ENERGY USE BY REFRIGERATIVE COOLERS
FOR ON-THE-FARM EGG STORAGE

BY

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PREFACE

The experimental work for this thesis research project was performed under the Agricultural Engineering Department as part of Oklahoma Agricultural Experiment Station Project 1001, Design and Performance of Egg Cooling Equipment. The main objective of this thesis was to study the factors involved in cooling eggs on the farm, and relate the factors in such a manner that a prediction equation could be formed. The equation could then be used to predict the amount of energy required to cool eggs under a given set of conditions. The egg coolers used in the tests were designed, constructed, and installed for use by the farm structures section of the Agricultural Engineering Department.

I should like to express my appreciation to Professor E. W. Schroeder for the manner in which all of the facilities of the Agricultural Engineering Department were put at my disposal. I am obligated to Professor George W. A. Mahoney and Jack I. Fryrear for the construction and installation of the two egg coolers used in the tests.

I also gratefully acknowledge the valuable guidance, timely counseling, and keen interest of Gordon L. Nelson, Professor of Farm Structures.

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CHAPTER I

INTRODUCTION

The egg is one of the most complete foods available to man (1), yet the egg is very easily rendered unfit for human consumption by improper handling. The freshly laid egg is at its highest quality, and it is on a continuous downward trend quality-wise until the time it is consumed. The most important interior characteristic of an egg to the consumer is that it have a good flavor. The flavor of a fresh egg is hard to describe, but it is this characteristic that is so vulnerable to the adverse effects of its environment. In the past few years, especially since World War II, the efforts of many researchers have been devoted toward the preservation of egg quality during storage by mechanical refrigeration. At the present, egg producers are the persons most concerned with maintaining high egg quality while the eggs are awaiting marketing because commercial egg producers and middle-men have almost unanimously, out of necessity, adopted the use of the refrigerator-type egg cooler. Many farmers though, due to low production, are not sure that these egg coolers would be an economic advantage.

If the decision is made to use mechanical refrigeration, the producer may select a cooler from the many commercial egg coolers offered for sale, or he may construct his own by following plans that are available through the Extension Service or other sources.

It is believed that egg producers need some kind of guide in in cooler selection. There should be a method of predicting egg cooling costs so as to give some indication to the prospective user as to whether the cooler is economically feasible or not.

"On-the-farm egg coolers" is the phrase generally used to designate that type of egg cooler used to maintain the egg's quality from the time it is gathered until it is marketed. Although egg storage time on the farm varies according to the time between marketings, which is usually relatively short, it is during this time that egg quality declines most rapidly (2).

CHAPTER II

OBJECTIVE

The objective of this study was to find a relationship between the many variables of the egg cooling process, as experienced by producers using mechanical refrigeration for the holding room, and express this relationship as a prediction equation. The equation in turn would be a very effective tool in predicting energy consumption of an egg cooling unit if the other pertinent factors were known.

CHAPTER III

REVIEW OF LITERATURE

In making this study, three primary factors were involved. These were the egg, egg cooler, and environment. Each factor will be discussed and information on each, thought to add to the meaning of the study, will be presented.

The Chicken Egg and Its Environment

The average freshly laid egg weighs about two ounces and has a temperature of approximately 104°F. The two distinct portions of the egg interior are the yolk and the surrounding albumen which are enclosed by the shell. According to Jull (3), the shell comprises eleven per cent of the total egg weight, while the yolk and white contribute 31 and 58 percent of the total weight respectively. The shell is porous, which allows water and gas to pass through rather easily. The egg is at its highest quality when laid, although not all freshly laid eggs are top quality due to defects of its makeup or to inherited undesirable characteristics. The whole egg's specific gravity is about 1.09, while its specific heat is approximately .722 (4).

The egg is a very perishable product and its quality is affected by several factors, as pointed out by Wilhelm (5). The factors that he enumerated were: length of time eggs are stored, temperature of the eggs during holding time, humidity of the surrounding air, and escape of carbon dioxide from the egg. Later, Henderson and Lorenz (6) found that the rate of cooling the eggs also had an influence on quality. Their findings indicated that the more rapid the cooling, the higher the egg quality maintained.

It is generally agreed that the most effective temperature for maintaining the quality of shell eggs is around 28° F. to 30° F., which is just above the freezing point of the albumen. Quality-wise, it would be preferable to hold the eggs at this temperature, but it would seldom be economically practical to do so. Several suggestions regarding temperatures to be maintained in on-the-farm coolers follow, but the optimum temperature is still controversial.

It has been recommended by Bennion and Price (7) that eggs be held somewhere in the temperature range between 40° F. to 50° F. Van Wagenen, Hall, and Altmann (8) stated that 45° F. was the most satisfactory temperature for on-the-farm coolers; whereas, Henderson and Lorenz (6) believed that 55° F. was the most practical. Dawson and Hall (2) merely recommended that the holding temperature be below 65° F.

Although low humidity will lower egg quality, its control does not seem to be as critical as that of temperature, since moisture evaporation rate from the egg is lowered when the egg temperature is dropped. Van Wagenen, Hall, and Altmann (8) found that at 85 per cent relative humidity over a period of time, the loss in egg weight was at a minimum, while the decrease in albumen quality was at a maximum. At 40 per cent relative humidity, there was the least change in all quality measurements except weight loss. It would seem that the optimum relative humidity would be somewhere between these extremes. Rice and Botsford (9) recommended that the relative humidity be from 75 per cent to 80 per cent.

The length of time that eggs are held has a definite effect on their quality at marketing time. Dawson and Hall (2) stated that the quality of eggs deteriorated the most rapidly during the first three days of storage regardless of the temperature. It has been found to be a good practice by many poultrymen to market eggs at least twice a week during the summer.

According to Lorenz (10), at the time he studied the relation of egg quality to rate of cooling, there was no evidence in literature that investigations had been made along this line. There seemed to be two generally held opinions on this subject. One belief was that too rapid cooling was detrimental to egg quality; whereas, the other belief was that eggs should be cooled at the maximum cooling rate in order to uphold quality. With the relative humidity held constant, Lorenz found that contrary to expectation, evaporation from the eggs was least when the eggs were the most rapidly cooled. Quality measurements other than weight loss failed to show significant trends with cooling rate. Due to moisture loss experienced at slow cooling rates, it would seem then that the optimum cooling rate would be the most rapid one economically feasible.

The Egg Cooler

Kinard, Garner, and Hudson (11), at the Agricultural Experiment Station, University of Georgia, have done considerable investigation into the most desirable cooler size commensurate with the laying flock size. Their calculations were based upon a flock production of 60 per cent and the practice of marketing eggs twice a week. Cabinet-type coolers were found to be satisfactory for flocks of under 1,000 birds, while walk-in coolers were recommended for flocks of 1,000 birds or over.

The cooler should be designed so that at the selected holding temperature, the refrigeration unit should not have to run for an excessively long period.

CHAPTER IV

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Egg Cooling Factors

In order to initiate a study on the phenomenon of egg cooling and its accompanying energy consumption, all factors thought to have a possible bearing on the issue were considered.

After some study, it was decided that any worthwhile investigation of this problem would entail the collection of information on the following list of factors.

1. Energy use by the refrigeration unit of the cooler.
2. Number of times the cooler door is opened.
3. Temperature of the eggs at the time of their placement within the cooler.
4. Temperature at which the cooler is maintained.
5. Ambient temperature.
6. Size of the cooler.
7. Design of the cooler (shape and construction details).
8. Time interval between egg gatherings.
9. The amount of eggs deposited in the cooler.
10. Specific heat of the hen egg.
11. Length of time the eggs were stored before marketing.

