110
514
THS

THESIS

3 1293 10064 3745

LIBRARY
Michigan State
University

This is to certify that the

thesis entitled

AN EVALUATION OF THE SUMMERTIME USE OF AN AIR

MEDIUM SOLAR COLLECTOR IN DRYING POULTRY EXCRETA

presented by

Ronald James Haney

has been accepted towards fulfillment
of the requirements for
Master of Science degree in

Agricultural Engineering Technology

Merle L. Esmay
Major professor

Date JAN 3, 1980

O-7639

AN EVALUATION OF THE SUMMERTIME USE OF AN AIR MEDIUM SOLAR COLLECTOR IN DRYING POULTRY EXCRETA

by

Ronald James Haney

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1979

ABSTRACT

AN EVALUATION OF THE SUMMERTIME USE OF AN AIR MEDIUM SOLAR COLLECTOR IN DRYING POULTRY EXCRETA

by

Ronald James Haney

A 90.6 m^2 flat plate, single air pass solar collector was used to provide more than 400 MJ of heat energy on 65 percent of the summer test days. Two different systems were employed in delivering the heated collector air over the excreta. With the tent system, 15 percent of the total excreta water (an average 72 kg) was evaporated on a daily basis, while with the perforated tube system, 25 percent of the total excreta water (an average 113 kg) was evaporated daily in 1977, and 23 percent (an average 90 kg) in 1978. Equations were developed to predict each collector and dryer performance from given weather data. The results of this study should apply to the use of solar heated air for drying material other than poultry excreta, while that material is above the critical moisture content.

Approved by

Merle L. Esmay
Major Professor

Richard H. Fiuler
Department Chairman

This thesis is dedicated

to my wife

Denisse

ACKNOWLEDGMENTS

The author wishes to express his thanks to:

Dr. M. L. Esmay for his guidance, encouragement, and helpful suggestions as major professor;

Dr. D. E. Linvill for his extra help with instrumentation and data acquisition, and for serving on the committee;

Dr. C. J. Flegal for his helpful cooperation throughout the research, and for serving as a committee member;

and to the graduate students of the Agricultural Engineering Department for their support.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Traditional methods of handling, storing, and disposing of poultry excreta have resulted in pollution problems. Zindel et al. (1977) stated that these problems have been brought into sharp focus recently, with the increased concentration of large poultry enterprises, the decline of public acceptance of animal waste odors, and legislation to limit or prevent environmental contamination. For these reasons, they indicated that new, pollution-free alternative disposal systems must be developed for today's poultry farmers.

Daily drying of poultry excreta is one possible alternative. Zindel et al. (1977) indicated that poultry excreta can be made into a valuable by-product feed or fertilizer, once most of the water has been removed. The process of drying excreta requires a great deal of energy input, however. Since the continued availability of fossil fuels is becoming more uncertain, investigation into alternative sources of energy for drying is now necessary.

Unutilized heat in the exhaust ventilation air from livestock houses may be used as an alternative energy source for drying excreta. Muiruri (1976) reported the use of ventilation air within a poultry house, exhausted ventilation air, and recirculated ventilation air, to maximize drying of excreta before final dehydration in a mechanical dryer. The research facility was the same as described in this study, less the solar collector and associated ducts. Muiruri found that 42% of the excreta water could be evaporated by ventilation air inside the poultry house.

He reported that an additional 7% of total excreta water was removed during movement of the excreta from the poultry house to a drying tunnel. While exhaust ventilation air was directed over the excreta in the drying tunnel for 24 hours, an additional 24% of the excreta water was removed. This amounted to an average excreta moisture reduction of 73%. The original voided moisture content or mass of excreta involved was not reported.

Recently, other researchers have applied solar energy to the drying of poultry excreta. DeBaerdemaeker and Horsfield (1976) employed a light greenhouse type sun drying structure with a mechanical stirring device to reduce the moisture content of 6,700 kg of excreta from 60% wet basis to 22%, in three sunny days in Southern California. This amounted to a reduction of 3,260 kg of water, or about 77% of the total water in the excreta.

