indicated that increased berry size did not correspond with an increase or decrease in the incidence of decay.

Hamann (1971) tested the possibility of sorting by vibration on the principle that firm berries (ripe) would bounce easier than soft (overripe or damaged) berries. These tests revealed that this method displayed promise, although significant softening occurred with vibration.

Milholland and Jones (1971) stated that cooling the blueberries soon after harvest increased the shelf-life of the fruit. Blueberries stored in $5^{o}C$ ($41^{o}F$) air 2 hours after harvest displayed less decay (authors didn't establish how much) than those stored 12 hours after harvest. A reduction in storage temperature from $21^{o}C$ ($69.8^{o}F$) to $5^{o}C$ ($41^{o}F$) also resulted in a significant reduction in decayed fruit.

Kushman and Ballinger (1962) investigated the possibility of forced-air cooling to improve the rate at which the fruit temperature was decreased. Cooling rates were found to be a function of container type, room temperature, air movement and the manner in which master containers were stacked. Kushman and Ballinger (1962) concluded that blueberries with a maximum temperature of $100^{o}F$ could feasibly be cooled to $55^{o}F$ or less within 2 hours compared to a conventional time (authors did not elaborate on the meaning of conventional time) of 4 to 8 hours. These investigators also reported that some moisture, occurring from dew, was removed.

Kushman and Ballinger (1962) cited the disadvantages of using other cooling methods. In hydrocooling, the water (not removed) caused loss of bloom and increased the potential for decay. Vacuum cooling caused juice loss through cracks in the skin and the fruit did not cool rapidly. Air-blast cooling was ineffective because the fruit was shielded to some extent by the shipping containers.

Kushman and Ballinger (1968) stated that the molded pint paper cup improved the cooling rate, using forced-air cooling, over that obtained with wooden pint cups because the former had more ventilating slits. Wooden master containers also allowed more rapid forced-air cooling than could be obtained with corrugated fiberboard boxes because the former containers had more ventilation.

Kushman (1971) investigated the possibility of using hot water treatments to control decay in the storage of blueberries. This investigator found that berries exposed to 130°F water for 3 min. controlled fungus growth, but this treatment damaged the fruit. A decrease in water temperature resulted in decreased fruit damage, but this temperature decrease also reduced control of fungus growth. At 105°F, this control was very small.

Handling of Blueberries in Water

An extensive search of the literature has resulted in very little information recovered on handling small fruits in water and subsequent moisture removal. Levin and Gaston (1956) reported that cherries for processing were handled in water from the orchard to the processing plant on a commercial basis. The benefits of such a system resulted in maintenance of quality, decreased handling costs, elimination of lugs and subsequent problems of maintenance, storage, etc., and less sorting since cherries handled in water were higher in quality.

Before considering any type of handling system, the capacity of the system, the influence of the system on the quality of the fruit, and the cost of the system must be considered (anon., 1971).

The only reference to surface moisture removal was found in the report of Kushman and Ballinger (1962) who commented that before a forced-air system could be used to remove large amounts of moisture from the surface of blueberries, factors such as humidity would have to be considered.

EXPERIMENTAL PROCEDURES

Laboratory Equipment

A plexiglass tunnel (Figure 2), measuring 6 in. square and 21 in. high, was designed and constructed to facilitate the collection of experimental data. A 3 in. diameter opening, located in the lower portion of the tunnel, allowed the introduction of air flow. The air moved upward through a 15 in. layer of plastic packing material to obtain a uniform distribution of air velocity. The air flow then passed through the bottom of a wire basket containing a single layer of blueberries. The basket was supported by plexiglass rails attached to the sides of the tunnel as shown in Figure 2.

To facilitate minimum handling of the basket, a plexiglass support panel was constructed as illustrated in Figure 2. Hooks were fastened to the inside of the door and a handle was attached to the outside. These hooks supported the basket on the panel and allowed easy removal of the panel from the basket prior to weighing. When the basket was inserted into the tunnel, the panel prevented air from escaping through the side before passing through the basket.

The air flow source was a 1/3 HP fan which provided a maximum air velocity of approximately 800 ft/min

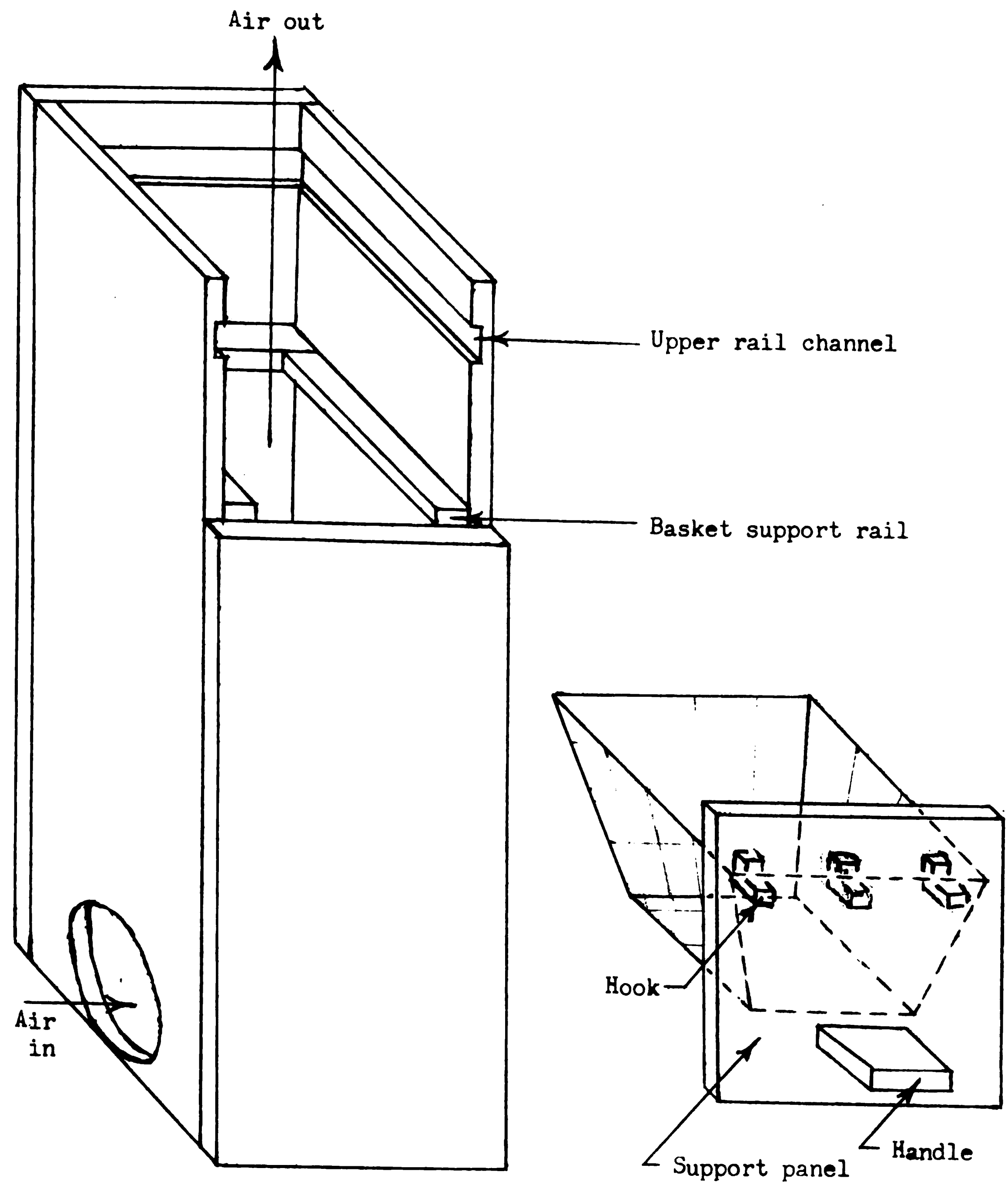

Figure 2. Plexiglass tunnel, with basket removed.

at the outlet of the tunnel. The fan was connected to the tunnel by 4 alternating segments of flexible and metal tubes as illustrated in Figure 3. The flexible tubes provided for independent positioning of both the fan and the tunnel. One of the metal tubes contained a heating coil for increasing the air temperature. The amount of heat added to the air was controlled by varying the current to the heating coil. Insulation on the outside of the tubing prevented heat loss to the surrounding air. The second metal tube, connected directly to the tunnel, contained a baffle which could be positioned from the outside to regulate air velocity.

The relative humidity of the air flow was increased by using 1.5 gallon humidifiers connected to the fan inlet by metal tubing (Figure 3). The increase in relative humidity was a function of the limited amount of control available with each humidifier and the number of humidifiers used.

Measurement Systems

The system utilized for measuring air temperature and relative humidity was an electric hygrometer. Air velocity measurements were obtained by using a hot wire anemometer and water temperature was measured using a mercury-in-glass thermometer. All samples were weighed on a Mettler top loading balance.

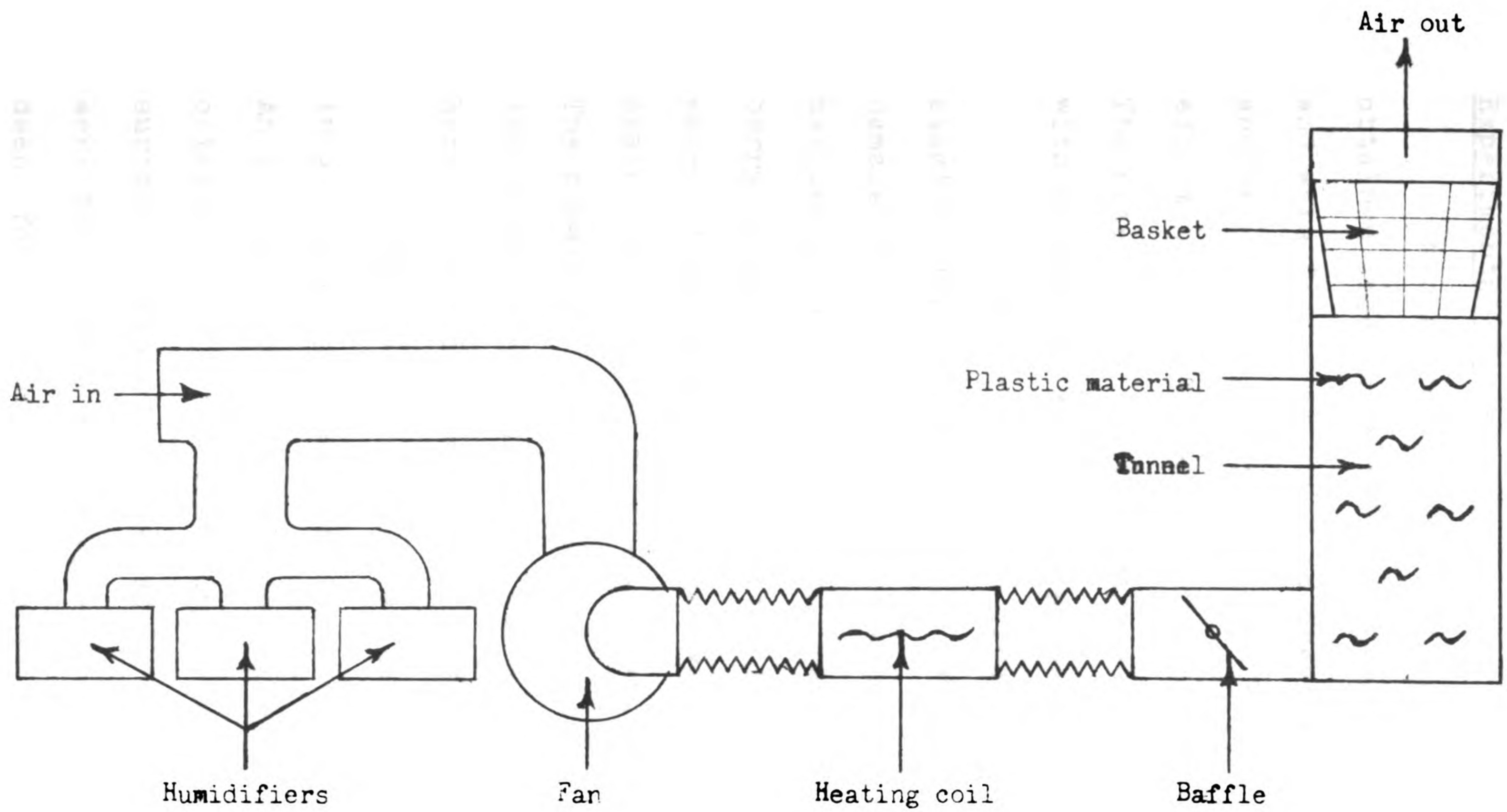

Figure 3. Schematic view of laboratory system for removing surface moisture from blueberries.

Experimental Procedures

Mechanically harvested Jersey blueberries were obtained from the Michigan Blueberry Growers Association and were frozen at -20^{o}F to prevent further deterioration and/or decay. (Freezing of the blueberries should not effect the rate at which surface moisture can be removed). The size of the berries averaged about 3/8 in. in diameter with an average weight of approximately 0.4 grams/berry.

Blueberries removed from cold storage were examined frozen for detection of green, cracked, and damaged berries. Stems were also removed while the blueberries were still frozen to prevent extraction of the berry interior. The inspected fruit was then thawed in water at ambient temperatures where the berries were again examined for cracked, leaky, and overripe fruit. The remaining blueberries were then spread out on paper towels to allow all of the surface moisture to evaporate. Berries that dehydrated during this time were discarded.

The blueberries were then placed into the basket in a single layer as close as possible without crushing. An initial dry weight of the basket and fruit was obtained. (In this text, dry weight will imply that all surface moisture was removed.) The basket and blueberries were then placed into a water bath, approximately 1 in. deep, for 1 minute. The temperature of the bath was adjusted by adding ice or hot water and recorded prior to inserting the blueberries. The depth of the water bath was maintained fairly constant in an attempt to hold the amount of moisture accumulated on the basket at a constant level. The holding time of 1 min, constant for all experiments, decreased the surface temperature of the blueberries to within 1^{o}F of the water bath (see Appendix B for calculations.)

After withdrawing the basket from the water bath, excess water was removed by tapping the basket 10 times on each side using approximately a constant force. This procedure removed the water that would have dripped off during transport of the basket and during the initial stages of the experiment. Before each experiment, the wet basket of blueberries was weighed, inserted into the tunnel, and withdrawn. This operation, accomplished in triplicate, eliminated most of the moisture lost by physical handling. The last weight obtained in this procedure became the initial wet weight.

The fan and other applicable equipment were activated and the wet basket of berries was again placed into the tunnel. Periodically, the basket was removed, weighed, and placed back into the tunnel. This procedure required approximately 30 sec. of time. The removal times, constant for all experiments, were 15 seconds, 30 seconds, 1 minute, 1.5 minutes, 2 minutes, 3 minutes, 4 minutes, 5 minutes, 6 minutes, and at intervals of 2 minutes, if required, for the remainder of the experiment.

The experiment was terminated when the weight of the basket and contents equalled that of the initial dry weight.

There were 4 sets of experiments containing 4 trials each. In each set, 3 of the 4 parameters, air velocity, water temperature, air temperature, and relative humidity, were held constant while the fourth was varied. The parameter variables investigated with corresponding parameter constants are given in Table 1. (The air temperature constant chosen was that of room temperature.) Each experiment was conducted in triplicate.

Table 1. Parameter variables investigated with corresponding parameter constants.

Variables	Air velocity (ft/min)	Water temp. (°F)	Air temp. (°F)	Relative humidity (%)
Air velocity, ft/min 200,400,600,800	800	--	76	19
Water temperature, °F - 45,55,65,75	--	45	76	16
Air temperature, °F - 62,72,82,87	800	45	--	13
Relative humidity, % - 16,26,36,50	800	45	76	--

The fraction of water remaining on the basket of blueberries at any time, t, was given by the expression

$$r = \frac{w_t - w_D}{w_o - w_D} \tag{1}$$

where w_t was the weight of the basket + blueberries at a given time interval, w_D was the initial dry weight of basket + blueberries, and w_0 was the initial wet weight of basket + blueberries. (In a commercial design, surface moisture must be removed from both the blueberries and the conveyer. In the experimental apparatus, the basket simulated the conveyor and, therefore, was included in the weight measurements.)

The values obtained for each triplicate of experiments along with corresponding time intervals were analyzed using a Wang Model 700 computer. The data was fit to a least square-exponential curve of the form

$$r = ae^{kt} \tag{2}$$

where k was the surface moisture removal rate constant or slope of the curve for a given set of parameters. (Equation (2) was selected because the data seemed to follow a logarithmic form.) A graph of each set of data was then drawn on semi-log paper using the slope, k, and the r intercept, a.