Egg Cooler Design

The problem of predicting the expense of cooling and holding eggs on the farm was studied by means of observing the performance of two different sized egg coolers. The size of a cooler would certainly determine, in part, the expense of cooling eggs. It is rather apparent that a larger cooler would have more surface area through which heat could pass than a smaller cooler, and the cooling load would be heavier. During 1955 and the early part of 1956, plans for the two coolers were drawn up, their construction completed, and installation was made on the Oklahoma State University poultry farm.

The two coolers, being of different size, simulated service for different sized laying flocks. The cabinet-type cooler, as shown in Figure 1, was recommended for flocks under 1,000 hens (11). Its capacity was six standard 30-dozen egg crates, plus two half-crate capacity gathering baskets. The practice of pre-cooling the crates, flats, and fillers before they were used to hold eggs was followed, and the eggs were not crated until they had been cooled to holding temperature while in the gathering baskets. This procedure does not decrease the cooling load of the cooling unit, but it does result in more rapid cooling of the eggs (6). The cooler's dimensions were roughly 3'x3'x6½'. It was constructed so that its door comprised one entire side of the box and swung back so that all of the cooler's interior was quite accessible. The cooler was equipped with a one-third horsepower refrigeration unit which was mounted in a side wall at the top of the cooler. Since the cooling unit was from an ordinary residence window cooler, its design was not well adapted for saving space in the box. After the cooler was completed, it was installed during March, 1956 in an egg cleaning and

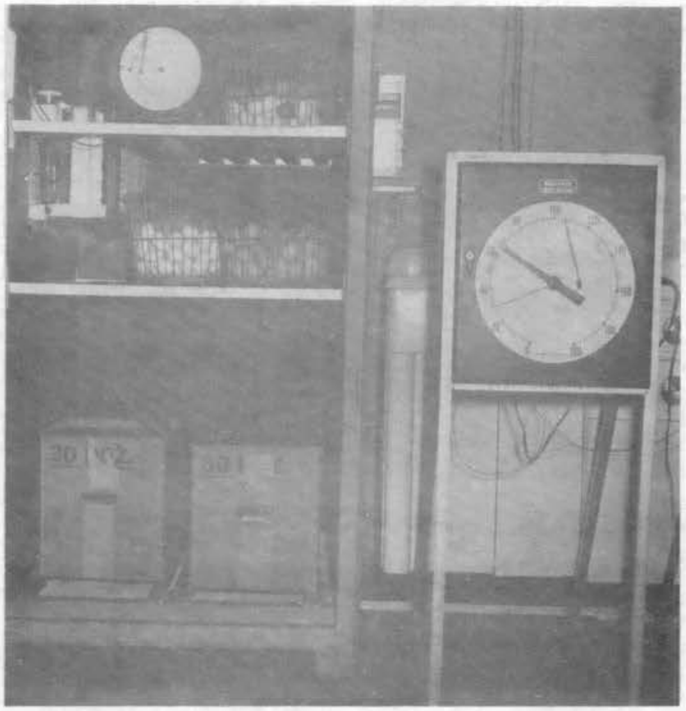

Figure 1. Interior of the Seven-Case Cooler.

Figure 2. Building in which the Seven-Case cooler was placed.

grading room, which was in the building pictured in Figure 2. The room in which it was installed was cooled part of the summer by an evaporative cooling unit.

The larger cooler, as pictured in Figure 3, was a 25-case walk-in type cooler which is the type recommended for laying flocks of 1,000 hens or more. It was installed in the building shown in Figure 4. Its cooling unit was a one-half horsepower residence window cooler. The wall construction of this cooler was very similar to that of the smaller one. As shown by Figure 5, its main difference from the seven-case cooler was that it had a thicker wall with more insulation. The cooler was also constructed so that it could be fairly easily dismantled and relocated. Its dimensions were roughly 6'x6'x6'. It did not have an integral floor and in this particular case, was set on a concrete slab floor. The interior of the cooler was arranged so that cased eggs and/or pre-cooling cases with fillers and flats could be stacked on one side of the room, while a low shelf was provided on the opposite side to accommodate baskets of freshly gathered eggs. The practice of cooling the eggs in baskets before crating them was followed. The cooler was located in the northwest corner of a feed room which was between two compartments that contained laying flocks. See Figure 4. Openings in the feed room were a door and some windows in both the north and south walls. Two sides of the cooler were within six inches of the room's walls.

The design of a cooler includes two other considerations besides size. The shape and the fabrication of the cooler would be influential on the amount of heat gained through the walls. Obviously, the ideal situation would be to have a cooler whose volume/area ratio was equal to the ratio of a sphere which had an equal volume. Insofar as heat

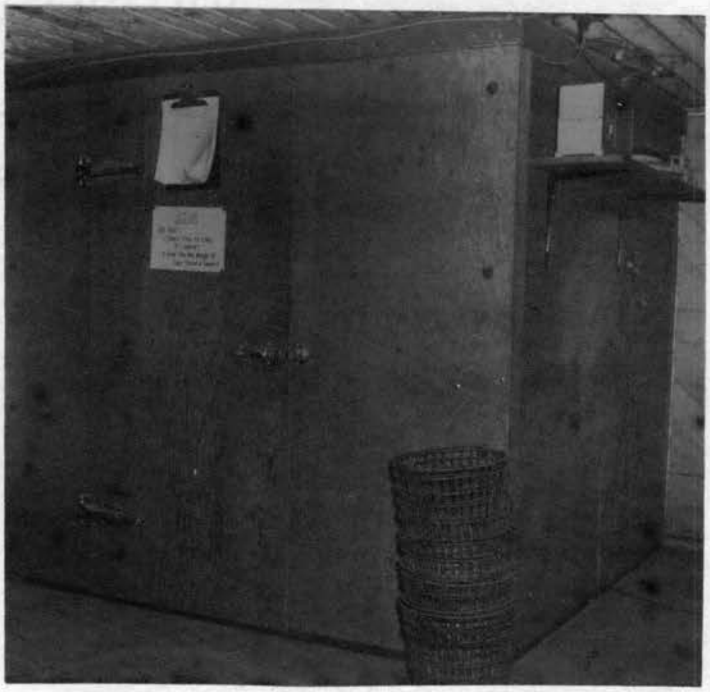

Figure 3. Twenty-five case cooler.

Figure 4. Location of Twenty-five case cooler.