In Mississippi, Brown and Forbes (1976) designed and tested a more involved counter-flow moving belt dryer, which received heated air from a 66.9 m^2, flat plate air medium solar collector tilted 15 degrees from the horizontal. The solar dryer removed an average 59% of the total excreta water in one run through the dryer (50 minutes residence time), and 81% in two runs (100 minutes residence time), during sunny test days.

1.1 Objectives

The purpose of this research was to utilize solar energy for drying excreta in an existing handling-drying system. Heat was supplied from a solar collector designed to provide supplemental heat to the poultry house in the cold winter months. One objective was to use the collector on a year-round basis to dry excreta during the warm summer months. The various weather conditions of the Michigan summer were studied.

Specifically, the objectives were to:

1. Determine the amount of daily heat energy available from the existing solar collector, during the summer months.
2. Determine the efficiency of the solar collector during the summer months.
3. Evaluate the effectiveness of two systems used to distribute heated air from the solar collector to the poultry excreta.
4. Make recommendations for the design of an optimal system to incorporate heated air from a solar collector into an excreta handling system.

1.2 Drying Theory

Wells (1972) performed laboratory tests and developed drying rate equations for deposited poultry excreta. He stated that the process of completely drying fresh poultry excreta is complex. He found, however, that a large portion of the moisture may be removed during the constant rate drying period. This was because at the extremely high initial moisture content (80% wet basis) a large portion of the moisture was free water. Sobel (1969) showed that the constant rate drying process applied to poultry excreta above 30% moisture content wet basis. Since all daily moisture content samples collected during this study contained more than the 30% critical moisture content, the constant rate drying process was assumed to prevail.

The constant rate process was explained by Wells (1972) as a transfer of heat from air to a liquid, and a transfer of a vapor away from the excreta surface. The rate of transfer depends on the driving force or potential (temperature difference) and the conductance of air through the material. Therefore, Ohm's law applies.

For heat transfer:

$$Q = h_c(t_1 - t_2)$$

where h_c = Conductance coefficient

$(t_1 - t_2)$ = The driving force

For mass transfer:

$$\dot{m}'' = h_d(H_1 - H_2)$$

where h_d = Conductance coefficient

$(H_1 - H_2)$ = The driving force

Kays (1966) stated that the conductance coefficients are essentially aerodynamic properties of the system, whereas the terms within the parenthesis, the potential differences, are essentially thermodynamic properties. The rate of evaporation from the saturated surface is completely determined by the rate at which water vapor can be transferred through the film layer of air adjacent to the wet surface and mixed with the main air stream. Thus, during constant rate drying the rate of evaporation is completely independent of the drying body, but rather is totally dependent on the characteristics of the environment surrounding the body.

Wells identified five alternatives for increasing poultry excreta drying rates:

1. Dehumidify the drying air
2. Increase dry bulb temperature of the drying air
3. Increase the mass flow rate of the drying air
4. Increase surface area of excreta exposed to the drying air
5. Increase evaporative surface temperature

While Wells' work was valuable in establishing drying rates under controlled drying conditions, it did not describe drying under varying weather conditions.

Dixon (1979) formulated a computer excreta drying model for the poultry house involved in this study. His model would predict the amount of water removed from the excreta by the ventilation air with given psychrometric data outside and within the poultry house. He adapted the sensible heat balance equation, Structures and Environment Handbook (1976):

$$Q_b + Q_a + Q_e + Q_m + Q_v = 0$$

where Q_b = Heat flow through exterior building surfaces, cal/hr

Q_a = Sensible heat from housed animals, cal/hr

Q_e = Heat from moisture evaporated or condensed, cal/hr

Q_m = Heat from mechanical systems and lighting, cal/hr

Q_v = Heat from temperature change in ventilating air, cal/hr

Dixon pointed out that each element of this equation except Q_m was a function of inside temperature, and that inside temperature could be estimated, once the physical parameters of the building, management practices, and flock size were known.