RESULTS AND DISCUSSION

Data Analysis

The results obtained from the experiments are presented in Appendix Tables A.1 to A.4. Equal numbers of data points for each set of 3 experiments were then analyzed by the computer. The least square fit-exponential curves obtained with experimental data from the parameter variables of 800 ft/min air velocity, 45°F water temperature, 62°F air temperature, and 26% relative humidity are illustrated in Figures 4, 5, 6, and 7, respectively. The curves obtained for the remaining parameter variables are presented in Appendix Figures A.1 to A.12.

In all the figures, the curve intercepted the vertical axis at values greater than one. This indicated that either there was a lag factor before the surface moisture removal rate became constant or the removal of surface moisture did not occur at a constant exponential rate. The latter factor seemed to be the case after careful examination of Figures 4 to 7 and Appendix Figures A.1 to A.12. In these figures, the majority of water fractions, r, fell below the curves during the first minute of surface moisture removal and also during the period after a water fraction of 0.1 had been obtained. During the remaining time, the majority of these values

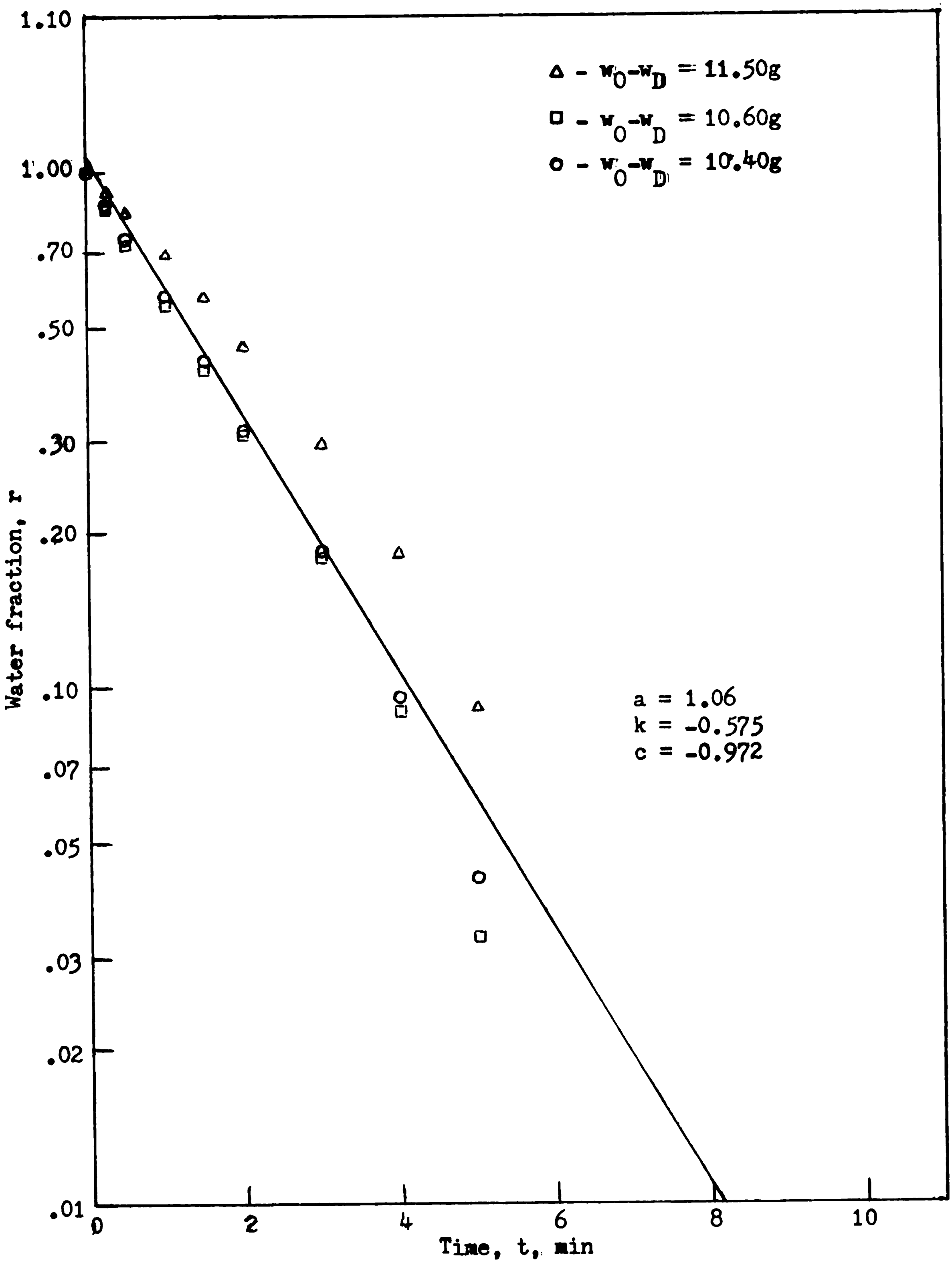

Figure 4. Determination of surface moisture removal rate constant, k, at air velocity variable of 800 ft/min (constants: $T_w = 45^oF$, $T_a = 76^oF$, RH = 16%).

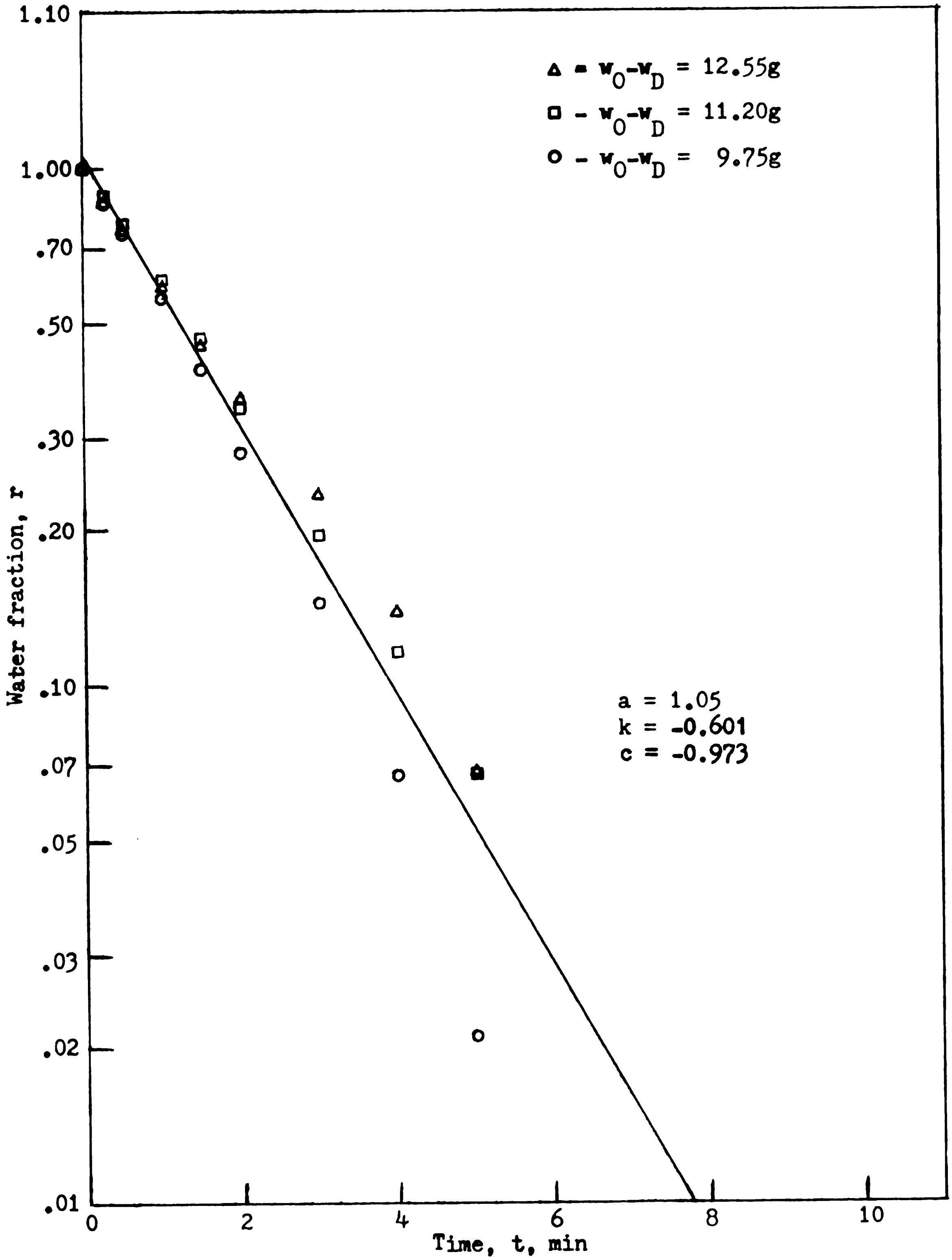

Figure 5. Determination of surface moisture removal rate constant, k, at water temperature variable of 45°F (constants: $\bar{u}$ = 800 ft/min, T_a = 76°F, RH = 19%).

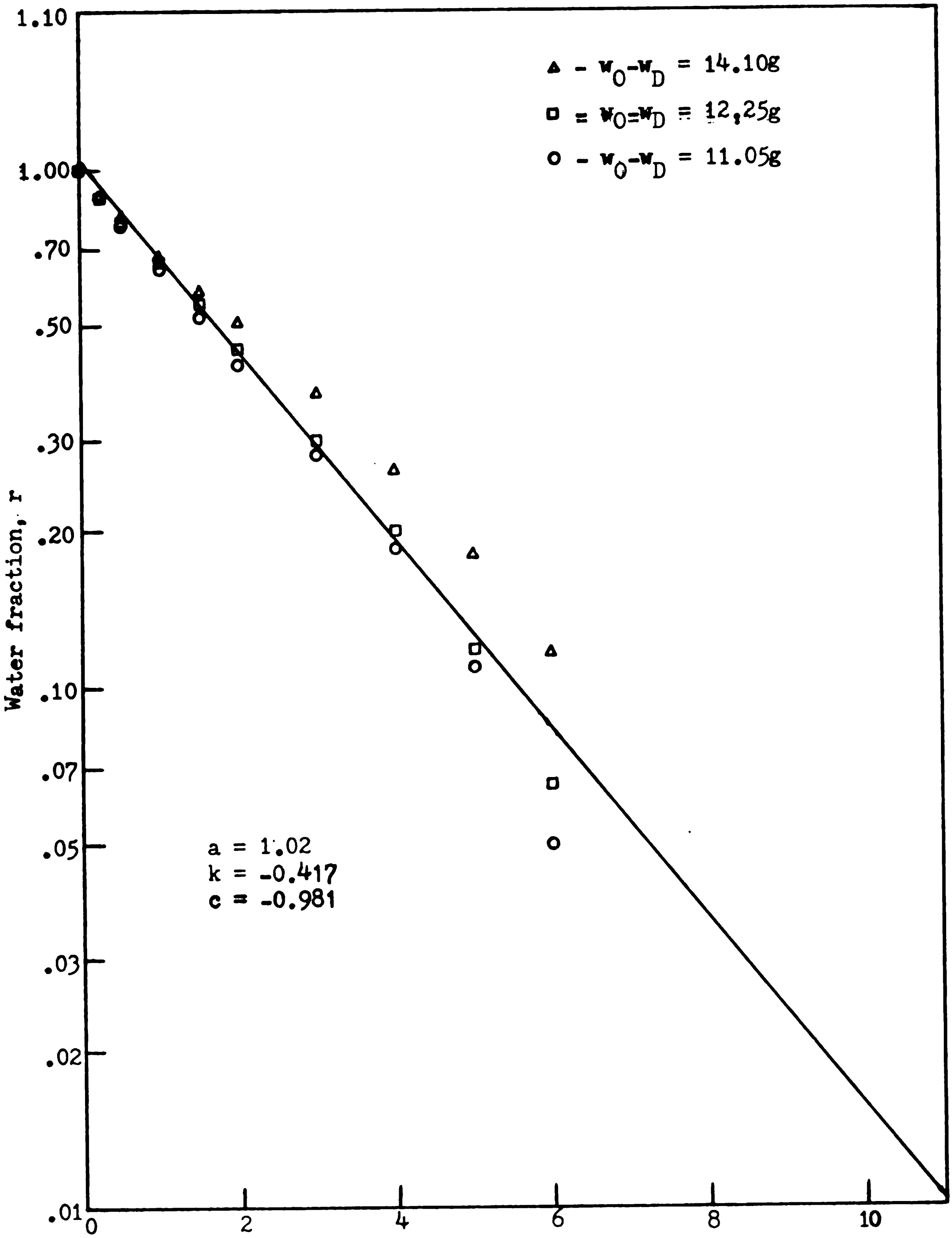

Figure 6. Determination of surface moisture removal rate constant, k, at air temperature variable of 62°F (constants: $\bar{u}$ = 800 ft/min, T_w = 45°F, RH = 13%).

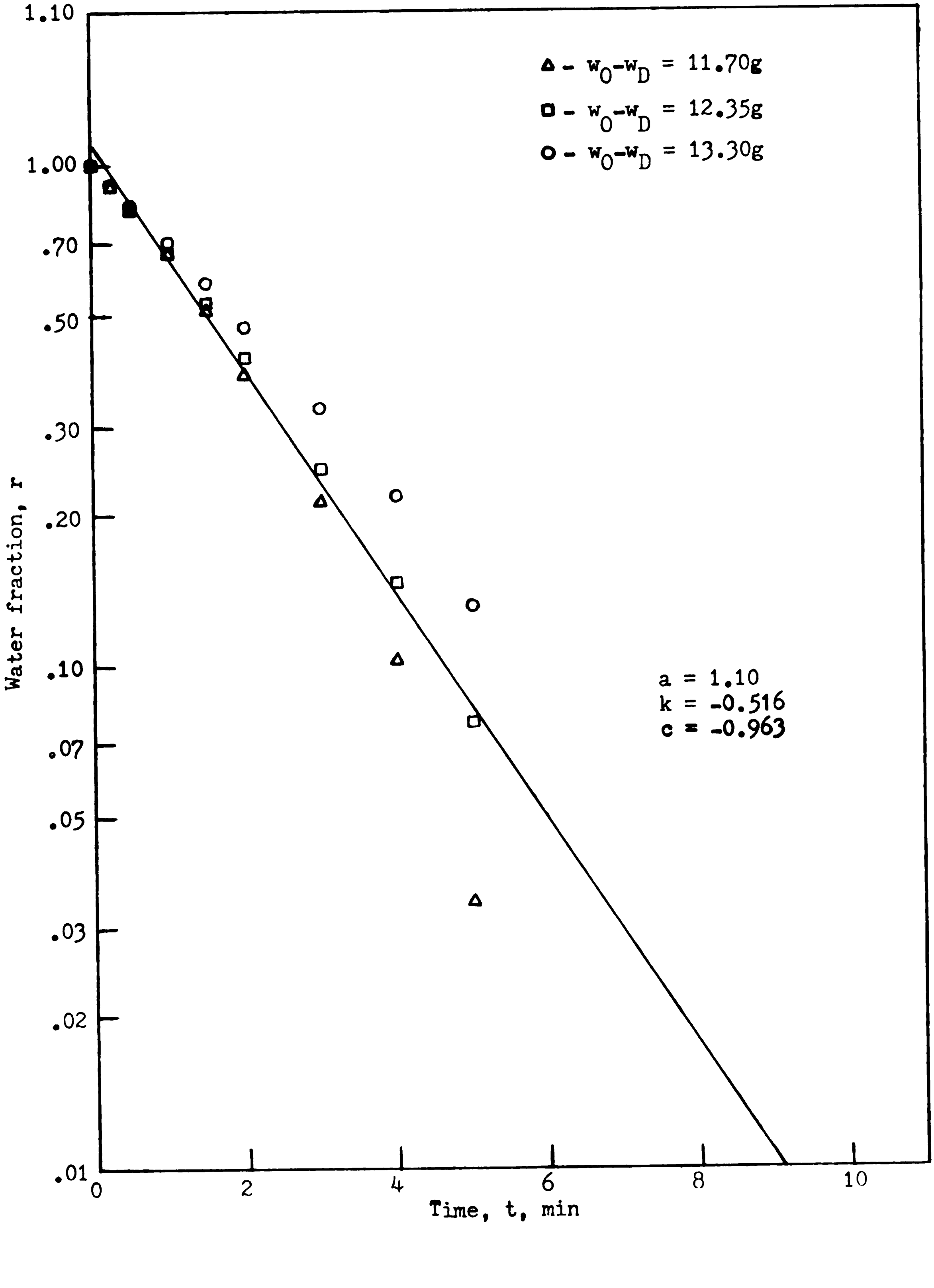

Figure 7. Determination of surface moisture removal rate constant, k, at relative humidity variable of 26% (constants: $\bar{u}$ = 800 ft/min, T_w = 45^{o}F, T_a = 76^{o}F).

were located above the curves. These observations indicated that there may have been two surface moisture removal rate periods. In the initial period, where the rate constant (k) would be less than that calculated from the original curve, approximately 90% of the surface moisture would be removed (the water fraction would equal 0.1). In the second period, where the rate constant would be greater than the computed value, the remaining moisture would be removed.