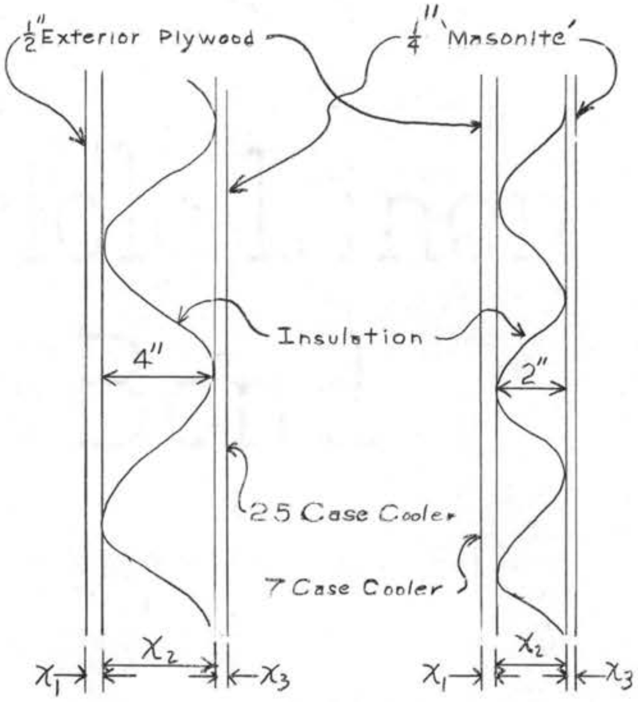

Figure 5. Cross Section of the Walls

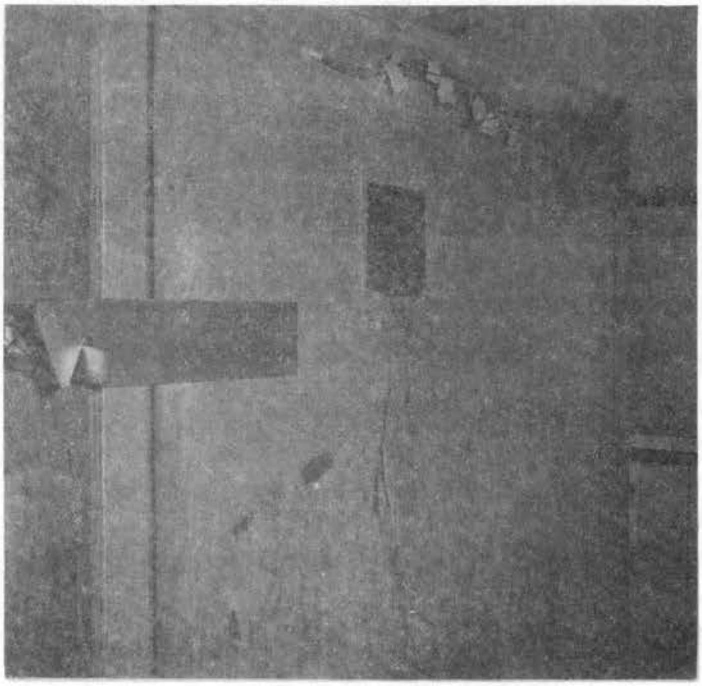

Figure 6. Heat Flow Meter Mounted on the Seven-Case Cooler.

gain is concerned, the type and thickness of insulation were of primary importance, with type and thickness of construction materials secondary. In order to serve as a check, the mean value for the coefficient of heat transmission (U) was determined for each cooler in two different manners. First, it was calculated by using the conventional formula $U = \frac{1}{R_t}$.

$$R_t = \frac{1}{f_i} + \frac{1}{f_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_m}{k_m}$$

Where

U = coefficient of heat transmission — btu/hr-ft^2—deg. F.

R_t = total resistance to heat flow — hr-ft^2—deg. F./btu.

f_i = inside wall surface conductance — btu/hr-ft^2—deg. F.

f_o = outside wall surface conductance — btu/hr-ft^2—deg. F.

($f_o = 1.6 + 0.3v$ v = wind velocity in miles per hour)

x = thickness of wall component — in.

k = thermal conductivity — btu/hr-ft^2-(deg. F./in.)

Since the 25-case cooler was installed on a concrete floor and the ceiling construction details were different from those of the walls, it was necessary to compute U for the ceiling, walls, and floor separately. The three values for U were then used to arrive at a weighted value by using the following formula:

$$U_m = \frac{U_w A_w}{A_t} + \frac{U_c A_c}{A_t} + \frac{U_f A_f}{A_t}$$

w = wall
f = floor
A = area
c = ceiling
t = total
m = mean

Table I lists the values from which U for each cooler was computed. In case of the seven-case cooler, it was only necessary to list one set of values for the walls and floor, as the construction details and surface wind velocities for both were essentially equal. The values were selected as suggested by Severns and Fellows (12).

TABLE I

VALUES USED TO DETERMINE "U"

		Seven-Case Cooler		Twenty-five-Case Cooler		
		Floor & Walls	Ceiling	Walls	Ceiling	Concrete floor
	f_i	1.65	1.65	1.65	1.65	1.65
$f_o = 1.6 + 0.3v$*	f_o	1.6	4.0	4.5	2.8	----
Outside plywood	x_1	0.5	0.5	0.5	0.25	----
Concrete floor	x_1	----	----	----	----	4.00
Insulation	x_2	2.0	2.0	4.0	4.0	----
Masonite	x_3	0.25	0.25	0.25	0.25	----
Fir (plywood)	k_1	0.76	0.76	0.76	0.70	----
Concrete	k_1	----	----	----	----	12
Mineral Wool	k_2	0.27	0.27	0.27	0.27	----
Fiberboard, (Masonite)	k_3	0.34	0.34	0.34	0.34	----

*v = wind velocity in miles per hour

The second method of determining an overall U value for each cooler was by use of the heat-flow meter. It was these values that were later used in applying dimensional analysis. The meter was installed in several different positions on the walls, ceiling, and floor of the 25-case cooler (See Figure 6) and the value for U was determined for each component individually. The 7-case cooler was constructed so that the walls, ceiling, and floor had the same cross-section. The value for U would be the same for each part except that airflow over the parts would vary. The average U value for the different components of the coolers are listed in Table II. Once again, the formula

$$U_m = \frac{U_w A_w}{A_t} + \frac{U_c A_c}{A_t} + \frac{U_f A_f}{A_t}$$

was used to obtain the mean U value. Table III lists the mean U values as determined by the two described methods. It is believed that the disparity in the two derived U values for the 25-case cooler is due to the wide variance in surface wind velocity over the cooler. On two walls the velocity was very low, while about the other walls and ceiling the velocity varied widely. No attempt was made to measure wind velocity.

TABLE II

VALUES FOR "U" AS DETERMINED BY THE HEAT FLOW METER

	Seven-Case Cooler		
	Date	U	$U_{Avg.}$
Ceiling	8/21	.2381	
	8/22	.2480	.2430
Wall	8/24	.0940	
	8/27	.0428	
	8/28	.0784	
	8/29	.680	.0716
	Twenty-five Case Cooler		
East Wall	6/28	.0500	
	6/29	.0428	
	7/2	.0441	
	7/5	.0441	.0452
Ceiling	7/10	.2270	
	7/12	.1639	
	7/11	.1400	.1769
Floor	7/14	.1447	
	7/16	.1686	
	7/17	.1410	
	7/18	.1728	
	7/19	.2117	.1677

TABLE III

COMPARISON OF VALUES FOR THE COEFFICIENT OF HEAT TRANSMISSION (U_m)

	Calculated	Heat Flow Meter
25-Case Cooler	.2220	.0867
7-Case Cooler	.0999	.0893

Egg Gathering and Farm Storage Practices

The manner in which freshly laid eggs are handled could largely determine the cooling load due to the eggs. For instance, if the eggs were gathered only once a day, it is apparent that their average temperature at the time they were put in a cooler would be much lower than the average temperature of eggs which are gathered and put in the cooler every two hours.

It was the practice of the management of the University poultry farm to have an approximate two-hour interval between egg gatherings. The eggs were laid in trap nests, as records were being kept on each hen. The eggs were marketed once a week, on Wednesday, and all eggs gathered on Wednesday were held for marketing until the following week. This is an important point, as it can be readily seen that the length of time the eggs are kept in storage before marketing could largely determine the expense of egg cooling. When warm eggs are placed in a cooler, the load on the cooling unit is comprised of the heat from the eggs, plus the heat that is constantly entering the cooler by conduction through the cooler walls. When the eggs have reached the holding temperature, the only heat that has to be removed from the cooler is the conductive heat. This heat has to be dealt with by the cooling unit whether the cooler be full or empty of eggs. It then follows that eggs marketed directly after being cooled would be the most inexpensively cooled eggs; whereas, the cost of cooling would mount higher, without bound, for eggs that are held indefinitely.