Dixon employed the equation to describe a moisture balance for the ventilating air:

$$M_o + M_r + M_m + M_w + M_v = 0$$

where M_o = Moisture in incoming ventilating air, g/hr

M_r = Moisture from animal respiration, g/hr

M_m = Moisture evaporated from excreta, g/hr

M_w = Moisture evaporated from waterers, g/hr

M_v = Moisture in outgoing ventilation air, g/hr

Dixon identified M_v as the only element of the equation associated with removing moisture from the system, but indicated that M_v was equal to the sum of the other elements.

The mass of moisture evaporated from the excreta (M_m) was calculated from the water removal equation:

$$M_m = A_m m_r \theta + I$$

where A_m = Surface area of the excreta, cm^2

m_r = Constant drying rate of excreta, g/cm^2-hr

θ = Time span, hrs

I = Moisture evaporated due to excreta energy level when voided.

Perry et al. (1963) estimated the constant drying rate (m_r) as:

$$\frac{dW}{d\theta} = h_t A(t-t_s')/\lambda$$

where $\frac{dW}{d\theta}$ = Drying rate, g of water/hr

A = Surface area, cm^2

λ = Latent heat of evaporization at t_s', cal/g

t = Dry bulb temperature, °C

t_s' = Temperature of evaporating surface, °C

h_t = Total heat transfer coefficient, $cal/hr\text{-}cm^2\text{-}°C$.

Perry et al (1963) reported that $h_t = h_c$, when heat was transferred by convection only. They also gave $h_c = \alpha G^n/D_c^m$

where h_c = Convective heat transfer coefficient, $cal/hr\text{-}cm^2\text{-}°C$

G = Mass velocity, $g/hr\text{-}cm^2$

and α, m, and n = Constants.

Dixon et al. (1977) determined the constants to be:

n = 0.40

α = 0.63

m = 0.60

for poultry excreta with a flat surface, and air moving parallel with the surface.

Dixon's model utilized an iterative process to calculate the amount of moisture removed from the poultry house with weather data given. He concluded that his simulation model satisfactorily described the in-house hot weather drying, as it agreed with the verification data.

2. EXPERIMENTAL FACILITIES

2.1 Solar Collector

Figure 2.1 shows the commercial scale, single air pass flat plate solar collector, used to provide the heat energy for drying the excreta. It faced south, was 3 m high, 31.6 m long, and tilted 60 degrees from the horizontal. These dimensions were established for use of the collector as a source of supplemental heat for the adjacent poultry house during the winter months. Collector glazing was 3 mm tempered glass, framed vertically with 3.8 cm wide wood laths every 42 cm of collector length. Net glazed area was 93.4 m^2. The lathing accounted for 7 m^2 of collector surface area. A 2 cm dead air space existed between the glass and the black painted, corrugated aluminum roofing absorber plate. Behind the plate, a 6 cm air channel was confined by a 1.3 cm plywood sheet with 20 cm of cellulose fiber insulation behind it. The bottom inlet to each collector air channel was restricted by an adjustable plywood baffle. The inlet slot openings were adjusted narrower near the middle to balance the air flow rates through the seventy-one 42 cm wide air channels.