Conclusive evidence that two surface moisture removal periods existed, however, was lacking because there was insufficient data to describe the curve during the second period. In addition, the experimental data seemed to be adequately defined by the least square fit-exponential curves in Figures 4 to 7 and Appendix Figures A.1 to A.12, indicated by the correlation coefficients ranging from -.907 to -.996, significant at the 1% level. Since these coefficients were very close to -1, the data points were located very close to the exponential curves indicating that these curves accurately described the relationship of water fraction, r, to time, t. The probability that these curves did not describe the relationship of water fraction to time was 1 out of 100, evidenced by the significance at the 1% level.

One factor which could not be controlled adequately for any of the experiments was the initial amount of moisture on the basket and blueberries. An increase in the initial amount of surface moisture would result in consistently higher water fractions causing the surface moisture removal rate constant to decrease. This was very evident in Appendix Figure A.2 where the rate constants for the 3 experiments were significantly different at the 1% level with the rate constant decreasing as the initial amount of surface moisture increased. (The 1% level implied that the probability of making the wrong conclusion was 1 out of 100). The justification for finding an average rate constant using the data from all 3 experiments, was that the initial amount of surface moisture would be expected to vary within a commercial design also.

In the latter stages of the replicated experiments, differences between water fractions at any given time, t, may have also resulted from variations in the amount of free surface water (water not physically held between the berries and between the berries and the basket) remaining.

A summary of the computed surface moisture removal rate constants appears in Table 2. The influence of each parameter on these rate constants was determined by fitting the parameter variables with the corresponding rate constants to a least square-exponential curve.

Table 2. Surface moisture removal rate constants obtained for experimental parameter variables.

Air velocity (ft/min)	Rate constant (1/min)	Water temp. (°F)	Rate constant (1/min)	Air temp. (°F)	Rate constant (1/min)	Relative humidity (%)	Rate constant (1/min)
200	-.277	45	-.601	62	-.417	16	-.649
400	-.333	55	-.631	72	-.518	26	-.516
600	-.465	65	-.699	82	-.678	36	-.457
800	-.575	75	-.695	87	-.751	50	-.366
T_w = 45°F T_a = 76°F RH = 16%		$\bar{u}$ = 800 ft/min T_a = 76°F RH = 19%		$\bar{u}$ = 800 ft/min T_w = 45°F RH = 13%		$\bar{u}$ = 800 ft/min T_w = 45°F T_a = 76°F	

Influence of Air Velocity

The influence of air velocity, $\bar{u}$, on the surface moisture removal rate constant, k , is illustrated in Figure 8. The correlation coefficient of the computed least square fit-exponential curve was .996, significant at the 1% level and showed that the rate constant increased exponentially with increasing air velocity. Although air velocities in excess of 800 ft/min could not be attained with the experimental equipment, higher air velocities would probably cause flotation of the blueberries in the basket and alter the rate constant significantly.

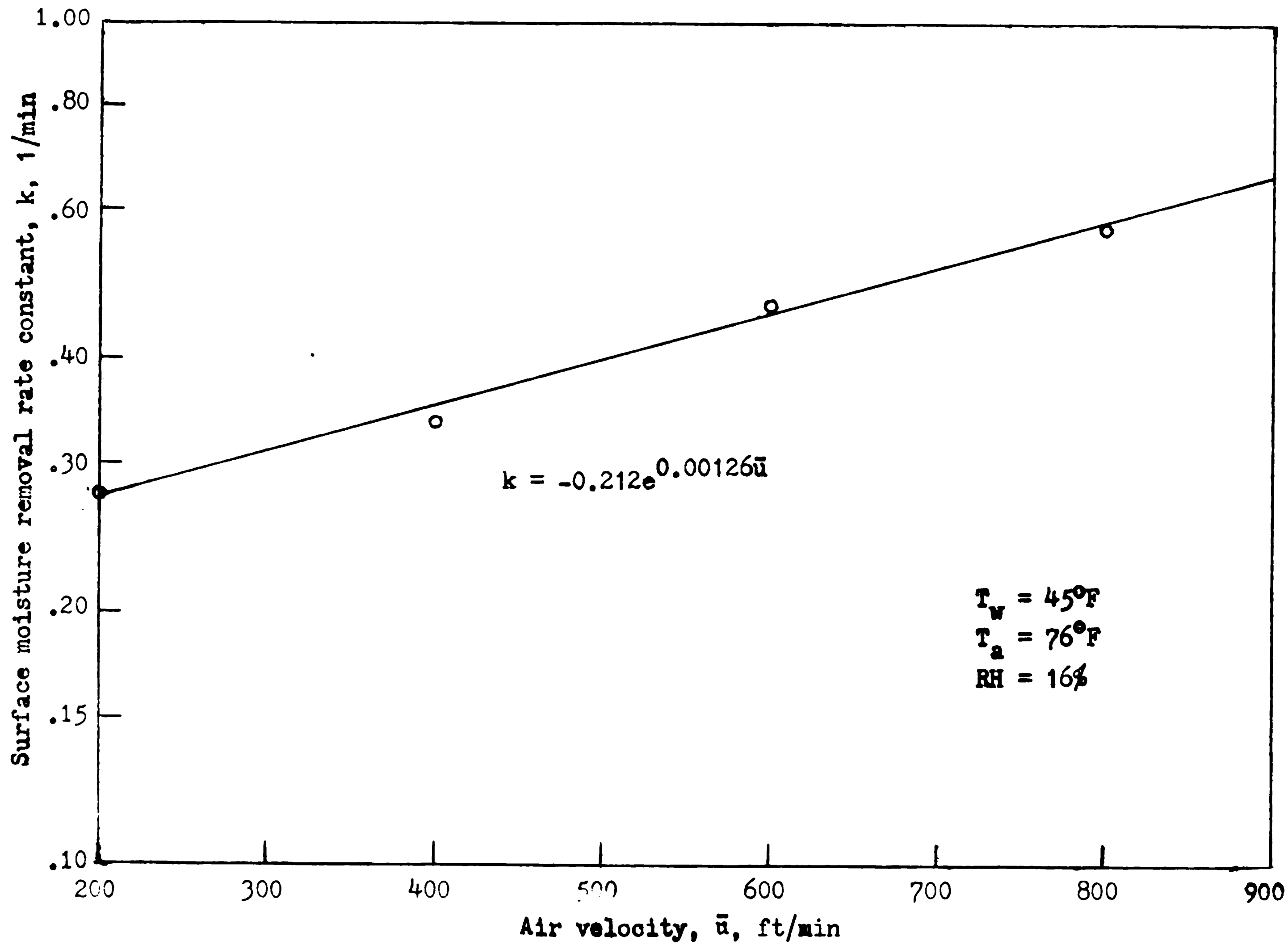

Figure 8. Influence of air velocity, $\bar{u}$, on the surface moisture removal rate constant, k.

Air velocity can effect the rate of heat transfer, expressed by the equation

$$Q = hA[T_a - T_s] \qquad (3)$$

where h is the surface heat transfer coefficient, A is the surface area to which heat is transferred, and T_a and T_s are the temperatures of the air and the surface, respectively. The surface heat transfer coefficient, h, can be increased by an increase in air velocity, $\bar{u}$, as displayed by the following equation presented by Earle (1966)

$$h = 1 + .21\bar{u} \quad \text{for } \bar{u} < 960 \text{ ft/min} \qquad (4)$$

$$h = 0.5\bar{u} \quad \text{for } \bar{u} > 960 \text{ ft/min} \qquad (5)$$

where the surface heat transfer coefficient, h, would be expressed in BTU/hr-ft^2-^{o}F.

The rate of heat transfer may also be expressed as

$$Q = M\lambda \qquad (6)$$

where M is the rate of water vapor transfer and λ is the latent heat of vaporization. From equations (3) and (6), an expression for rate of moisture transfer was presented by Earle (1966):

$$M = hA(T_a - T_s)/\lambda \qquad (7)$$

The more familiar form of expressing rate of moisture transfer is probably

$$M = K_g A(P_s - P_a) \qquad (8)$$

where K_g is the mass transfer coefficient, A is the surface area upon which moisture is removed and P_s and P_a are the water vapor pressures at the surface and in the air, respectively. (The rate of moisture transfer, M, predicted by equation (7) will be identical to that given by equation (8) only when the surface temperature, T_s, is equal to the wet bulb temperature of the air.) The value of K_g was predicted by Earle(1966) in the equation

$$K_g = 4h \qquad (9)$$

where h is the surface heat transfer coefficient of the airflow.

With increasing air velocity, the rate of water vapor transfer should increase as predicted by equations (7) and (8), assuming that temperature and vapor pressure gradients, respectively, remain constant. This would account for the increase of the surface moisture removal rate constant with increasing air velocity illustrated in Figure 8.

Influence of Water Temperature

The surface moisture removal rate constant, k, increased exponentially with increasing water temperature, T_w, (Figure 9). The maximum water temperature that could be implemented without damaging the fruit was less than 130°F (Kushman, 1971). Relatively high water temperatures, however, would be contrary to a primary objective of a water handling system - cooling of the blueberries.

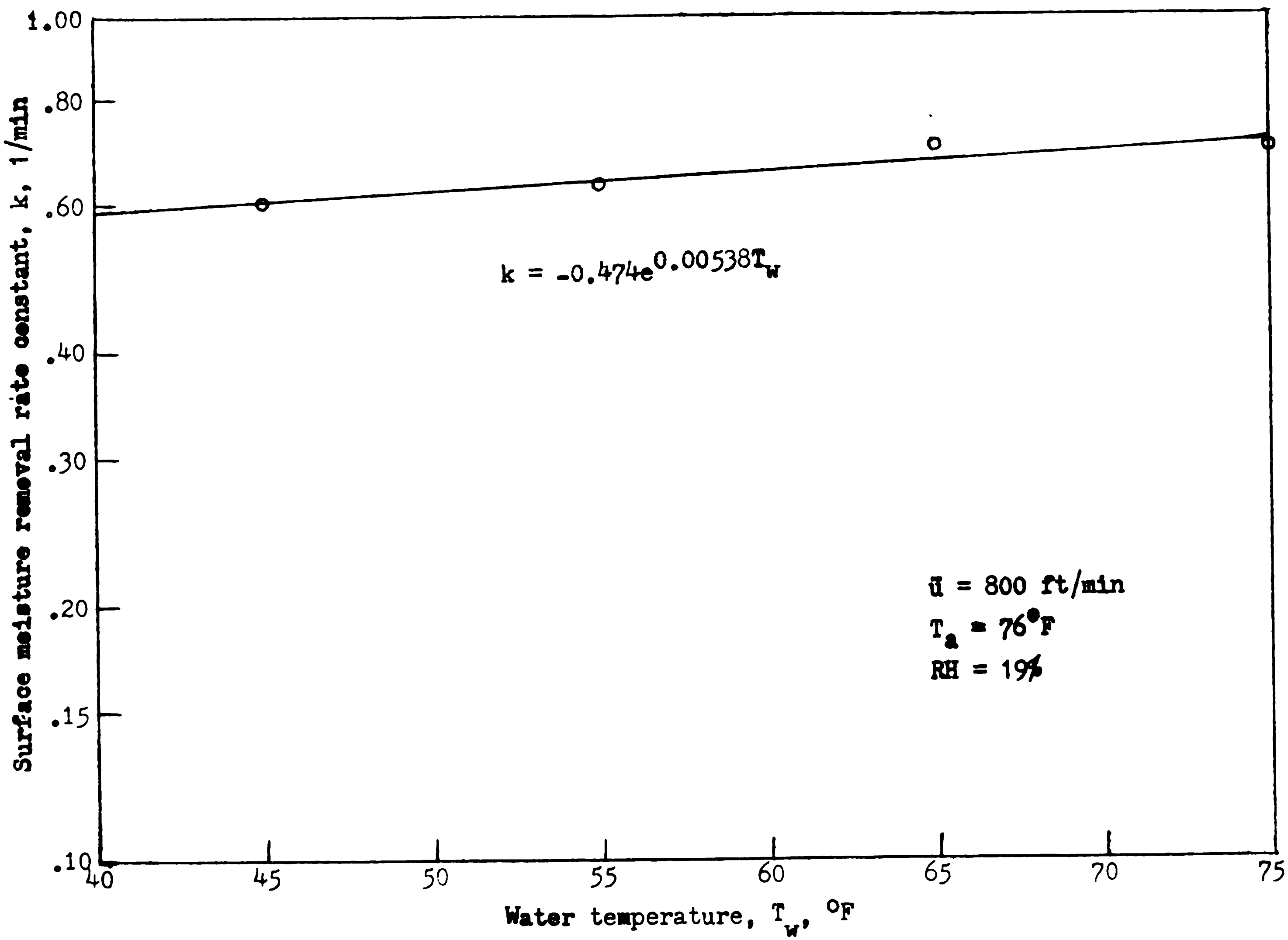

Figure 9. Influence of water temperature, T_w, on the surface moisture removal rate constant, k.

The correlation coefficient of the least square-exponential curve in Figure 9 was relatively high at -.936, but was insignificant at the 5% level, since the curve was determined from only 4 data points. The insignificance apparently resulted from the slightly larger surface moisture removal rate constant obtained experimentally at 65°F than that obtained at 75°F, which was contrary to the predicted values in Figure 9. This was apparently caused by the relatively large water fractions in experiment II at 75°F after 3 minutes, compared with those in experiments I and III (Appendix Table A.2), which, as discussed earlier, would effect a decrease in the rate constant. Since the initial amount of surface moisture in all 3 experiments at 75°F water temperature was essentially the same (Figure A.6 in Appendix A), the larger water fractions associated with experiment II probably resulted from significant fluctuations in one or more of the parameter values.

The exponential increase of the rate constant, k, with increasing water temperature, evident by the equation in Figure 9, was probably a net result of 2 factors. Increasing the water temperature raised the water vapor pressure on the surface increasing the vapor pressure gradient, assuming constant air temperature and relative humidity. This would cause an increase in the rate of water vapor transfer, as predicted by equation (8), and, therefore the rate constant would increase. The difference in the rates of water vapor transfer, however, approached zero since the surface temperature approached the wet bulb temperature of 53.5°F. (Since the surface temperature was not equal to the wet bulb temperature, equation (7) could not be used to describe the increase of the rate constant.) This not only nullified part of the effect of water temperature on the rate constant, but also supports the argument, discussed earlier, that the surface moisture removal rate was not constant for any of the experiments.

The time required for the temperature gradient between the surface and the wet bulb temperature to decrease 50% was calculated to be 3.5 min (see Appendix B). In computing this time, the blueberry surface was assumed to be completely exposed to the air stream. This was generally not true in the experiments because of physical contact between blueberries and between blueberries and the basket. The time calculated, however, should be a good approximation illustrating that the temperature gradient was not constant for a given experiment.