Instrumentation and Collection Of Data

The amount of heat that the eggs contained when placed in the cooler would vary directly as their average temperature. A separate test was run in which the shell and interior temperature was measured with a thermocouple just before the eggs were placed within the cooler. The data recorded from these tests are listed in Tables IV and V of the Appendix. Figures 7 and 8 show the resultant regression curves as determined by Snedecor's method of regression analysis (13). Figure 9 presents the regression of egg interior temperature on ambient temperature. The curve in this Figure was plotted from information taken from Figures 7 and 8. It is hypothesized that the average egg temperature would be greatly influenced by the time interval between gatherings. The time interval is subjective, and is determined by each producer for his particular farm system. It has been suggested by some poultrymen that eggs be gathered three or four times daily (9).

A temperature just above the freezing point of the albumen maintains highest egg quality, but this temperature (28 - 30 degrees F.) would be too low to be practical for on-the-farm cooling, as the expense

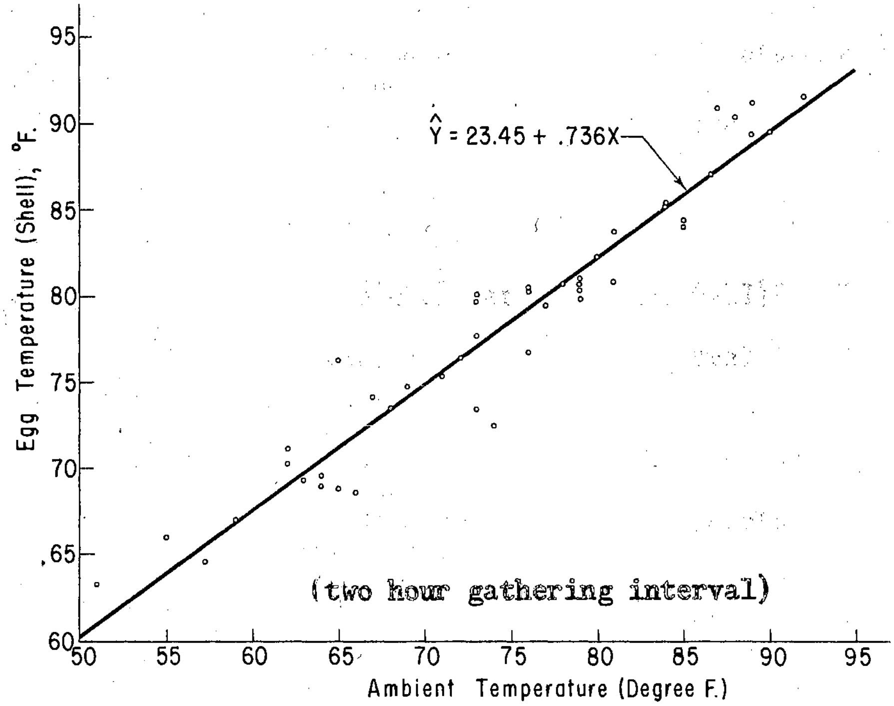

Figure 7. Regression of Egg Shell Temperature on Ambient Temperature.

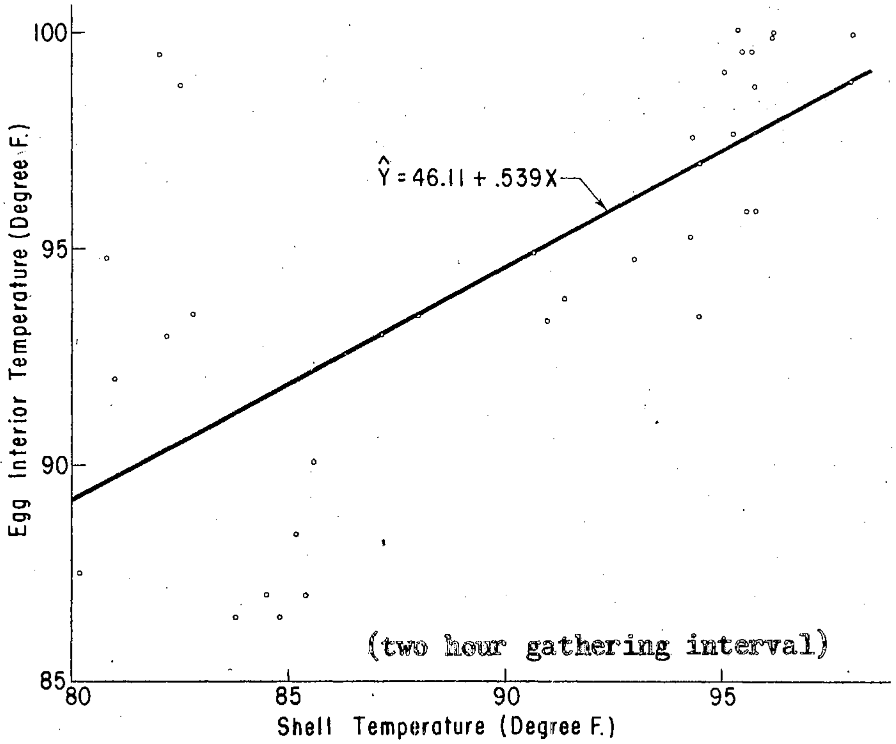

Figure 8. Regression of Egg Interior Temperature on Egg Shell Temperature.