Outside air was drawn through the inlet slots, up the air channels (gaining heat), to a 46 cm diameter sheet metal duct on top of the collector. A 61 cm diameter sheet metal transfer duct channeled heated air from the collector to the poultry house and delivered it to the drying tunnel (see Figure 2.7). A shadow of the transfer duct was cast over part of the collector face during operation. The area of the shadow was

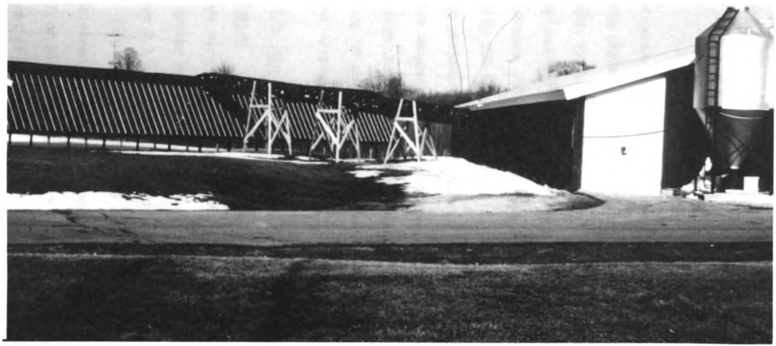

Figure 2.1 View of the solar collector showing air delivery duct for transporting heated air to the poultry house.

estimated at 2.8 m^2, so the net collector area was 90.6 m^2. Both ducts were insulated with 15 cm of fiber glass blanket, and covered by 0.15 mm polyethylene black plastic. A 61 cm direct drive axial flow fan delivered the heated air.

2.2 Drying Tunnel

Heated air from the collector was used to dry the excreta from the house in a special excreta drying tunnel (see Figure 2.2). Tunnel dimensions were 1.9 m wide, by 2.4 m high, by 35 m long. It housed a 76 cm, by 30.5 m long continuous PVC excreta conveyor belt, suspended from the poultry house trusses. The belt was loaded daily with 272 to 635 kg of excreta at 65% to 75% moisture content wet basis, about 10 cm deep. After each 24 hour period, the dried excreta was weighed off the belt and fresh excreta weighed on. The dried excreta could either be transported directly from the conveyor into a mechanical dryer at the end of the belt, or out of the house by a cross conveyor also located at the end of the conveyor drying belt.

2.3 Air Delivery Systems

2.3.1 Perforated Tube System

Two different systems were employed to deliver heated collector air over the excreta on the drying belt. The first was a perforated tube system as shown in Figures 2.3 and 2.4. It employed a 61 cm clear plastic air distribution duct suspended about 15 cm above the excreta surface. This system delivered the heated air perpendicularly to the excreta surface through 5 cm diameter holes every 15 cm of duct length. The system allowed movement of the house exhaust ventilation air across the surface of the excreta on the belt. The drying belt and tunnel

Figure 2.2 Excreta drying tunnel with PVC conveyor belt being loaded with wet excreta.

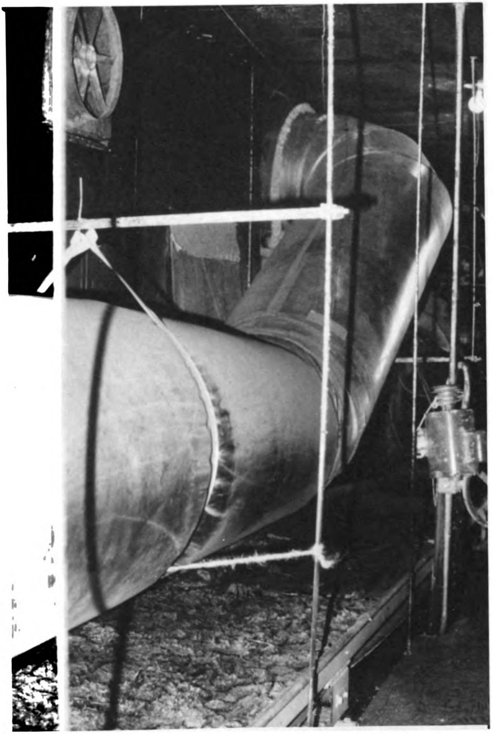

Figure 2.3 Solar heated air entering the perforated tube.