Influence of Air Temperature

An increase in air temperature, T_a, produced an exponential increase in the surface moisture removal rate constant, k, as illustrated in Figure 10. The correlation coefficient of the least square-exponential curve was .999, significant at the 1% level. Air

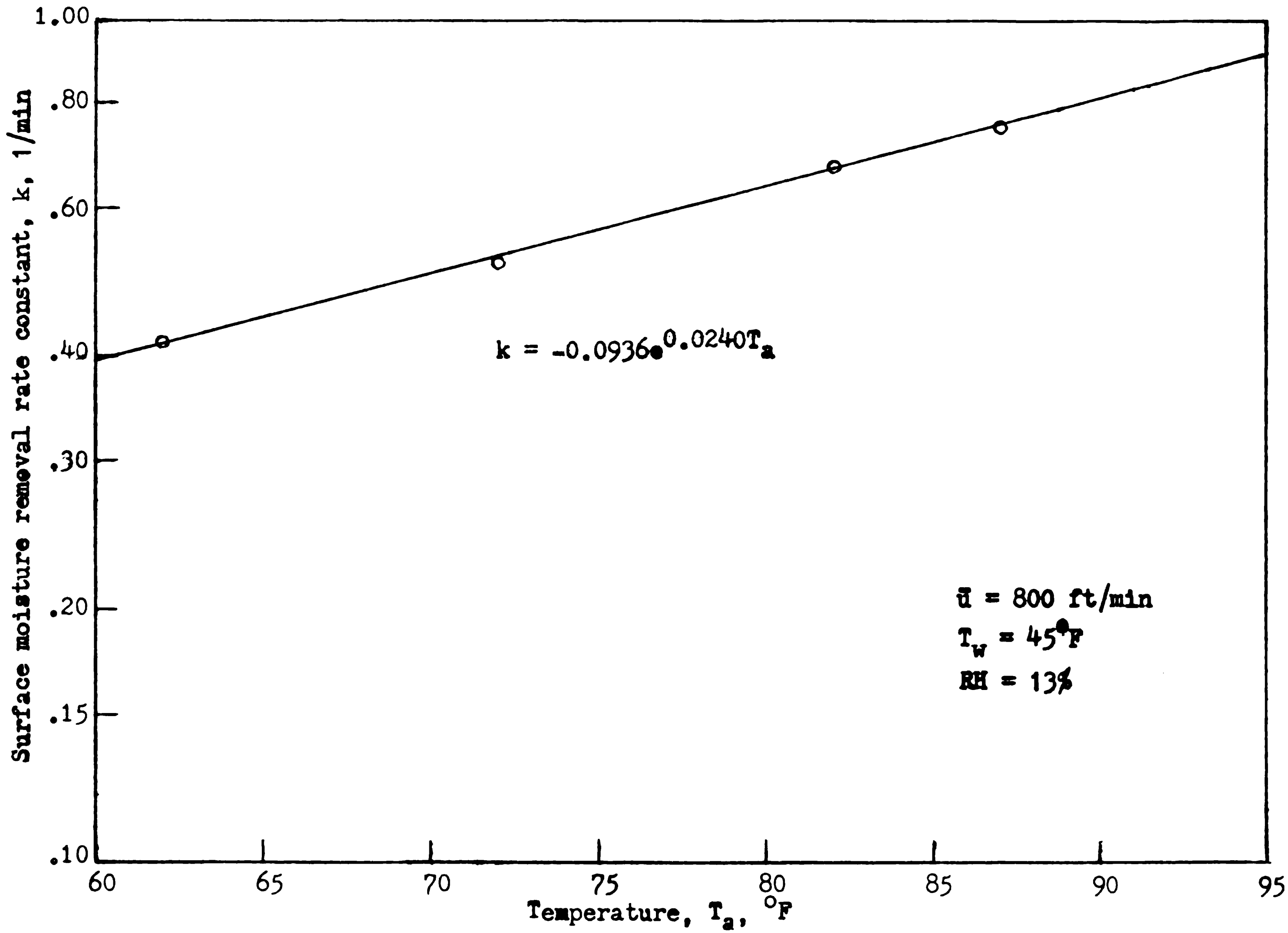

Figure 10. Influence of air temperature, T_a, on the surface moisture removal rate constant, k.

temperatures at an air velocity of 800 ft/min could not be varied in the experiments much beyond the range of 62 to 87°F. The limiting factors on increasing the air temperature would be the quantity of heat available and the effect on the blueberries. The latter would not be a factor as long as evaporative cooling prevented heat damage to the fruit.

The exponential increase of the rate constant, k, resulted from increases in the rates of heat transfer and water vapor transfer. Increased air temperature difference (between dry bulb and wet bulb) in equation (3) increased the rate of surface heat transfer. An increase in air temperature also raised the saturation vapor pressure which allowed the air to hold a larger capacity of moisture. This increased the rate of water vapor transfer resulting from an increase in vapor pressure gradient as revealed by equation (8).

The influence of air temperature on the surface moisture removal rate can also be expressed in an Arhenius-type plot (Figure 11). The exponent of the equation in this figure can be expressed as follows

$$-6810/\mathcal{T}_a = -E/R\mathcal{T}_a \qquad (10)$$

$$E = 6810R \qquad (11)$$

where E is the energy of activation, R is the universal gas constant, and $\mathcal{T}_a$ is the absolute temperature. Since the gas constant, R, has a value of 0.238 BTU/mole-°R,

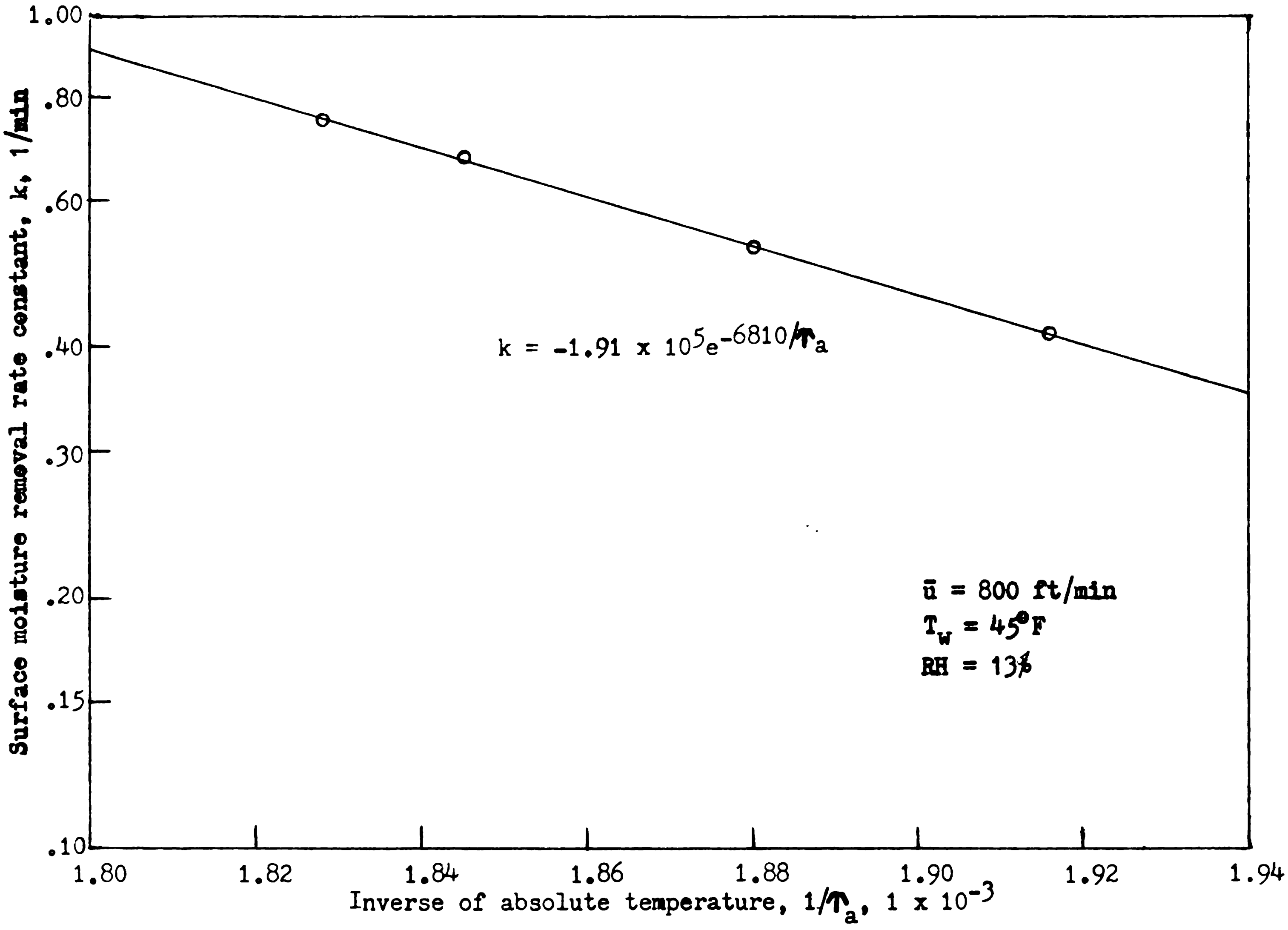

Figure 11. Influence of air temperature on surface moisture removal rate constant, k, using an Arrhenius-type plot.

the activation energy required for moisture removal, computed from equation (11), was 1621 BTU/mole.

Influence of Relative Humidity

The influence of relative humidity on the surface moisture removal rate constant is revealed in Figure 12. An increase in the relative humidity, RH, exponentially decreased the rate constant, k. The exponential curve produced a correlation of .993 with the data, significant at the 1% level. Relative humidities at an air velocity of 800 ft/min could not be varied in the experiments much beyond the range of 16 to 50% RH.

An increase in relative humidity of air at a constant temperature resulted in a decrease in the capacity of the air to hold water vapor. This resulted in decreased rates of evaporation since the partial pressure of the water vapor in the air increased with increased relative humidity. This was observed in equation (8) where the amount of moisture transferred to the air per unit time decreased as the vapor pressure gradient decreased. The rate of heat transfer in equation (3) also decreased due to the decrease in the difference between the dry bulb (air) and wet bulb (surface) temperatures resulting from increasing relative humidity. These factors accounted for the decrease in the surface moisture removal rate constant with increasing relative humidity, as described by the equation in Figure 12.

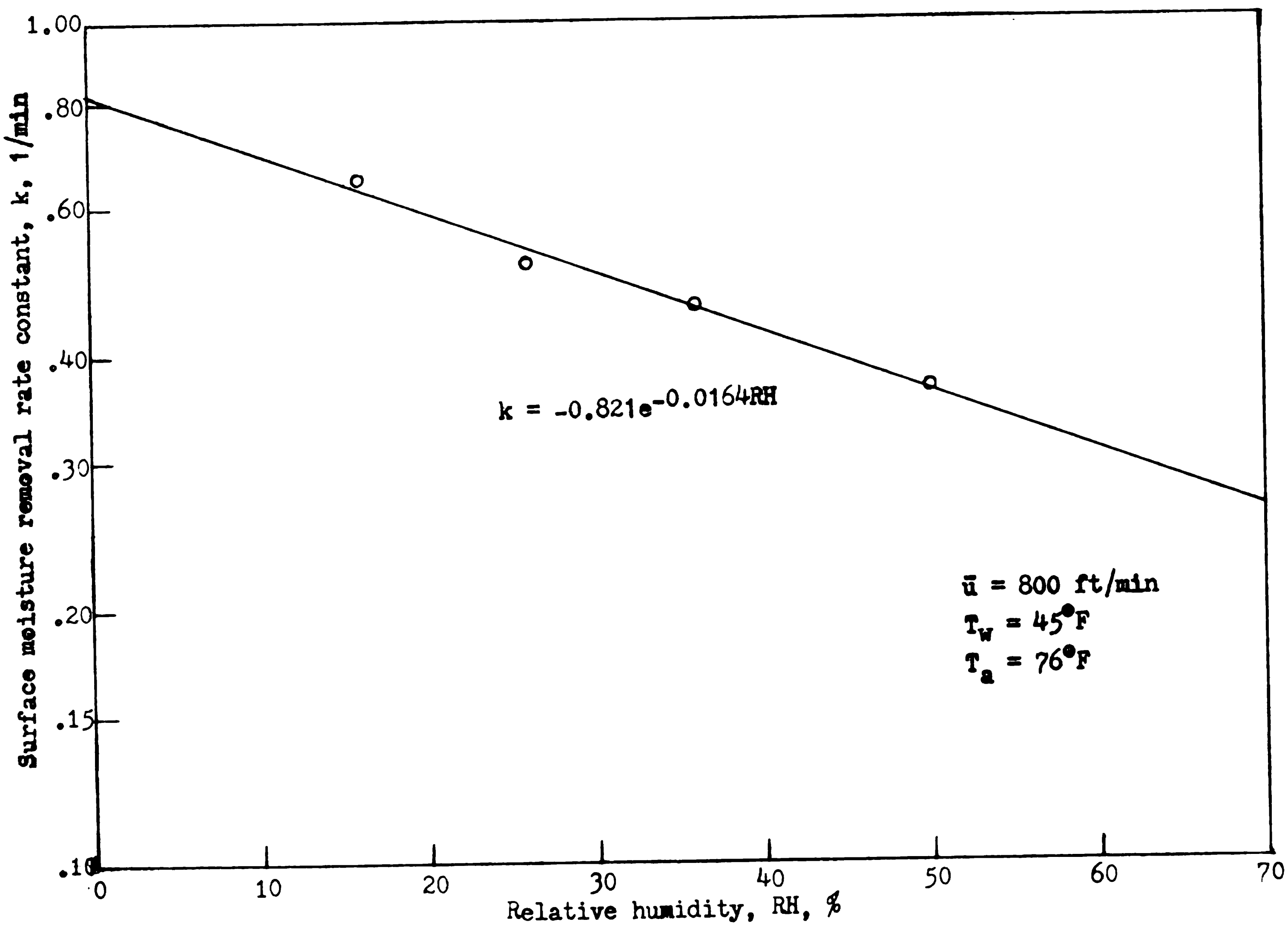

Figure 12. Influence of relative humidity, RH, on the surface moisture removal rate constant, k.

The k value for 100% RH predicted by the curve in Figure 12 does not appear to be realistic. When the air is saturated with water vapor, the moisture removal rate should be zero because the vapor pressure gradient in equation (8) would be 0. This would indicate that the k value should be an infinitely small number at 100% RH. The relationship at this humidity then would not be the one expressed in Figure 12 and may indicate that the exponential equation in this figure may not be the best one for 0 to 100% RH.

<u>Systems Design Equation</u>

A multiple linear regression was performed on the parameter variables with corresponding surface moisture removal rate constants (Table 2) utilizing the Wang Model 700 computer. The resulting equation was as follows:

$$k = .959 - .000475\,\bar{u} - .00509T_w - .01366T_a + .00648\ RH \quad (12)$$

Equation (12) can be used with confidence only when the parameters used to determine the rate constant, k, are within the experimental limits. This equation should provide reasonable estimates of the rate constant with air temperature, water temperature, and/or relative humidity values outside these limits, provided the relationships given in Figures 9, 10, and 12, respectively, do not change significantly. (As discussed earlier, air velocities in excess of 800 ft/min probably would change the relationship in Figure 8).

The time required to remove 90% of the surface moisture, obtained experimentally, was compared, in Table 3, to the time computed from the surface moisture removal rate constant predicted by the exponential and design equations. (The computation of these time periods will be discussed later.) This comparison was made for the minimum and maximum variables of each parameter investigated.

Table 3 shows that the time periods derived from the exponential equations were in excellent agreement with those obtained experimentally. The time periods derived from the design equation were generally in somewhat less agreement, with the maximum difference being approximately 1/2 min. This should not be considered excessive, however, since this difference also existed between two experimental time periods, in Table 3, obtained under identical conditions - air velocity of 800 ft/min, water temperature of 45°F, air temperature of 76°F, and relative humidity of 16%. The experimental difference probably resulted from fluctuations in the parameter values, in the initial amount of surface moisture, and/or in the amount of free surface moisture, discussed previously.

The average time periods derived from the design equation may be more accurate than those obtained experimentally because all of the experimental variables

Table 3. Comparison of time required to remove 90% of the surface moisture, obtained experimentally with that predicted by the corresponding exponential equation and by the design equation.

Variables		Constants				Time, min.				
							Exponential Equation		Design Equation	
Parameter	Value	$\bar{u}$,ft/min	T_w, °F	T_a, °F	RH,%	Experimental	Predicted	Difference	Predicted	Difference
Air velocity (ft/min)	200	-	45	76	16	8.32	8.45	+0.13	7.66	-0.56
	800	-	45	76	16	4.00	3.98	-0.02	3.94	-0.06
Water temp. (°F)	45	800	-	76	19	3.83	3.82	-0.01	4.07	+0.24
	75	800	-	76	19	3.31	3.25	-0.06	3.20	-0.11
Air temp. (°F)	62	800	45	-	13	5.52	5.57	+0.05	5.57	+0.05
	87	800	45	-	13	3.07	3.06	-0.01	3.05	-0.02
Rel.humidity %	16	800	45	76	-	3.55	3.63	+0.08	3.94	+0.39
	50	800	45	76	-	6.30	6.37	+0.07	6.30	0.00

and constants were used in the determination of the design equation. This, however, can only be proven by many repetitions of the same experiments.

Implementation of Design Equation

A commercial surface moisture removal system for blueberries may be designed from the surface moisture removal rate constant provided that both the capacity of the experimental system, C_e, in pints from which the rate was obtained, and the product capacity of the commercial process, C_c, are known.