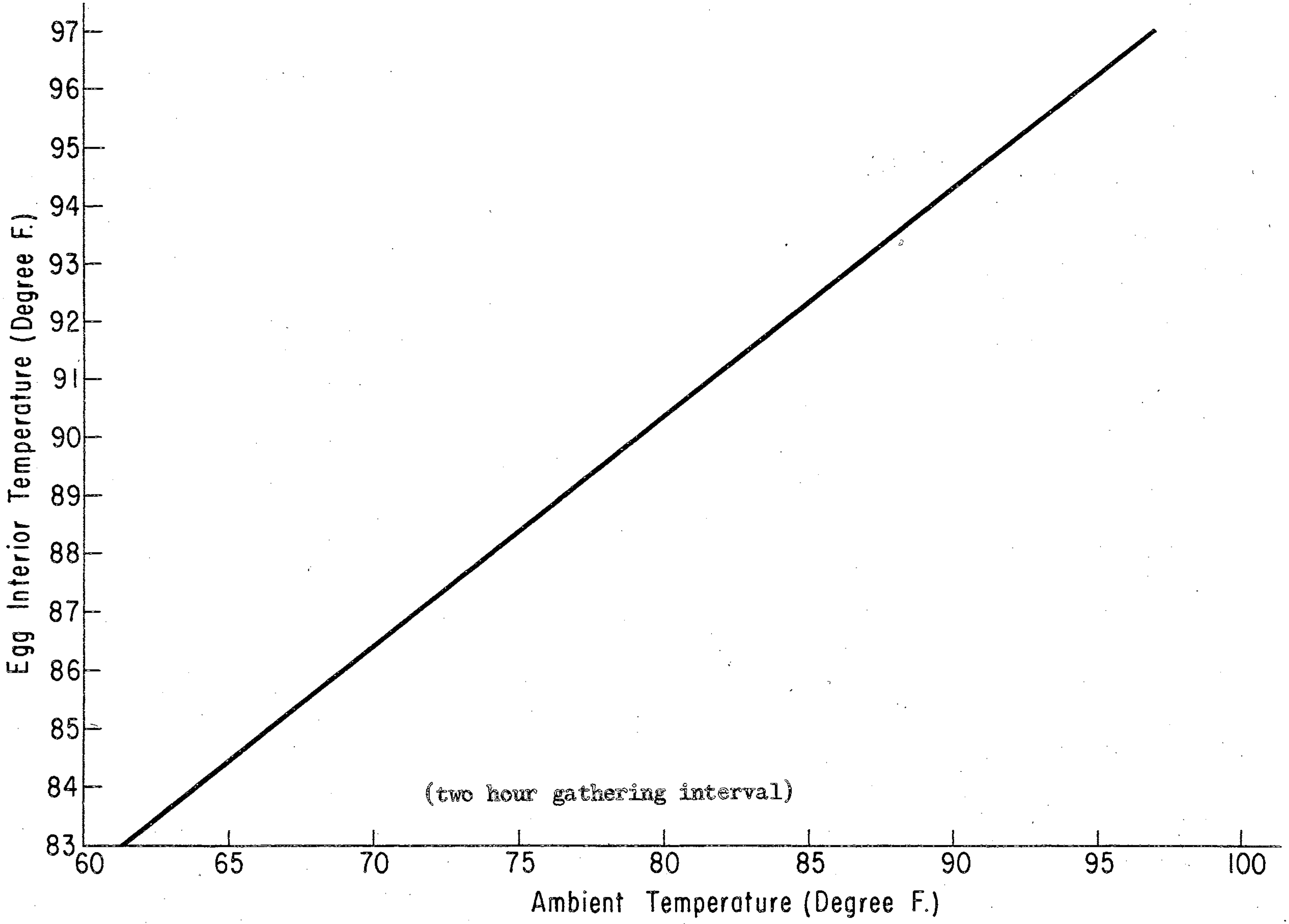

Figure 9. Regression of Egg Interior Temperature on Ambient Temperature.

of constructing a cooler that could reasonably maintain such a temperature would be prohibitively expensive. The temperatures at which the experimental coolers were maintained followed the recommendation of Dawson and Hall (2), and were held close to 60° F. A recording hygrothermograph was installed in each cooler to keep a record of the interior temperatures. It was placed on the top shelf of the 7-case cooler and on the floor of the 25-case cooler. The instrument charts were changed weekly. It is believed that the recorded temperature was representative of the entire box , as the fan blowing air over the evaporator coils of the cooling unit circulated the air within the cooler.

The records of ambient air temperatures were kept by means of hygrothermographs. In case of the 25-case cooler, an instrument was mounted on a shelf that was attached to the outside of the egg cooler, approximately five and one-half feet above the concrete floor on which the cooler was setting. For the 7-case cooler, a hygrothermograph was placed within the egg cleaning and grading room in which the cooler was located, to record the ambient temperature. The ambient temperature would have a direct bearing on egg cooling costs, as the temperature differential across the cooler wall would determine the amount of heat that passes through the wall.

Recording watt-hour meters were used to record the amount of electrical energy consumed by the individual coolers. A record of electrical energy consumption was also made from the daily readings taken from a visual accumulative-type watt-hour meter. This variable (energy consumed) is influenced by the rest of the factors that were discussed above.

In order that the number of cooler door openings per day could be recorded, a form for the door log was drawn up which provided space in which to record the time the door was opened, and the pounds of eggs deposited within, if any. It was believed that the workload of the refrigeration system would be influenced a great deal by the number of times the cooler door was opened because of the interchange of warm and cool air.

CHAPTER V

ANALYSIS OF DATA AND PRESENTATION OF RESULTS

Method of Analysis

Murphy (14), stated that in order for an engineer to successfully build an object, it is desirable that he be able to predict its behavior before it is constructed. Of the three prediction methods that are presently available (formulas based on numerous experiments, experiments on full sized units, or model studies), Murphy only presents additional information on similitude or model study. By means of the theory of similitude and dimensional analysis, performance of a system can be predicted.

The writer is aware that dimensional analysis is not a new concept in analyzing data, but since it is not as widely used as some of the other methods, a word of explanation was thought to be necessary on how the data pertaining to this study was analyzed.

Dimensional analysis is based upon two axioms, as set forth by Murphy (14).

Axiom 1. Absolute numerical equality of quantities may exist only when the quantities are similar qualitatively.

Axiom 2. The ratio of the magnitudes of two like quantities is independent of the units used in their measurement, provided that the same units are used for evaluating each.

As stated elsewhere, the object of this study was to develop a prediction equation whereby the consumption of energy for egg cooling under given conditions may be predicted with reasonable accuracy. This is to be accomplished by means of the Buckingham Pi Theorem. The theorem states, in general, that the relationship among the variables of any phenomenon may be expressed by dimensionless and independent terms whose number must equal the quantities involved, less the number of dimensions used to measure the quantities. Equation-wise, the theorem is expressed by $s = n - b$.

s is the number of dimensionless and independent terms,
n is the total number of quantities involved, and
b is the number of basic dimensions involved.

The dimensionless and independent terms referred to in the general statement of Buckingham's theorem will hereafter be called Pi terms. From the theorem, it follows that if a phenomenon such as egg cooling were described in eight quantities, and the eight quantities were measured in five basic dimensions, it would require three Pi terms to express the relationship of the variables involved. The relationship equation may then be written as $\pi_1 = F(\pi_2, \pi_3)$.

The Pi terms for any phenomenon may be formulated by combining the quantities involved in any manner whatsoever, so long as the terms stay dimensionless and independent.

The Analysis

From the list of factors first thought to be pertinent to the egg cooling process (see page 8), the following quantities were finally selected:

No.	Symbol	Quantity and Usual Dimension	Symbolic Dimension
1	Q	Energy use by cooler in 24 hours--btu/24 hrs.	HT^{-1}
2	Δt_e	Gathering time average egg temperature less avg. cooler temp.--deg. F.	Θ

No.	Symbol	Quantity and Usual Dimension	Symbolic Dimension
3	Δt_c	Average ambient temperature less average cooler temperature--deg. F.	θ
4	λ	Amount of cooler surface--ft^2	L^2
5	U_m	Mean "U" value for cooler, btu/ft^2--deg. F. - hr.	$HT^{-1}L^{-2}\theta^{-1}$
6	ρ	Amount of eggs placed in the cooler in 24 hours--lbs/24 hrs.	MT^{-1}
7	C_e	Specific heat of eggs--btu/lb.-deg. F.	$HM^{-1}\theta^{-1}$

Note that three of the original quantities have been dismissed and that the three temperatures involved have been reduced to two temperature differentials. The three quantities; number of times the cooler door is opened, etc. (see page 8), were omitted after preliminary studies indicated that they were not pertinent to the study.

Analysis of the data was first attempted on a weekly basis, but the results seemed to be inconclusive. Since the temperature and amounts of eggs put in the cooler sometimes varied widely within a week, it was felt that the resultant dimensionless values were not sensitive enough, and that the trend of the data would have been more clearly indicated if the time interval had been twenty-four hours instead of one week. It was decided that the length of time the eggs were stored in the cooler would not be pertinent if more refined Pi terms were obtained by putting the analysis on a 24-hour basis.