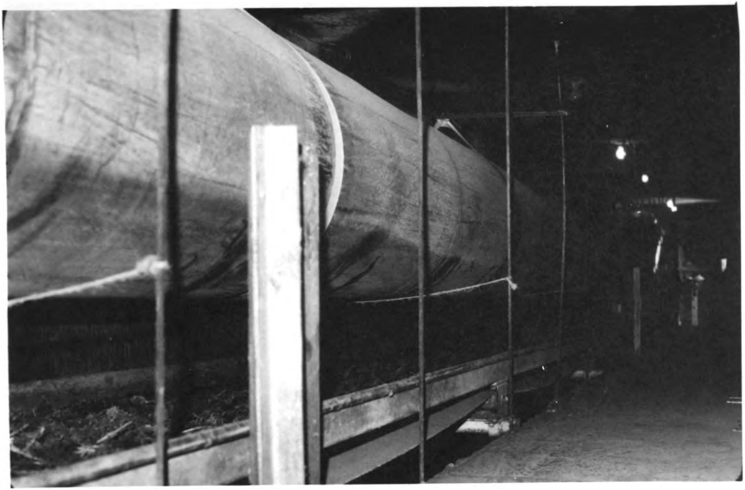

Figure 2.4 View of perforated tube system showing clearance for exhausted ventilation air from the poultry house.

were originally designed to utilize any additional drying potential of the exhaust ventilation air. The solar system was also able to take advantage of that capability. The perforated tube system was operated from August 11 to September 28, 1977, and from August 18 to October 15, 1978.

2.3.2 Tent System

The second was a tent system as shown in Figure 2.5. It was employed from July 21 to August 17, 1978. The tent system consisted of a clear plastic cover in the shape of an isosceles triangle. The air channel had 76 cm sides over the excreta belt. Solar heated air entered the tent channel and was forced to travel the length of the drying belt. The air exchanged sensible heat for latent heat as it moved the length of the belt.

In order to facilitate moisture sampling, eight 15 cm diameter openings were made in the plastic, one each 3 m of length. These holes remained open during operation and some of the heated air was lost through them. The tent system excluded any additional drying potential from the poultry house exhaust ventilation air.

2.4 Excreta Handling Equipment

Inside the house, four 22 m long rows of vertical triple deck cages contained 5000 laying hens. There were three birds per cage (see Figure 2.6). The top two decks had dropping boards which were scraped daily. A commercial cable-blade type scraper was used to remove droppings daily to a cross-conveyor at the northeast end of the house. The cross-conveyor elevated the excreta for easy loading into a garbage barrel or onto the drying belt. Figure 2.7 is a schematic view of the laying house, solar collector, and drying tunnel.

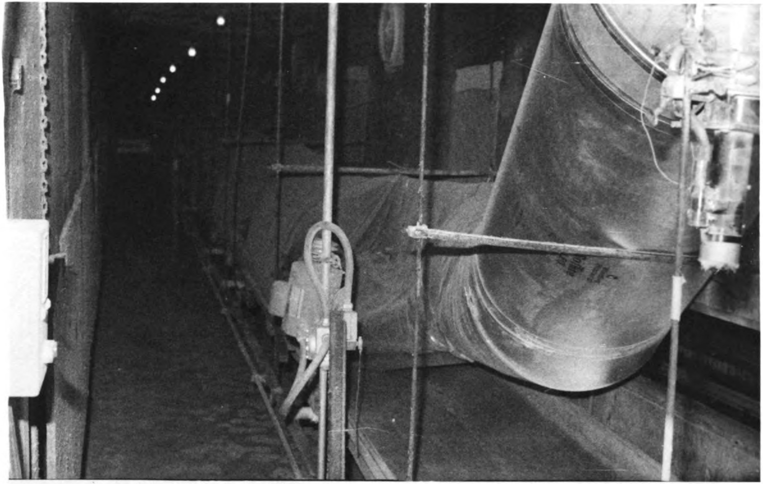

Figure 2.5 Tent system of air delivery in operation.