The capacity of the experimental system was approximately 90g/.25 ft^2 of blueberries, one berry-layer deep. Assuming 1 pint of fruit weighs 360g, then 1 pint of blueberries, one berry-layer deep, will occupy 1 ft^2, the value of C_e. The area calculated here for 1 pint of blueberries probably exceeded the commercial requirement resulting in less surface water per ft^2. This would indicate that less time would be required to remove the surface moisture provided the rate constant remained unchanged.

Given a surface moisture removal rate constant, k, the time may be computed from the following equation

$$\text{slope} = k/2.303 = (\log r_2 - \log r_1)/(t - t_1) \quad (13)$$

where t_1, is the initial time, t, at the origin and, therefore, equals 0. In one log cycle, where the slope is negative,

$$\log r_2 - \log r_1 = -1 \tag{14}$$

so that equation (13) becomes

$$t = -2.303/k \tag{15}$$

where t is the time required to remove 90% of the surface moisture (initial log cycle).

If the commercial system consists of a surface moisture removal tunnel through which a conveyor belt passes, the length of the tunnel, L, can be calculated from the equation

$$L = C_e C_c t/B_w \tag{16}$$

where B_w is the width of the conveyor belt and L is expressed in ft.

Assuming a product capacity, C_c, of 10 pints/min and a conveyor belt 5 ft wide, the tunnel lengths, L, required for given sets of parameters are displayed in Table 4. The percent surface moisture removed was then plotted against tunnel length, L, on semi-log paper (Figure 13).

In Table 4, an initial set of parameters is represented by Set I. Each parameter was then increased by 25% with the others held constant except where an increase in air temperature and in relative humidity effected a decrease in relative humidity and in air temperature, respectively. These increases are displayed by Sets II through V.

Table 4. Tunnel lengths computed for given sets of parameters.

Set	Air velocity (ft/min)	Water temp. (°F)	Air temp. (°F)	Relative humidity (%)	k (1/min)	Time (min)	Tunnel length (ft)
I	800	60	80	40	-.560	4.11	8.22
II	1000	60	80	40	-.655	3.52	7.04
III	800	75	80	40	-.637	3.62	7.24
IV	800	60	100	22	-.949	2.43	4.86
V	800	60	73	50	-.399	5.77	11.54

As illustrated in Figure 13, increasing the air temperature, decreasing the relative humidity, effected the largest reduction of tunnel length (41%) with the same surface moisture removal capacity as that required by the original set of parameters. Increased air velocity and water temperature resulted in relatively small tunnel length reductions (14 and 12%, respectively) of the original length. As expected, increased relative humidity with decreased air temperature effected a substantial increase in tunnel length (40%) over that of the initial length, required to remove similar amounts of surface moisture.

Unless the tunnel length can be adjusted, the design of the commercial system will have to feature means of regulating the air temperature, air velocity, and/or relative humidity to accomodate for fluctuating

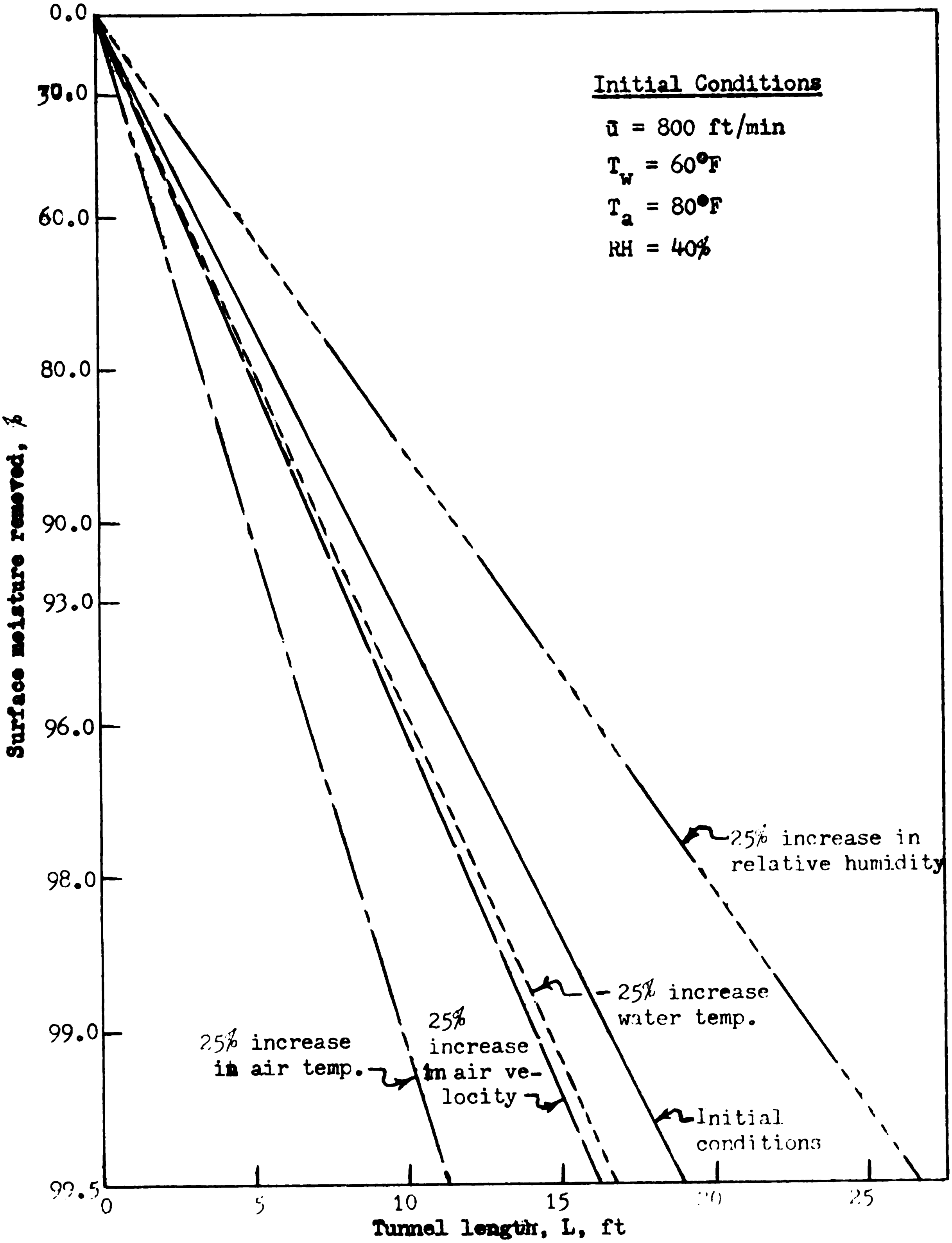

Figure 13. Influence of parameter increases on tunnel length.

air temperature, relative humidity, and/or water temperature.

CONCLUSIONS

1. The relationship of the data points for each set of triplicated experiments for moisture removal from surfaces of blueberries was described by a least squares-exponential curve from which a surface moisture removal rate constant was obtained.
2. Increase in air velocity or air temperature in the ranges of 200 to 800 ft/min and 62 to 87°F, respectively can be described by an exponential increase in the surface moisture removal rate constant.
3. An increase in water temperature in the range of 45 to 75°F was not significantly related to an exponential increase in the surface moisture removal rate constant.
4. An increase in relative humidity in the range of 16 to 50% was significantly related to an exponential decrease of the surface moisture removal rate constant.
5. The systems design equation can be used with confidence to determine the surface moisture removal rate constant only when the parameters used are within the following limits: air velocity, 200-800 ft/min, water temperature, 45-75°F; air temperature, 62-87°F; and relative humidity, 16-50%.
6. The time computed from the surface moisture removal rate constant obtained from the systems design

equation should be more than adequate to remove a designated quantity of surface moisture.

7. Air temperature is the parameter which has the most significant influence on the time required to remove a specified percent of surface moisture from blueberries in a commercial operation.

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APPENDIX A

Table A.1. Fraction of water, r, vs time, t, obtained with varying air velocity.

	200 ft/min			400 ft/sec			600 ft/sec			800 ft/sec		
Time, min	I	II	III	I	II	III	I	II	III	I	II	III
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.25	.949	.937	.937	.922	.911	.961	.893	.905	.931	.865	.854	.917
.50	.889	.859	.894	.865	.842	.933	.795	.814	.850	.750	.726	.835
1.0	.799	.762	.827	.743	.708	.870	.647	.670	.733	.577	.557	.696
1.50	.718	.665	.769	.641	.604	.806	.521	.552	.628	.433	.415	.574
2.0	.645	.578	.706	.551	.505	.743	.409	.448	.530	.317	.311	.461
3.0	.504	.437	.600	.416	.366	.630	.256	.303	.381	.183	.179	.296
4.0	.406	.325	.506	.302	.257	.525	.140	.199	.263	.096	.090	.183
5.0	.325	.238	.424	.212	.163	.426	.070	.118	.170	.043	.033	.091
6.0	.248	.160	.353	.139	.094	.331	.028	.054	.101	.005	-	.026
8.0	.137	.063	.235	.045	.020	.180	-	-	.020	-	-	-
10.0	.064	.015	.145	-	-	.074	-	-	-	-	-	-
12.0	.021	-	.078	-	-	.014	-	-	-	-	-	-
14.0	-	-	.031	-	-	-	-	-	-	-	-	-

Table A.2. Fraction of water, r vs time, t, obtained with varying water temperature.

Time, min	45°F			55°F			65°F			75°F		
	I	II	III	I	II	III	I	II	III	I	II	III
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.25	.862	.884	.865	.871	.860	.822	.832	.841	.826	.842	.817	.826
.50	.749	.781	.761	.772	.740	.698	.707	.726	.702	.774	.742	.706
1	.564	.607	.594	.605	.574	.527	.516	.552	.541	.560	.581	.536
1.5	.410	.469	.458	.455	.438	.385	.391	.415	.405	.423	.450	.409
2	.282	.344	.363	.339	.340	.280	.293	.293	.298	.316	.345	.306
3	.144	.196	.235	.197	.204	.149	.158	.154	.165	.175	.197	.166
4	.067	.116	.139	.107	.111	.065	.070	.085	.083	.073	.100	.068
5	.021	.067	.068	.047	.051	.022	.019	.035	.021	.017	.052	.017
6	-	.027	.016	-	.017	-	-	.005	-	-	.017	-

Table A.3. **Fraction of water, r, vs time, t obtained with varying air temperature.**

Time, min	62°F			72°F			82°F			87°F		
	I	II	III	I	II	III	I	II	III	I	II	III
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.25	.882	.886	.887	.888	.891	.896	.885	.897	.874	.882	.869	.879
.50	.778	.796	.812	.787	.790	.796	.771	.784	.772	.768	.738	.762
1.0	.643	.665	.688	.614	.643	.652	.588	.629	.602	.589	.533	.570
1.5	.520	.547	.589	.493	.504	.524	.443	.491	.445	.430	.376	.426
2	.421	.449	.504	.393	.395	.412	.302	.416	.331	.312	.262	.309
3	.281	.302	.369	.245	.248	.264	.172	.213	.173	.152	.109	.141
4	.186	.200	.262	.141	.155	.156	.088	.093	.083	.061	.031	.051
5	.109	.118	.181	.072	.088	.088	.034	.024	.028	.011	-	.008
6	.050	.065	.117	.036	.046	.040	.008	-	-	-	-	-
8	-	.004	.050	-	-	-	-	-	-	-	-	-

Table A.4. Fraction of water, r, vs time, t, obtained with varying relative himidity.

Time, min	16%			26%			36%			50%		
	I	II	III	I	II	III	I	II	III	I	II	III
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.25	.863	.887	.887	.914	.903	.910	.918	.919	.926	.952	.957	.956
.50	.749	.770	.785	.831	.814	.816	.836	.834	.857	.900	.905	.900
1	.581	.609	.623	.703	.668	.667	.694	.702	.730	.811	.797	.790
1.5	.441	.468	.482	.586	.530	.517	.566	.583	.602	.719	.697	.690
2	.335	.351	.377	.474	.413	.380	.461	.477	.496	.635	.610	.598
3	.181	.181	.231	.327	.247	.214	.311	.302	.328	.490	.468	.441
4	.088	.077	.134	.218	.146	.103	.205	.183	.205	.365	.351	.319
5	.031	.016	.069	.132	.077	.034	.137	.094	.115	.261	.251	.205
6	-	-	.024	.068	.024	-	.091	.043	.053	.177	.177	.122
8	-	-	. -	.019	-	-	.023	-	-	.060	.065	.-17

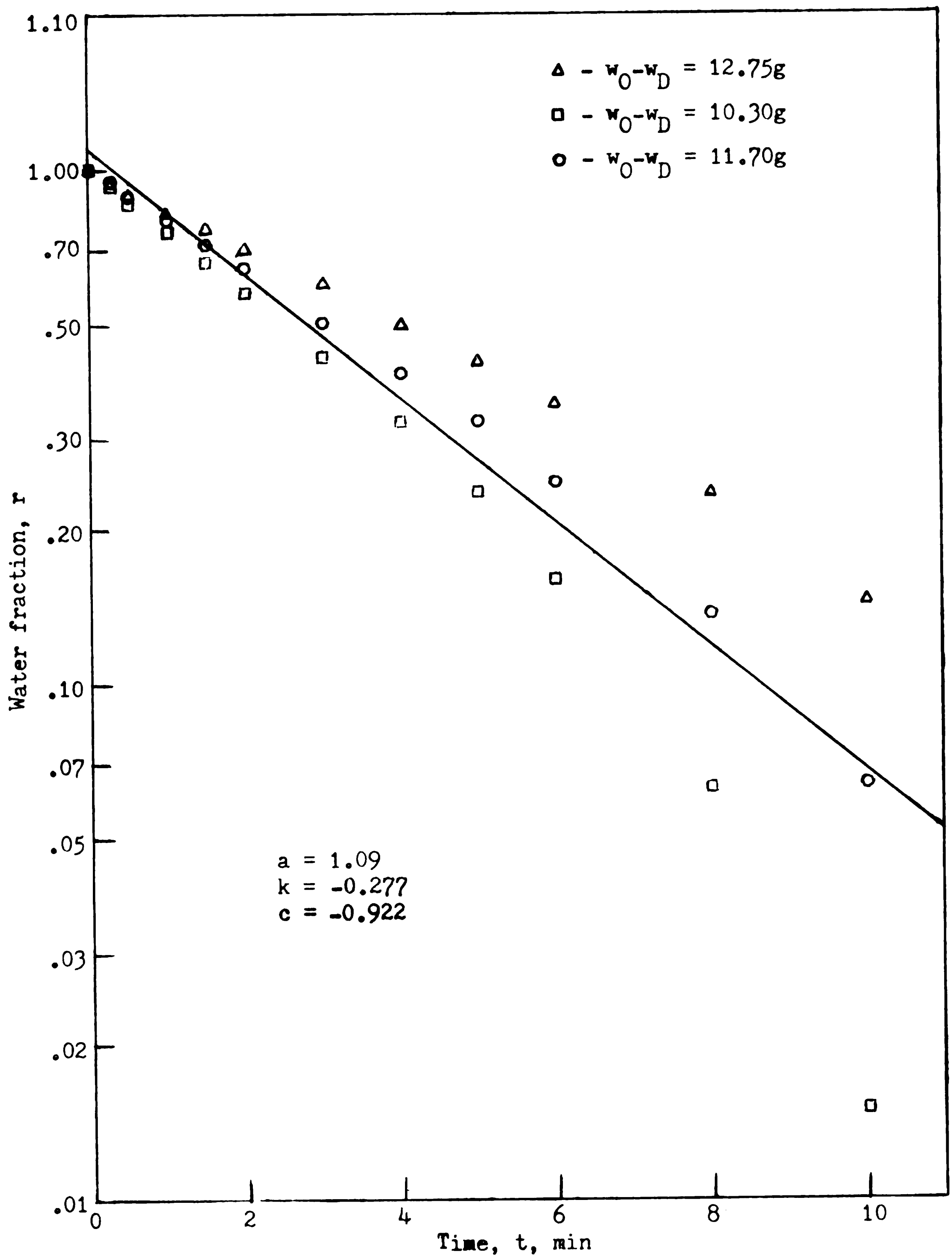


Figure A.1. Determination of surface moisture removal rate constant, k, at air velocity variable of 200 ft/min (constants: $T_w = 45^oF$, $T_a = 76^oF$, RH = 16%).