The variable of time between egg gatherings was omitted in the final analysis for the following reason. The overall egg temperature would vary somewhat with the time interval between gatherings, but it was felt that this variable was given due consideration by taking into account the difference between cooler and average egg temperature.

For instance, if the egg gathering interval were three hours instead of two hours, the temperature differential would be somewhat smaller.

The number of times the cooler doors were opened was deemed unimportant after the preliminary study indicated that cooler door openings had insignificant effect on the relationship of the other variables. Another conclusion drawn from the trial study was that the length of time they were closed, was insignificant.

The Pi terms formed of the given quantities are as follows:

$$\pi_1 = \frac{Q}{C_e \rho \Delta t_e}$$

$$\pi_2 = \frac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}$$

For each twenty-four hour period of June, July and August, in which precise data could be recorded, values for the four varying quantities ($Q, \rho, \Delta t_c, \Delta t_e$) were determined for each cooler as listed in Tables VI and VII of the Appendix. Q was determined by converting the daily amount of electrical energy used into equivalent btu's. ρ was computed by totaling the amount of eggs entered on the door logs as having been put in the cooler during each twenty-four hour period. Δt_c and Δt_e were determined daily by subtracting the average cooler temperature from the average ambient temperature and average gathering time egg temperature respectively. The values for egg cooling quantity constants for each cooler are listed in Table VIII of the Appendix.

Values for the Pi terms for each cooler were computed and are listed in Table IX. The corresponding values for π_1 and π_2 of each cooler were plotted on the same chart. Separate regression curves and coefficients (B_1 and B_2) were computed for each set of data. The values for the individual regression coefficients for the 25-case and 7-case coolers were .7345 and .8977 respectively. Figure 10 portrays the results of the individual regression analyses as plotted on log-log paper, along with a common regression curve obtained by an analysis of co-variance (See Table X). All statistical analyses was carried out as outlined by Snedecor (13).

Significance was not obvious, and a test of the hypothesis that $B_1 = B_2$ was made by means of the "F" test. From the analysis of co-variance, $F = 5.32$, which corresponds to the 3.1 per cent point in an F table for 1 and 106 degrees of freedom. Hence, there are only about three chances in 100 that two samples will be drawn from populations that are the same that will have a larger value for F. Evidently, the regression coefficients are for populations with different means, i.e., the initial hypothesis is rejected. Although the regression curves do not coincide for the two sets of data, it would seem that by using the common regression curve, $\Pi_1 = 68\,\Pi_2^{.81}$, relatively accurate values for either Pi term may be calculated if the other is known to be within the limits of the extremes of the curve as drawn.

The sought after prediction equation as shown in Figure 10 was

1. $\Pi_1 = 68\ \Pi_2^{.81}$

Since $\Pi_1 = \dfrac{Q}{C_e \rho \Delta t_e}$ and $\Pi_2 = \dfrac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}$ the above equation may be written.

2. $$\frac{Q}{C_e \rho \Delta t_e} = 68 \left(\frac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}\right)^{.81}$$

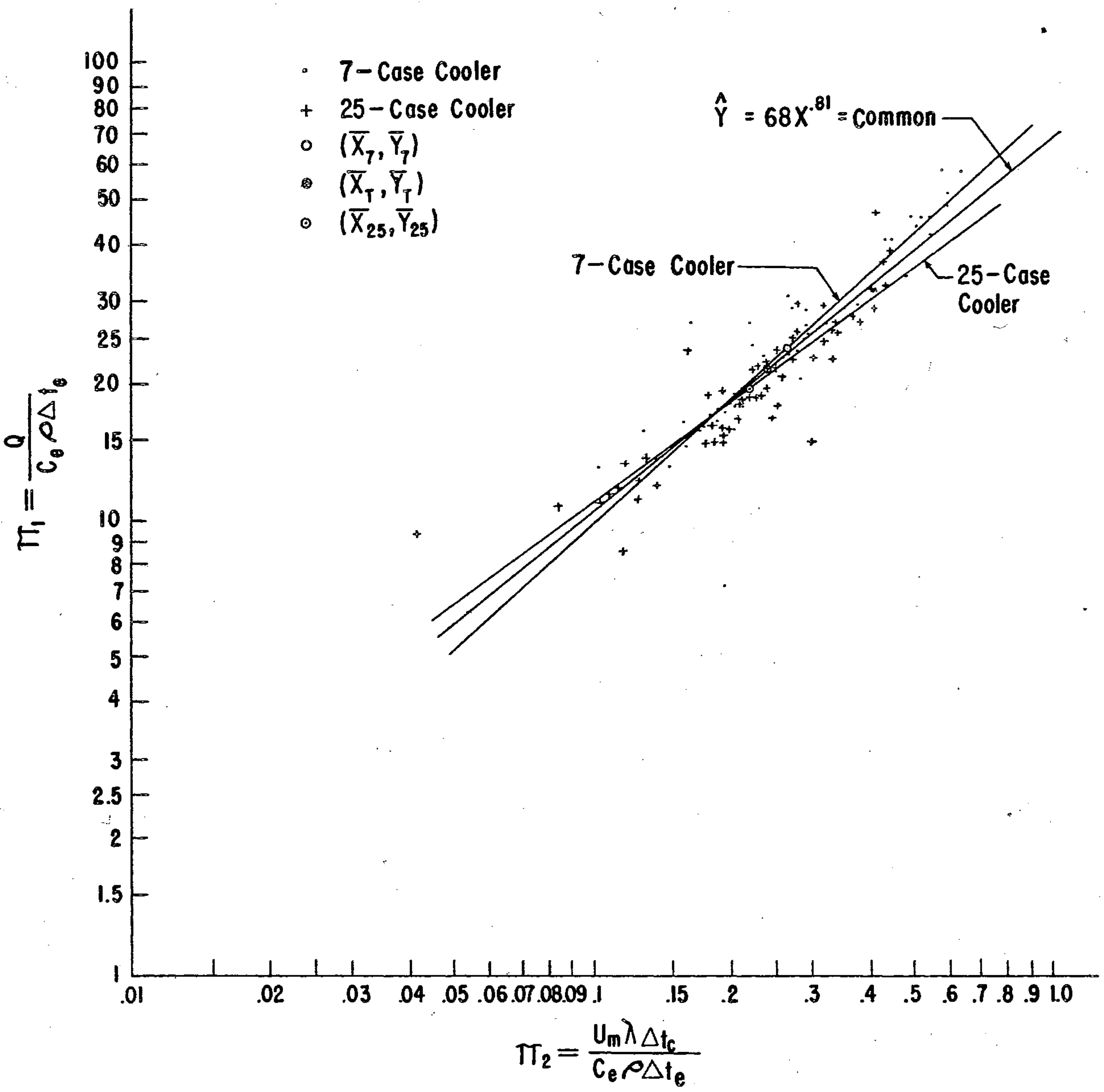

Figure 10. Pi terms as computed from the data of the twenty-five and seven-case coolers.

Since Q, the energy used in cooling eggs, deserves special attention, the equation can also be written

$$3.\quad Q = 68\,(U_m\,\lambda\Delta t_c)^{.81}\ (C_e\,\rho\,\Delta t_e)^{.19}\ .$$

Note that equations 1 and 2 are dimensionless; whereas, equation (3) has dimensions of btu's/24 hours. Equation 3 could be used to predict the amount of energy required for a farm egg cooler before it is built if the other quantities are known. The quantities raised to the .81 power indicate the amount of heat gained through the wall, while those quantities raised to the .19 power indicate the heat load from the eggs. Observe that the value for any one of the quantities involved in the Pi terms may be determined in much the same manner as was done in determining the value for Q.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Because of the growing interest in maintaining the quality of eggs by on-the-farm cooling, a study was made of egg cooling at the Oklahoma State University poultry farm in cooperation with the Poultry Department. A 25-case and a 7-case egg cooler were constructed and installed in different locations on the farm. Data were kept on those factors thought to be pertinent to the egg cooling process, and the subsequent analysis of the data was completed by means of dimensional analysis.