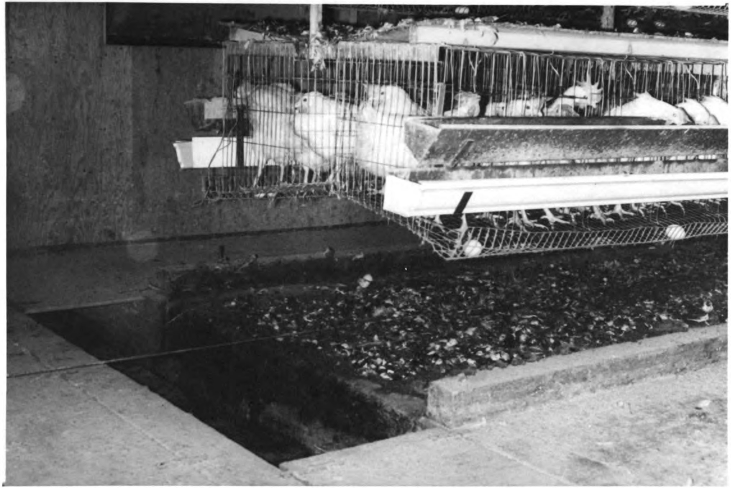

Figure 2.6 Laying hens in bottom cage row of triple deck cages, with excreta pit below.

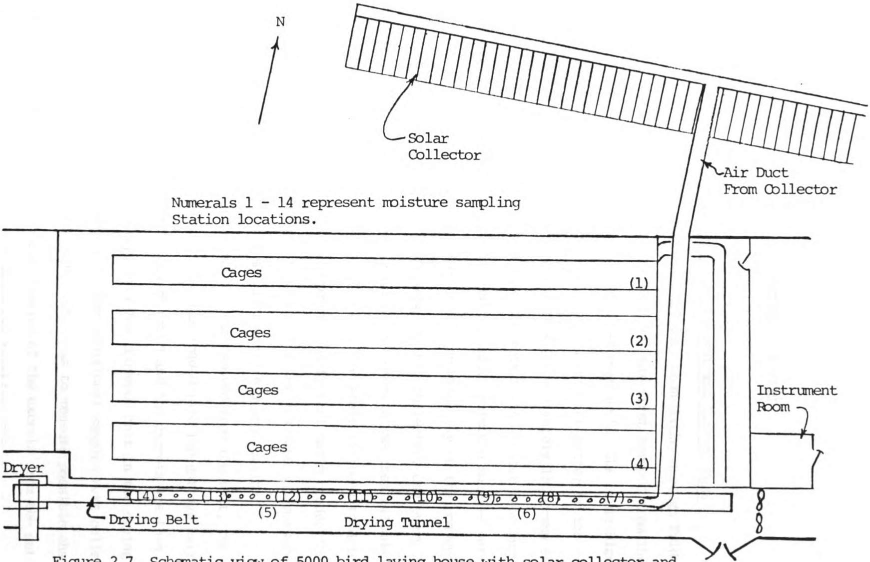

Figure 2.7 Schematic view of 5000 bird laying house with solar collector and drying tunnel for excreta drying, and moisture sampling station map.

3. EXPERIMENTAL PROCEDURE

3.1 Sampling of Moisture Content and Excreta Mass

Daily operations began about 7:30 a.m. from Monday through Friday. Excreta which had accumulated for 24 hours was first scraped from the dropping boards to the pit below the lower cage deck. The cable-blade scrapers then were used to move the excreta into the gutter at the northeast end of the house. Four samples (approximately 150 grams each) were removed from the freshly scraped excreta in the gutter (one sample from each of the four cage row accumulations). Moisture samples were then taken of excreta which had dried the previous day on the conveyor belt in the drying tunnel. Eight samples were collected, one every 3 m of conveyor belt length. The "solar dried" excreta was then unloaded into a 114 l metal garbage barrel. A platform scale was used to determine the total mass of the dried excreta. A typical day's production of dried excreta was from 6 to 8 barrels. After its mass was measured, the excreta was emptied into a spreader for field application.