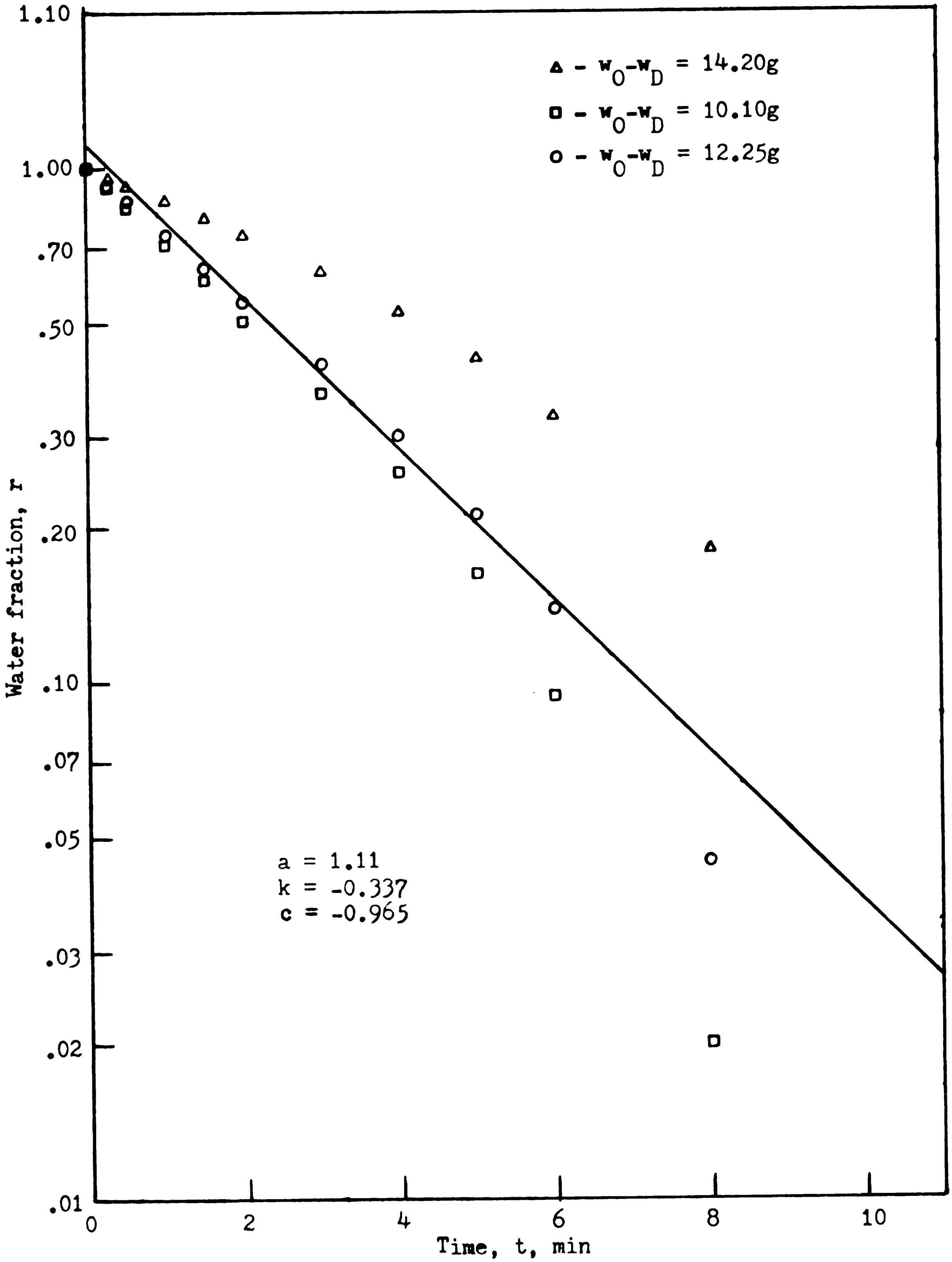


Figure A.2. Determination of surface moisture removal rate constant, k, at air velocity variable of 400 ft/min (constants: T_w = 45°F, T_a = 76°F, RH = 16%).

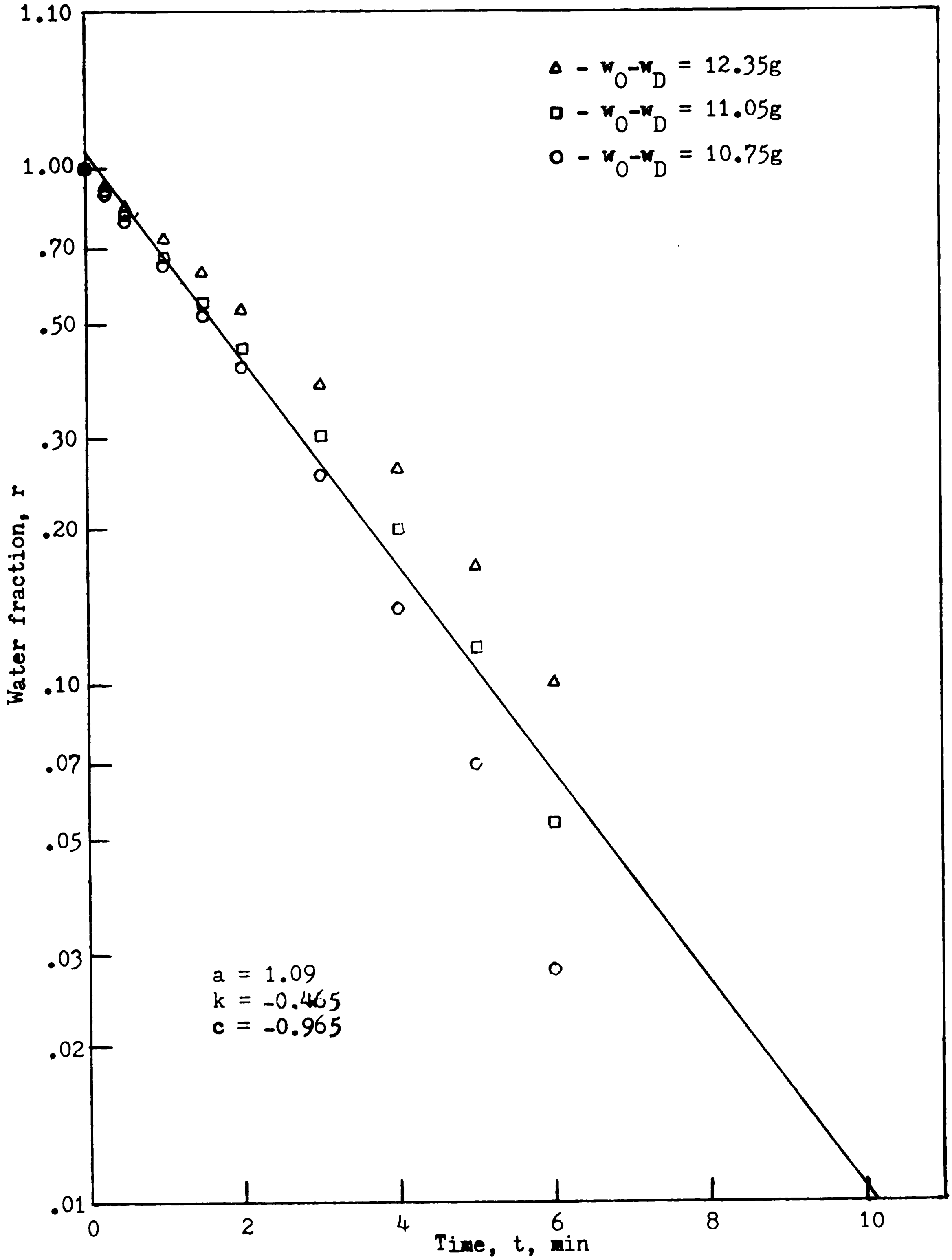


Figure A.3. Determination of surface moisture removal rate constant, k, at air velocity variable of 600 ft/min (constants: $T_w = 45^{\circ}F$, $T_a = 76^{\circ}F$, RH = 16%).

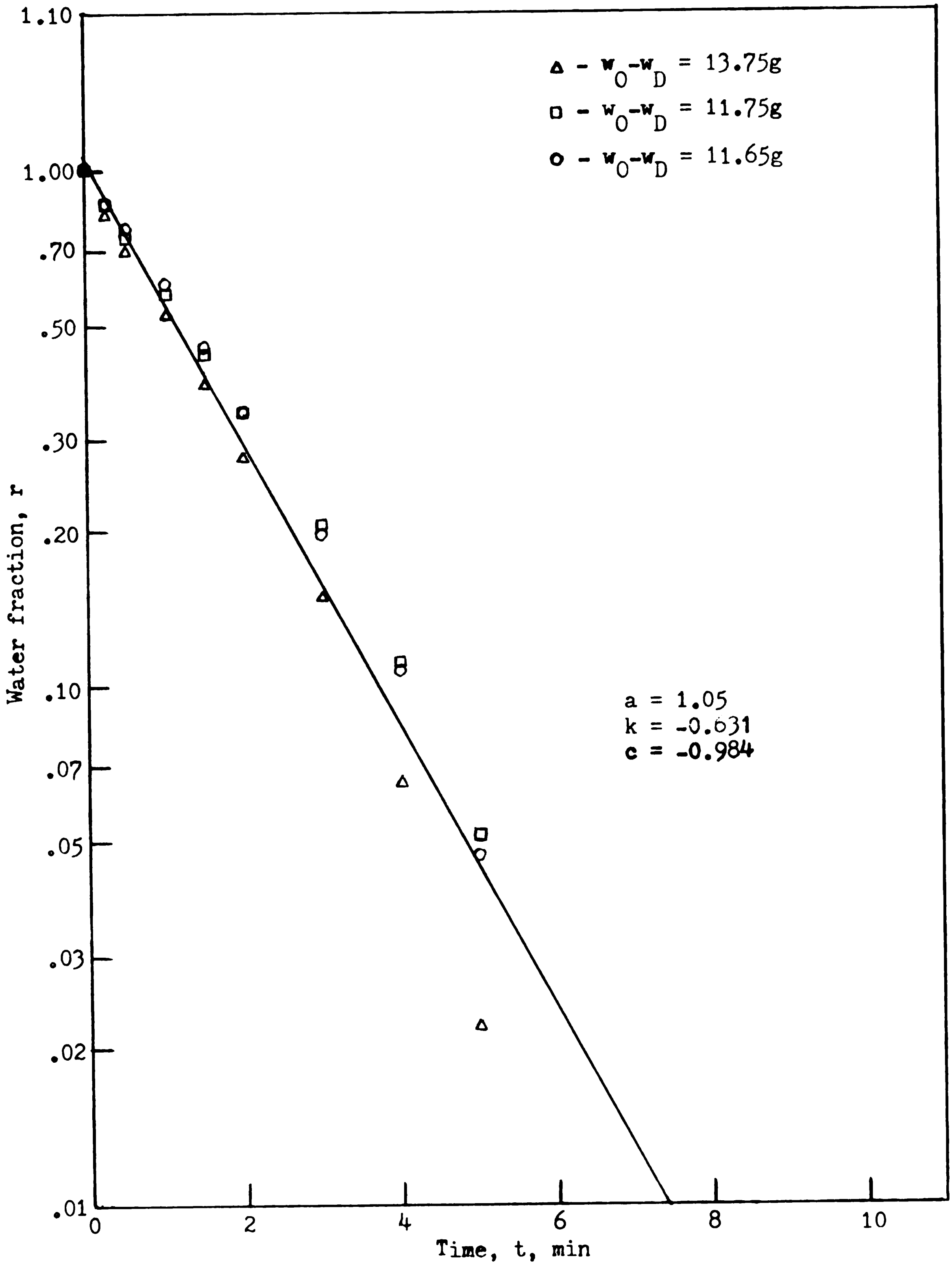


Figure A.4. Determination of surface moisture removal rate constant, k, at water temperature variable of 55°F (constants: $\bar{u}$ = 800 ft/min. T_a = 76°F, RH = 19%).

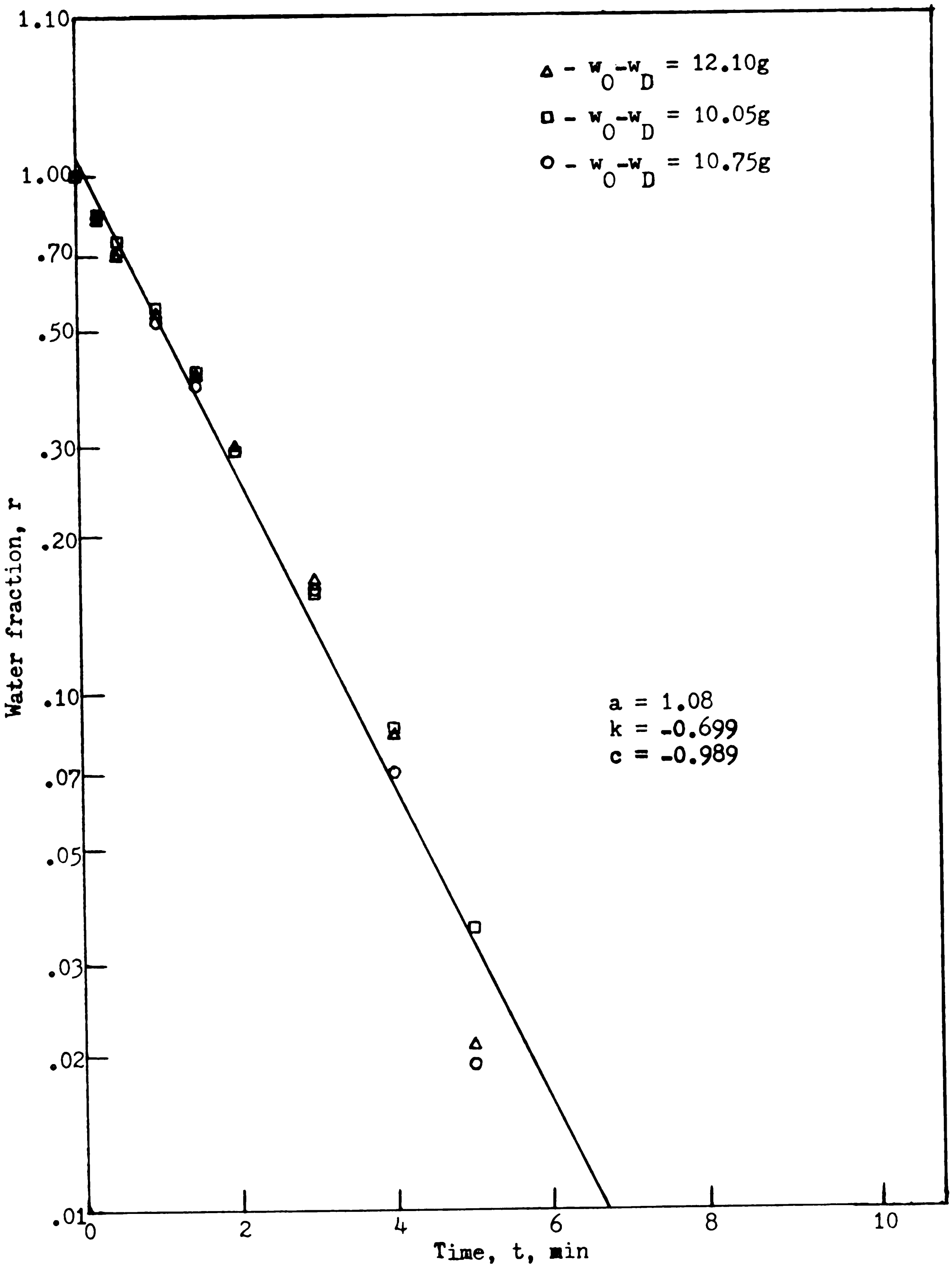


Figure A.5. Determination of surface moisture removal rate constant, k, at water temperature variable of 65°F (constants: $\overline{u}$ = 800 ft/min. T_a = 76°F, RH = 19%).