The following conclusions were reached as a result of the study.

1. For an array of factors involved in a phenomenon such as egg cooling, dimensional analysis seemed to be the most efficient method of analyzing the data.
2. Although the data obtained from the 7-case cooler appeared to be significantly different from the data of the 25-case cooler, the regression lines were so similar in slope and elevation that a common regression line was believed to define a relationship that was reasonably accurate. Further, it was felt that this curve could be used for computational purposes with little reservation within the limits of the data range.
3. The variables that were finally selected as being important to this study are as follows:
   (a) The amount of energy used by the coolers.

- (b) The specific heat of a hen egg.
- (c) The ambient temperature at the coolers.
- (d) The temperature at which the cooler interior was maintained.
- (e) The average egg temperature at gathering time.
- (f) The mean heat transfer coefficients of the cooler sides.
- (g) The amount of cooler surface area.
- (h) The amount of eggs deposited within the coolers.

4. Those variables considered, but dismissed as being relatively unimportant were:
   - (a) Time interval between gatherings.
   - (b) Cooler surface efficiency, ie., the volume/surface ratio of the cooler as compared to a sphere of equal volume.
   - (c) The egg average holding period.
   - (d) The number of times that the cooler doors were opened.

5. The prediction equation $\Pi_1 = 68\ \Pi_2^{.81}$ is very versatile, and may be put into many different forms. The cost of egg cooling is of paramount interest to many egg producers, and this may easily be predicted by substituting quantities in the initial equation $\frac{Q}{C_e \rho \Delta t_e} = 68 \left(\frac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}\right)^{.81}$ and solving for Q $Q = 68\ (U_m \lambda \Delta t_e)^{.81}\ (C_e \rho \Delta t_e)^{.19}$.

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APPENDIX

TABLE IV

AVERAGE EGG SHELL TEMPERATURE WHEN PLACED IN EGG COOLER

(Two Hour Gathering Interval)

Date	Ambient Temp. F.	Avg. Egg Shell Temp. F.
April 12	66	68.64
12	74	72.54
12	78	80.80
12	76	80.55
19	63	69.31
19	67	74.16
19	69	74.77
19	68	73.65
26	76	80.30
26	84	85.47
26	88	90.58
26	87	91.03
May 4	65	76.48
4	73	77.71
4	79	79.90
4	79	80.46

TABLE V

EGG SHELL AND INTERIOR TEMPERATURES

(Two Hour Gathering Interval)

Date	Avg. Egg Shell Temp. F.	Egg Interior Temp. F.
May		
10	82.0	84.0
10	83.8	86.5
10	84.5	87.0
10	84.8	86.5
15	81.0	92.0
15	80.2	87.5
15	82.2	93.0
15	82.8	93.5
24	82.5	98.8
24	80.8	94.8
24	80.0	95.0
24	82.0	99.5
June		
15	85.6	90.1
15	85.2	88.4
15	85.4	87.0
15	85.0	85.2
18	91.0	93.4
18	91.4	93.9
18	96.2	100.0
18	96.2	99.9
20	95.1	99.1
20	95.5	99.6
20	94.4	97.6
20	94.3	95.3
21	93.0	94.8
21	95.4	100.1
21	95.8	95.9
21	95.6	95.9
22	95.8	98.8
22	95.3	97.7
22	98.1	100.0
22	98.8	102.0

TABLE VI

EGG COOLING QUANTITY VALUES FOR TWENTY-FOUR HOUR PERIODS (TWENTY-FIVE CASE COOLER)

Date	Q Energy Use---BTU	ρ Lbs. of Eggs Put In Cooler	Δt_e Egg Temp. - Cooler Temperature	Δt_c Ambient Temp. - Cooler Temperature
June				
1	23,222.0	120.22	26.7	5.5
4	32,101.0	134.64	29.0	13.5
5	32,442.5	134.98	28.7	16.5
6	36,540.5	111.82	31.4	17.0
7	38,589.5	131.44	31.4	21.0
8	34,491.5	130.34	31.0	20.5
11	35,857.5	129.64	31.4	18.0
12	34,833.0	127.72	32.2	19.5
13	35,857.5	128.76	31.0	18.5
14	30,735.0	109.18	30.4	19.0
15	34,833.0	107.58	30.4	17.5
18	40,980.0	103.28	34.6	27.0
19	41,321.5	105.38	34.6	26.0
20	45,761.0	106.08	34.6	27.0
21	45,419.5	103.58	34.6	27.0
22	42,346.0	103.46	35.4	28.5
25	39,955.5	83.04	34.6	24.5
26	38,931.0	84.64	31.0	20.5
27	39,272.5	89.88	34.4	26.0
28	34,150.0	84.48	29.4	25.5
29	39,614.0	87.88	30.8	19.5
July				
2	40,980.0	98.58	33.6	26.0
9	32,442.5	87.74	31.2	21.5
12	44,736.5	81.64	33.6	25.0
13	47,468.5	95.44	35.0	29.0
16	44,053.5	87.16	35.4	27.5
17	36,199.0	86.76	31.8	27.5
18	39,955.5	85.56	33.4	24.5
19	35,516.0	75.64	31.4	23.0
20	34,833.0	84.76	33.4	22.5
23	33,467.0	62.96	31.4	18.5
24	39,955.5	66.86	33.0	22.5
25	44,395.0	64.06	35.8	27.0
26	47,468.5	77.18	36.6	28.5
27	46,444.0	74.68	35.0	29.0
30	39,955.5	58.94	35.4	28.0
31	50,542.0	71.58	35.4	28.5

TABLE VI (Continued)

Date	Q Energy Use---BTU	ρ Lbs. of Eggs Put In Cooler	Δt_e Egg Temp. - Cooler Temperature	Δt_c Ambient Temp. - Cooler Temperature
Aug.				
1	52,591.0	71.46	38.4	30.5
2	46,785.5	87.06	37.6	30.0
3	48,151.5	86.78	38.4	31.0
6	49,176.0	77.66	40.8	34.0
7	48,834.5	69.16	40.4	34.0
10	41,663.0	57.46	36.4	30.0
13	47,127.0	55.96	40.4	35.0
14	59,079.5	49.86	40.0	35.5
15	49,517.5	48.56	40.4	35.0
16	58,055.0	49.46	41.2	35.5
17	78,886.5	52.26	41.6	36.5
20	30,052.0	55.96	30.1	11.0
21	26,295.5	36.36	31.7	13.0
22	35,857.5	44.74	35.6	20.5
23	40,638.5	43.26	38.0	27.0
24	38,931.0	44.34	39.2	28.5
27	40,297.0	50.02	36.8	27.5
28	46,444.0	63.76	38.4	32.0
29	44,053.5	55.96	37.2	28.0
30	45,761.0	66.36	39.7	34.5
31	31,759.5	82.26	33.6	19.5

TABLE VII

EGG COOLING QUANTITY VALUES FOR TWENTY-FOUR HOUR PERIODS (SEVEN-CASE COOLER)