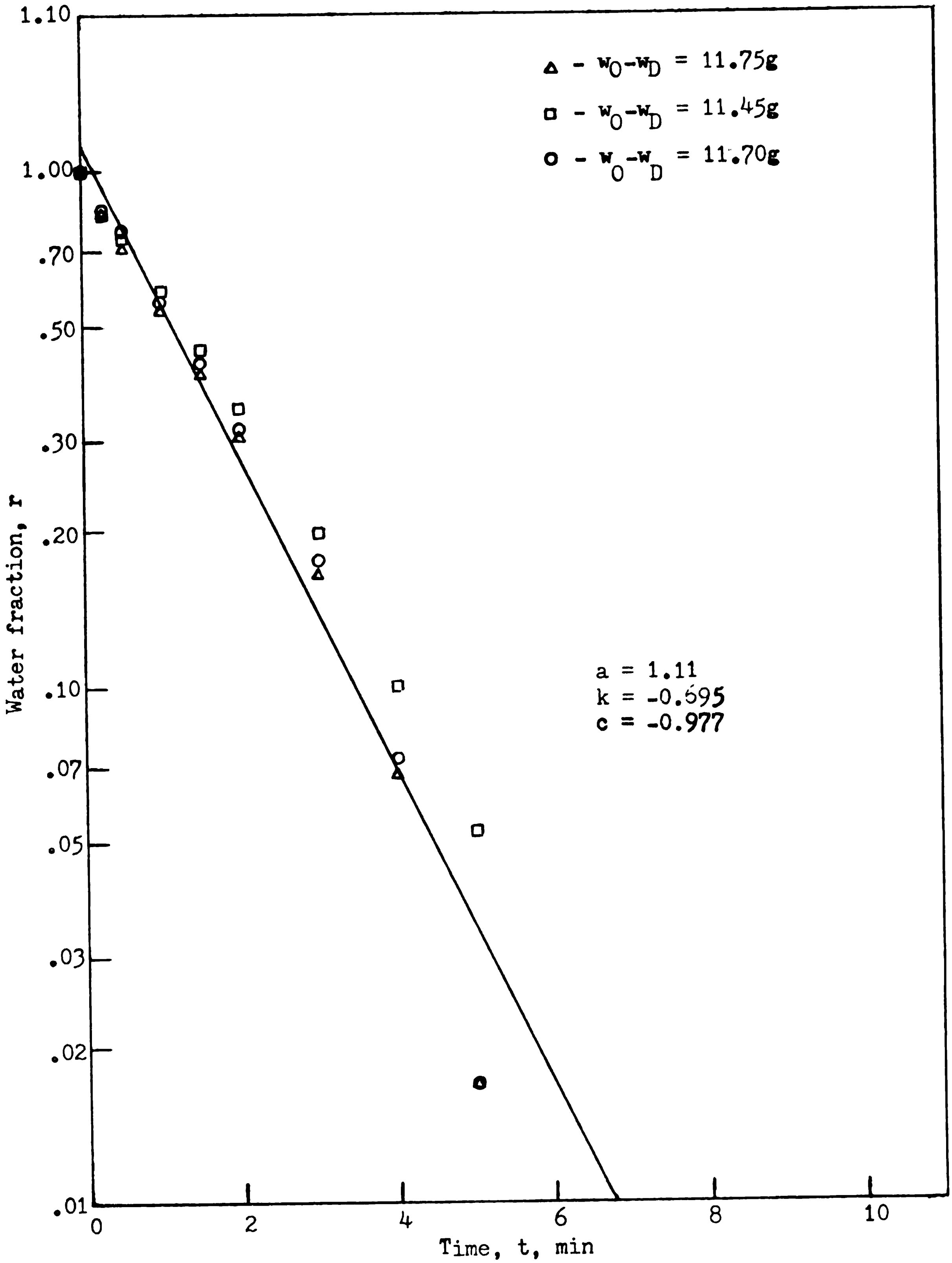


Figure A.6. Determination of surface moisture removal rate constant, k, at water temperature variable of 75°F (constants: $\bar{u}$ = 800 ft/min. T_a = 76°F, RH = 19%).

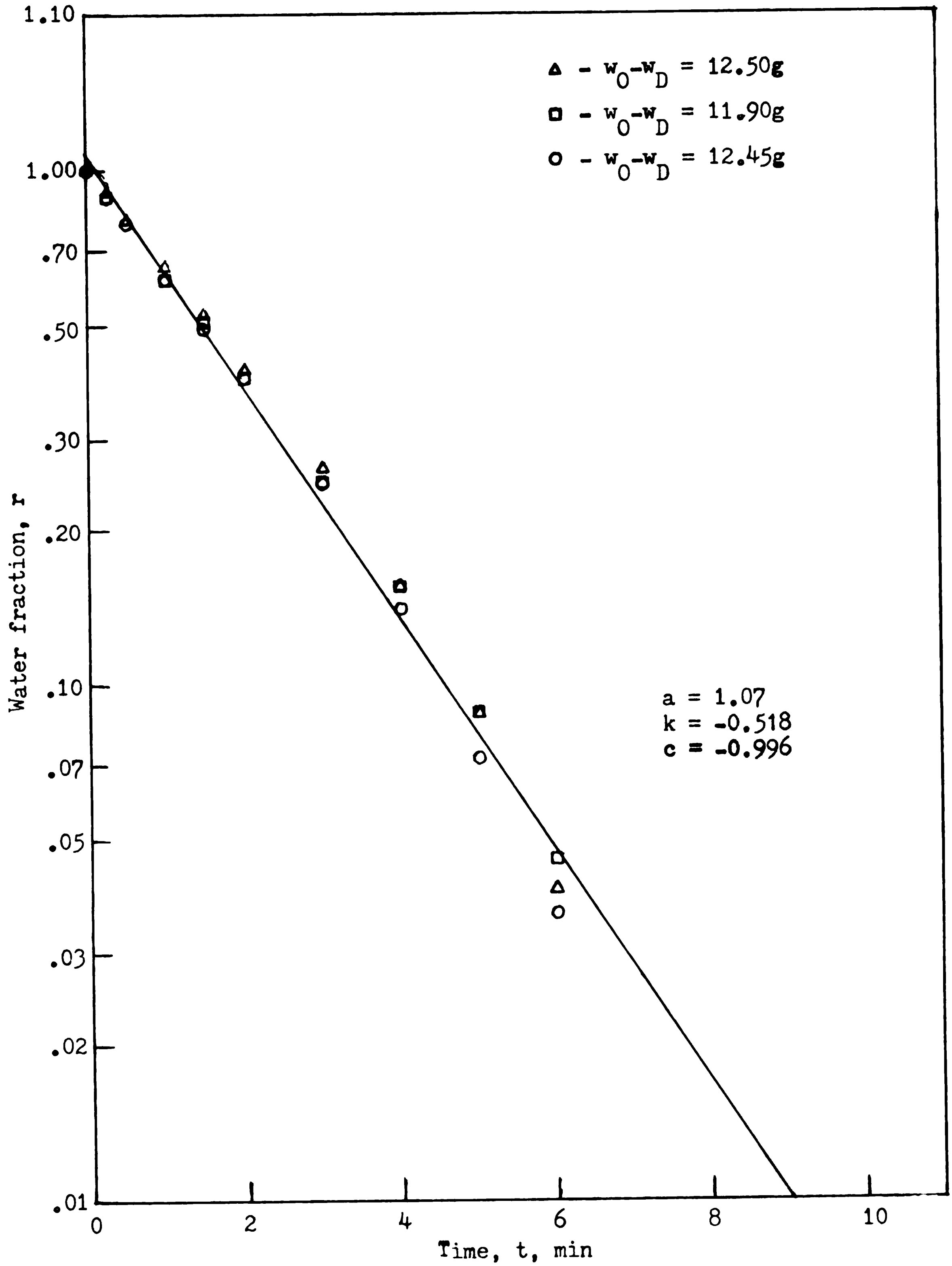


Figure A.7. Determination of surface moisture removal rate constant, k, at air temperature variable of 72°F (constants: $\bar{u}$ = 800 ft/min. T_w = 45°F, RH = 13%).

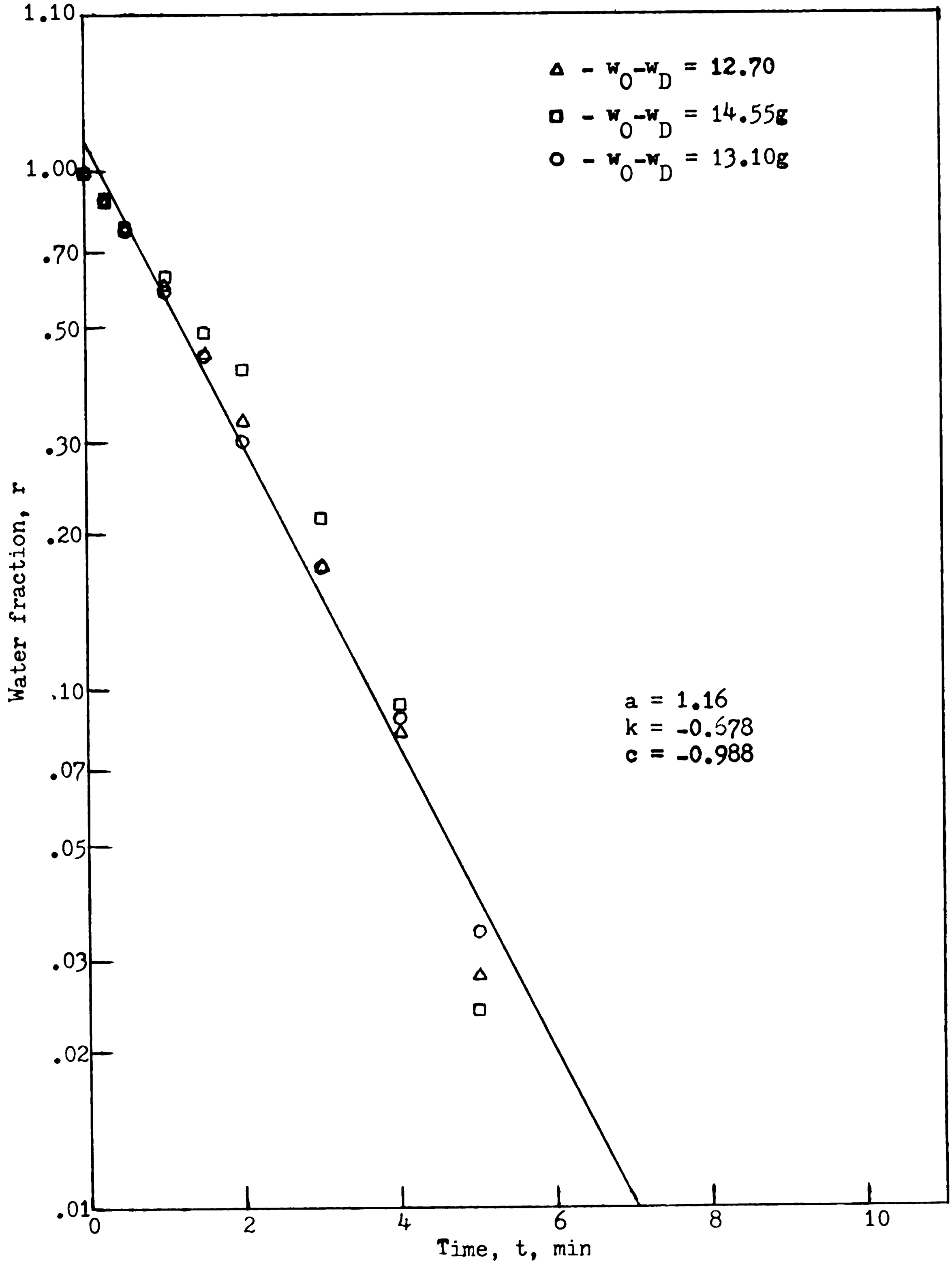


Figure A.8. Determination of surface moisture removal rate constant, k, at air temperature variable of $82^{o}F$ (constants: $\overline{U}$ = 800 ft/min, T_w = $45^{o}F$, RH = 13%).

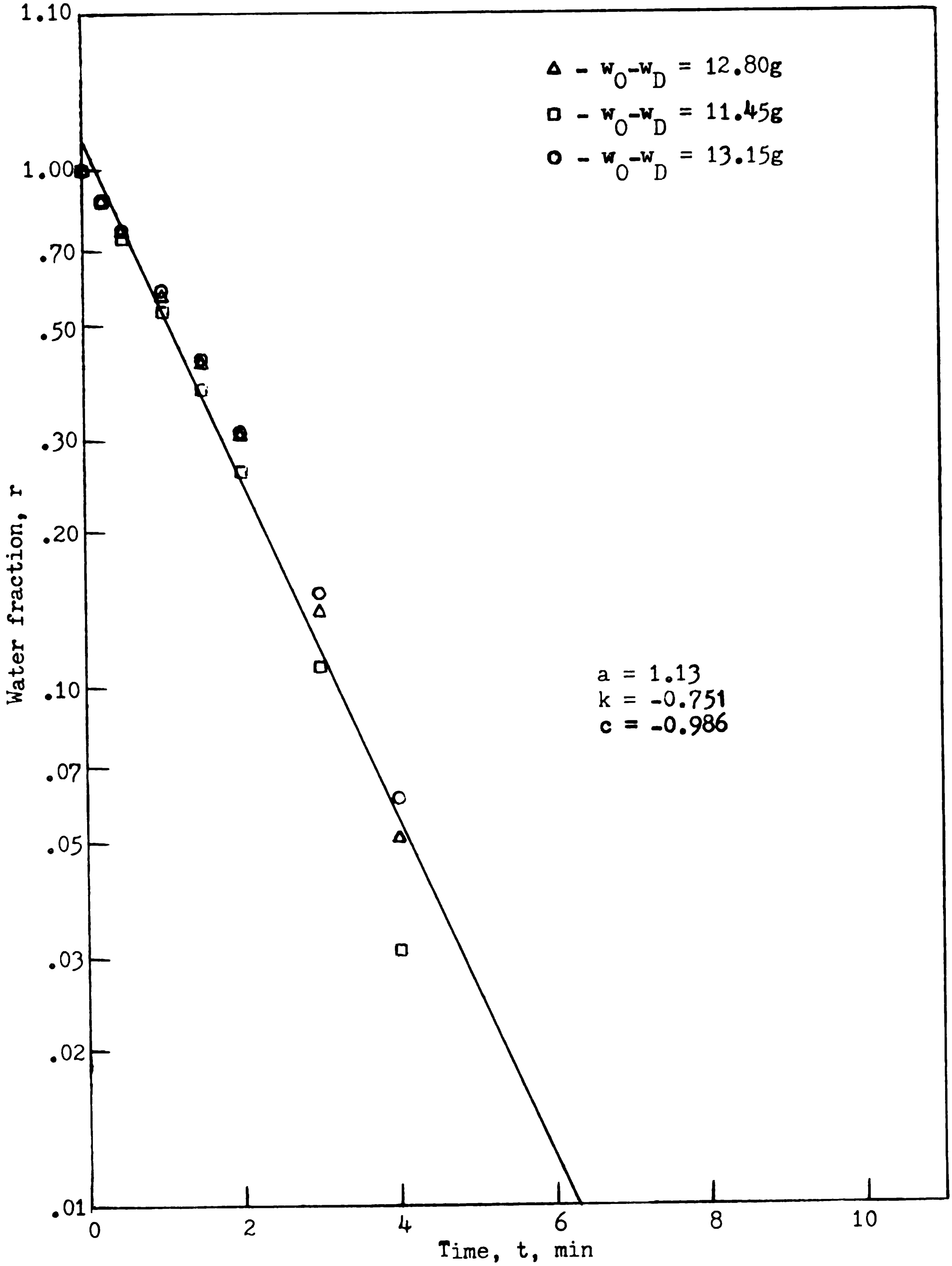


Figure A.9. Determination of surface moisture removal rate constant, k, at air temperature variable of 87^{o}F (constants: $\bar{U}$ = 800 ft/min. T_w = 45 F, RH = 13%).

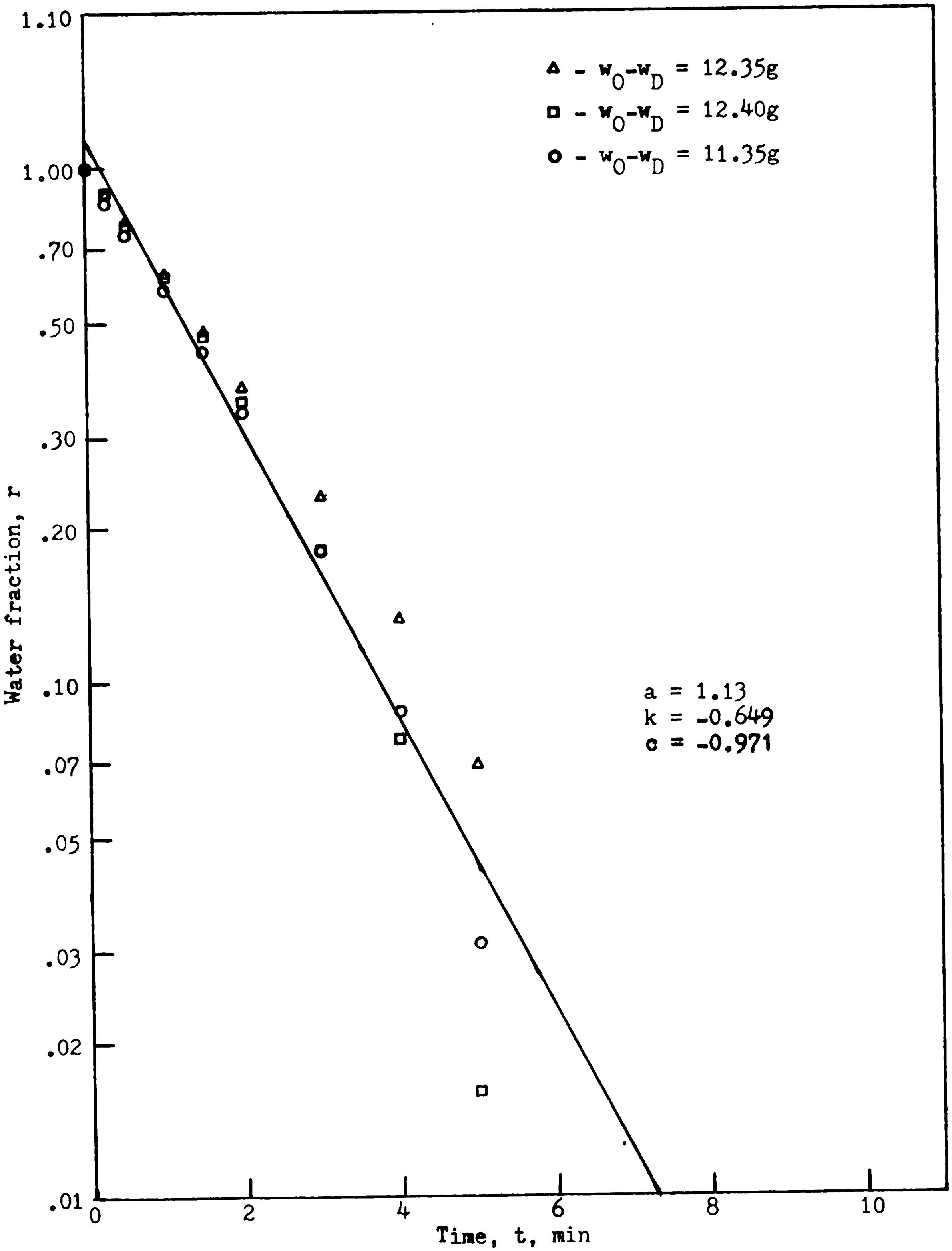


Figure A.10. Determination of surface moisture removal rate constant, k, at relative humidity variable of 16% (constants: U = 800 ft/min. T_w = 45°F, T_a = 76°F).

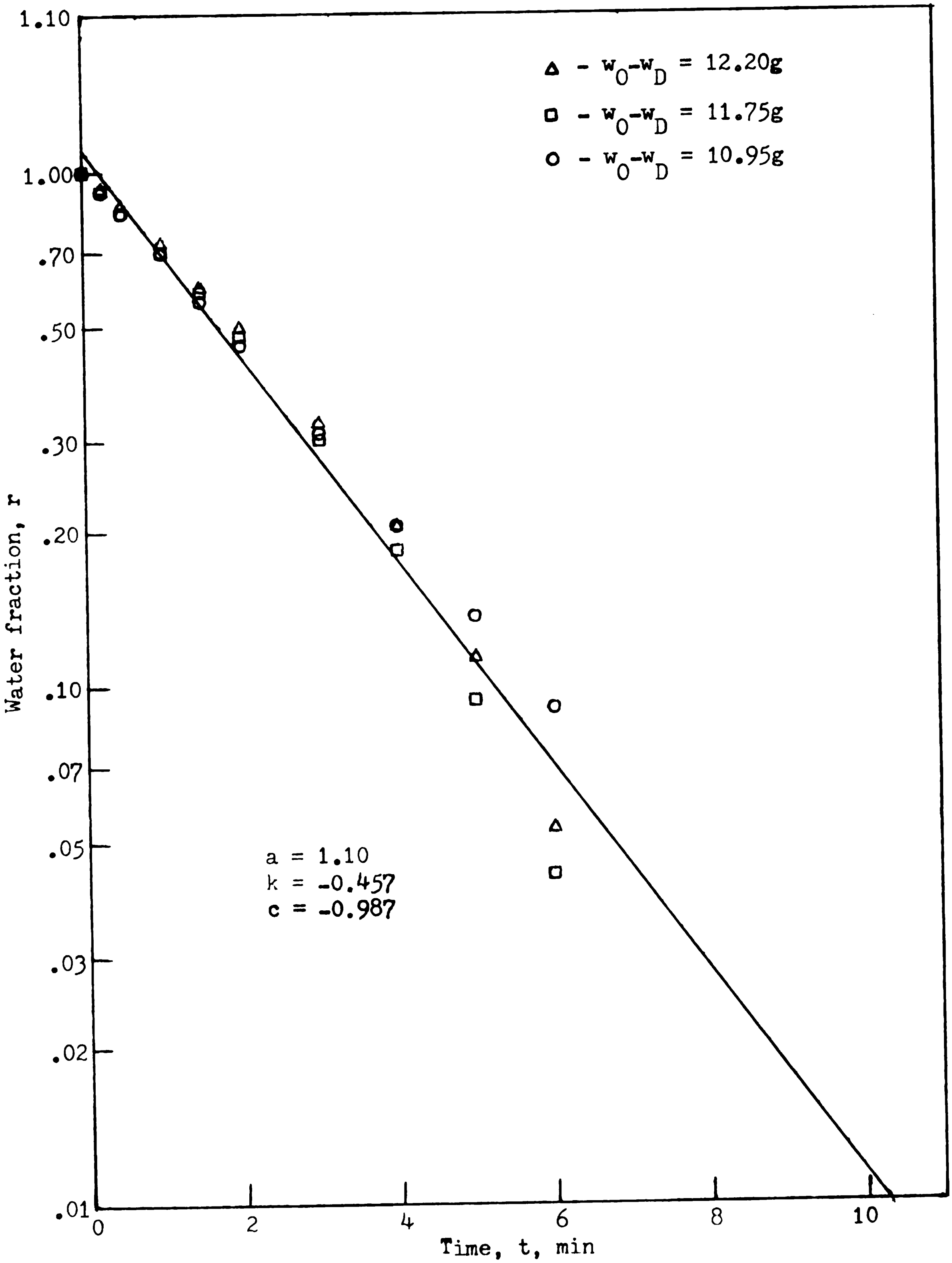


Figure A.11. Determination of surface moisture removal rate constant, k, at relative humidity variable of 36% (constants: $\bar{u}$ = 800 ft/min. T_w = 45^{o}F, T_a = 76^{o}F).

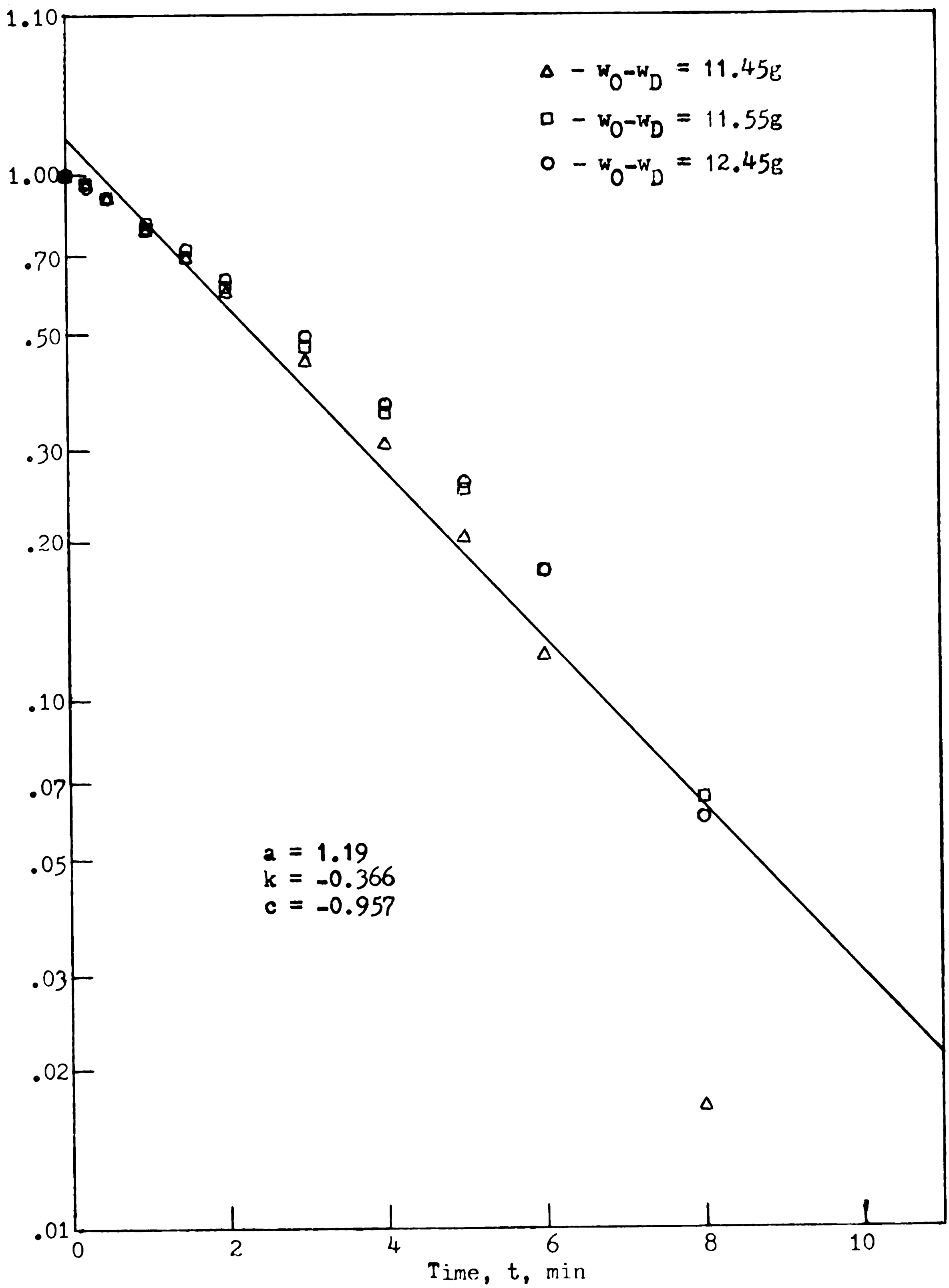
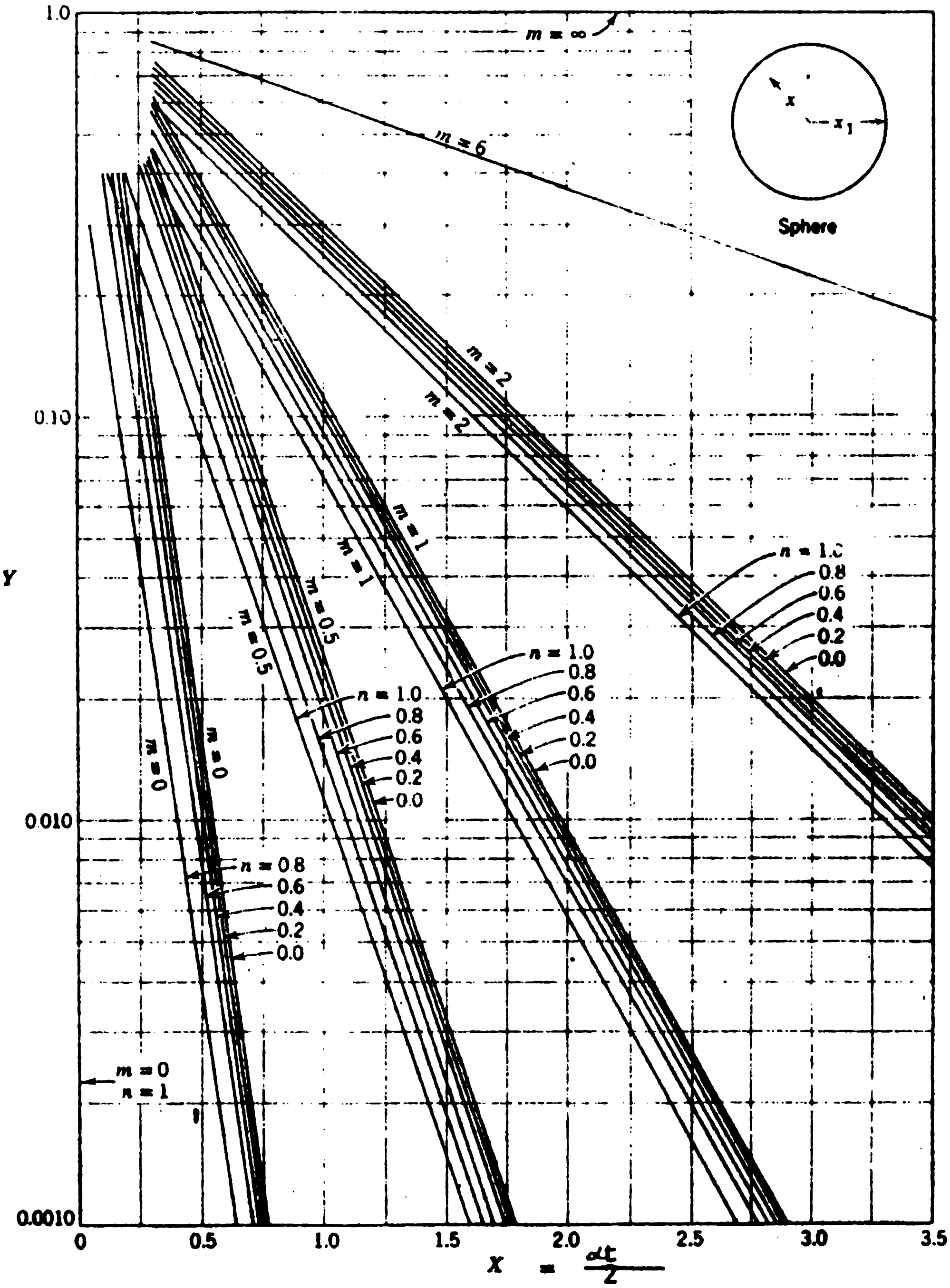


Figure A.12. Determination of surface moisture removal rate constant, k, at relative humidity variable of 50% (constants: $\bar{u}$ = 800 ft/min. T_w = 45°F, T_a = 76°F).



$$\frac{T - T_1}{T_o - T_1} = Y$$

$$n = \frac{X}{X_1}$$

$$m = \frac{k}{h\ X_1}$$

$$X = \frac{\frac{\alpha t}{2}}{X_1}$$

Figure A.13. Unsteady-state temperature distributions in a sphere (Foust et al., 1960).

APPENDIX B

APPENDIX B - CALCULATIONS

Determination of time, t, from Figure A.13 in Appendix A for:

I. Surface temperature of blueberries to decrease to within $1^{o}F$ of the water bath temperature.

II. Initial difference between surface temperature and wet bulb temperature to decrease 50%.

Constants used in both sets of calculations (thermal and density properties of blueberries assumed to be those of water, since blueberries are 85% water):

$k_t = 0.35$ BTU/lb-ft-^{o}F $\rho = 62.6$ lb/ft^3

$C_p = 1.0$ BTU/lb-^{o}F r = 0.0156 ft (3/16 in.)

I. 1) $n = x/x_1 = 1$ (for surface of sphere - blueberry)

2) $m = k_t/(h)(r)$

where h = 100 BTU/lb-ft^2-^{o}F (from Earle 1966)

$m = 0.35/(100)(0.0156)$

$= 0.22$

3) $Y = (T - T_\infty)/(T_o - T_\infty)$

$= (46-45)/(76-45)$

$= 0.032$

4) $X = \alpha t/r^2 = 0.33$ (from Figure A.13 - by interpolation)

$0.33 = \alpha t/r^2 = k_t t/\rho C_p r^2$

$0.33 = 0.35t/(62.6)(1.0)(0.0156)^2$

$t = 0.014$ hr $= 0.84$ min

The time of 0.84 min would be the maximum time for the surface temperature of the blueberries to decrease to within $1^{o}F$ of the water temperature at $45^{o}F$. Increased water bath temperature, T , would result in decreasing this time as the value of Y would increase as indicated in Figure A.13 in Appendix A.

II. 1) $n = x/x_1 = 1$ (for surface of sphere - blueberry)

2) $m = k_t/(h)(r)$

where $h = 1 + 0.21\bar{u}$ (from Earl, 1966)

$= 1 + 0.21(800/60)$

$= 3.80$

$m = 0.35/(3.80)(0.0156)$

$= 6$

3) $Y = 0.5$

4) $X = \alpha t/r^2 = 1.35$

$1.35 = \alpha t/r^2 = k_t t/\rho C_p r^2$

$1.35 = 0.35t/(62.6)(1.0)(0.0156)^2$

$t = 0.059$ hr $= 3.5$ min