Date	Q Energy Use——BTU	ρ Lbs. of Eggs Put In Cooler	Δt_e Egg Temp. - Cooler Temperature	Δt_c Ambient Temp. - Cooler Temperature
June				
1	12,635.5	38.18	29.7	23.0
4	15,367.5	40.08	34.0	28.5
5	12,635.5	37.78	32.7	27.5
6	16,733.5	39.28	33.4	29.0
7	20,148.5	37.28	34.4	35.5
12	13,660.0	34.28	34.2	26.5
13	14,343.0	35.38	33.0	25.0
14	12,294.0	33.28	32.4	22.0
15	12,977.0	32.48	32.4	22.5
18	16,733.5	27.12	36.6	31.5
19	15,709.0	31.68	36.6	30.0
20	17,416.5	27.48	36.6	33.5
21	17,075.0	23.68	36.6	35.0
25	15,709.0	20.32	31.5	31.5
26	14,343.0	26.60	33.0	27.5
27	16,050.5	20.46	37.4	33.5
28	11,269.5	21.66	32.4	19.0
29	14,684.5	21.36	33.8	23.0
July				
2	13,318.5	20.28	36.6	25.5
9	11,952.5	38.14	34.2	15.5
12	14,684.5	29.70	37.6	25.5
13	15,026.0	31.50	38.0	27.0
16	16,050.5	32.90	39.4	30.5
17	15,026.5	31.80	35.8	29.0
18	15,367.5	32.30	-----	-----
19	13,318.5	32.30	-----	-----
20	11,952.5	29.70	35.4	16.0
23	12,977.0	32.60	33.4	20.5
24	14,001.5	28.60	36.0	24.5
25	13,318.5	35.40	39.8	22.0
26	14,343.0	17.70	40.6	23.5
30	12,635.5	9.48	39.4	25.0
31	14,343.0	9.08	39.4	25.5
Aug.				
1	11,611.0	19.20	39.4	26.5
2	13,660.0	10.08	38.6	26.0
3	14,343.0	10.38	38.4	24.5
6	14,001.5	10.78	40.8	24.0

TABLE VII (Continued)

Date	Q Energy Use---BTU	ρ Lbs. of Eggs Put In Cooler	Δt_e Egg Temp. - Cooler Temperature	Δt_c Ambient Temp. - Cooler Temperature
Aug.				
7	14,001.5	10.98	40.4	25.0
10	13,660.0	9.38	37.4	25.5
13	14,343.0	9.88	41.4	27.0
14	16,392.0	9.08	41.0	26.5
15	14,684.5	10.68	41.4	27.5
16	15,709.0	11.18	42.2	28.0
17	14,343.0	10.48	42.6	30.0
20	11,269.5	15.78	30.1	16.0
21	9,220.5	13.68	31.7	9.0
22	11,611.0	15.68	35.6	15.5
23	13,660.0	18.68	37.0	20.0
24	13,318.5	19.88	39.2	23.5
27	14,343.0	18.86	37.8	26.0
28	16,733.5	30.98	39.4	30.0
29	15,026.0	31.38	37.2	27.5
30	16,392.0	40.80	39.7	30.0
31	11,611.0	30.48	33.6	21.0

TABLE VIII

CONSTANT EGG COOLING QUANTITIES

Symbol	7-Case Cooler	25-Case Cooler
U_m	.0893	.0867
λ	68.56 ft^2	220 ft^2
C_e	.772	.772

TABLE IX

PI VALUES FOR THE TWENTY-FIVE CASE AND SEVEN-CASE EGG COOLERS

Twenty-Five Case Cooler			Seven-Case Cooler	
II_1 $\frac{Q}{C_e \rho \Delta t_e}$	II_2 $\frac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}$	DATE	II_1 $\frac{Q}{C_e \rho \Delta t_e}$	II_2 $\frac{U_m \lambda \Delta t_c}{C_e \rho \Delta t_e}$
		June		
9.37	.042	1	16.05	.179
10.64	.085	4	17.12	.194
10.84	.105	5	15.09	.201
13.47	.119	6	17.57	.186
12.11	.126	7	22.29	.240
11.05	.125	8	------	-----
11.34	.109	11	------	-----
8.59	.117	12	16.03	.190
11.64	.114	13	16.94	.180
11.99	.141	14	15.74	.172
13.80	.132	15	17.02	.180
14.85	.186	18	23.10	.266
14.68	.176	19	18.19	.217
16.15	.182	20	23.72	.279
16.41	.186	21	26.99	.339
14.97	.193	22	------	-----
18.01	.210	25	28.94	.355
19.22	.193	26	22.53	.264
16.45	.208	27	29.53	.377
17.81	.254	28	22.92	.236
18.95	.178	29	28.91	.277
		July		
16.02	.194	2	25.31	.296
15.35	.194	9	13.01	.103
21.12	.225	12	19.06	.202
18.40	.214	13	7.20	.194
18.49	.220	16	17.85	.208
16.99	.246	17	19.24	.227
18.10	.212	18	------	-----
19.37	.239	19	------	-----
15.94	.196	20	15.60	.128
21.93	.231	23	16.42	.158
23.45	.252	24	19.21	.206
25.07	.291	25	13.61	.137
21.76	.249	26	28.68	.287
23.01	.274	27	------	-----

TABLE IX (Continued)

Twenty-Five Case Cooler			Seven-Case Cooler	
II_1	II_2	DATE	II_1	II_2
23.01	.274	27	----	----
25.81	.331	30	48.76	.589
25.84	.278	31	57.80	.629
		Aug.		
24.83	.274	1	20.40	.285
18.51	.226	2	46.68	.544
18.72	.231	3	46.61	.487
20.35	.265	6	41.23	.432
22.64	.300	7	40.88	.447
25.80	.340	10	51.82	.592
27.00	.382	13	46.54	.536
38.37	.439	14	58.46	.578
32.55	.438	15	44.08	.505
36.90	.430	16	34.10	.482
47.00	.414	17	42.61	.545
23.47	.161	20	30.73	.267
29.54	.278	21	27.54	.164
29.16	.318	22	26.94	.220
32.02	.406	23	24.96	.223
29.01	.404	24	22.13	.239
28.35	.368	27	26.76	.297
24.57	.322	28	18.22	.200
27.41	.332	29	16.67	.187
22.50	.323	30	13.11	.147
14.88	.300	31	14.66	.162

TABLE X

ANALYSIS OF COVARIANCE

Line	No. of Cases	d.f.	Σx^2	Σxy	Σy^2	Reg. Coef.	Deviations From Regression		
							d.f.	$\Sigma y^2 - (\Sigma xy)^2/\Sigma x^2$	Mean Square
1	7	51	2.03208	1.82420	1.97535	.8977	50	.33777	.00676
2	25	57	2.26016	1.66016	1.44839	.7345	56	.22888	.00409
3	Within						106	.56665	.00535
4	Reg. Coef.						1	.02847	.02847
5	Common	108	4.29224	4.29224	3.42374	.8118	107	.59512	.00556

7-Case $= \Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2} = 1.97535 - \frac{(1.82420)^2}{2.03208} = 1.97535 - 1.63758$

$= 0.33777$

25-Case $= 1.44839 - \frac{(1.66021)^2}{2.26016} = 1.44839 - 1.21951 = .22888$

Common $= \Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2} = 3.42374 - 2.82862 = 59512$

$F = \frac{.02847}{.00535} = 5.3214$, d.f. = 1,106

Significance level = 3%

VITA

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