Once all the solar dried excreta was removed from the belt, the fresh excreta from the poultry house was loaded into the garbage barrels. The mass of each loaded barrel was recorded and the excreta was then spread evenly, about 10 cm deep, over the conveyor belt in the drying tunnel. After the belt was loaded, two additional samples were collected at specified points along the belt. This was to measure possible changes in moisture content during transportation of the excreta from the gutter to the drying belt. Figure 2.7 shows the location of each moisture sampling station. The moisture samples for 1977 were deposited in plastic bags, sealed, and sent to a laboratory for moisture content determination. In 1978, samples were collected in small pie plates and dehydrated in an "on-site" air oven at 100°C for 24 hours.

A 24-hour oven drying time was found adequate, based on test results of July 24 and 25, when the masses of the samples were first measured after 24 hours in the oven and then remeasured after an additional 24 hours of oven drying. The average sample mass loss for the first 24-hour period was 67 g from the average 114 g sample. The average sample mass loss during the second 24-hour period in the oven was only 0.17 g, which was not found statistically significant. All sample containers were numbered to maintain sample identity.

3.2 Collector Operation

The solar collector and heated air delivery systems were designed to be as automatic and maintenance free as possible. The collector fan operated on a time clock from 9 a.m. to 8 p.m. daily, regardless of solar irradience. The air volume flow rate was held constant for the entire experimental period, except for minor fluctuations due to outside wind forces on the collector air inlet slots.

The glass face of the collector was cleaned twice weekly in order to remove accumulated dust which might lower collection efficiency.

3.3 Weekend Procedures

On Friday mornings, fresh excreta was loaded onto the belt after its mass was measured. This excreta was then allowed to remain on the drying belt until Monday mornings, when it was sampled for moisture content and measured for remaining mass. This procedure tripled the residence time of the excreta in the drying tunnel, and solar heat was delivered over it for three days.

The fresh excreta was removed from the house by a front-end loader and tractor on Saturday and Sunday mornings. Access doors were opened. The front-end loader bucket was positioned over the conveyor belt in the drying tunnel, and filled by the cross conveyor system. The loaded bucket was then emptied into a spreader for field application.

3.4 Alterations in Procedure

The described procedure was followed during July, August, and September of 1978. However, in 1977 there were some variations in the experimental procedure. On August 21 and 28, a mechanical dryer at the end of the drying tunnel was operated. Waste heat from the dryer may have affected excreta drying on the belt. The excreta on the belt was stirred once every hour from 12 to 4 p.m. on September 13, and once every 1.5 hours from 12 to 4 p.m. on September 14. During the week of September 5 through 9, 1977, wall fans directed exhaust ventilation air from the adjacent poultry house across the excreta on the belt for 24 hours each day.

3.5 Cumulative Weather Effects

It should be noted that each day's deposited excreta was affected by the weather conditions of two days, as the droppings spent up to 24 hours drying in the house and 24 hours drying on the belt. For weekend tests, four days of weather conditions affected excreta drying.

4. INSTRUMENTATION AND DATA ACQUISITION

4.1 Environments

It was realized that the reliability of solar research data depends largely upon the accuracy of the instrumentation employed to measure the various parameters. It was also realized that the environment in which an instrument is placed often affects the accuracy of its output. For this reason, a brief description of the environments in which the instruments operated is offered.

The two materials under study were the drying air and the excreta. Conditions of three types of air were monitored:

1. Clean, outside air
2. Clean, solar heated air
3. Dusty air, exhausted from the poultry house ventilation system.

It was necessary to use instrumentation flexible enough to handle below freezing as well as warm air temperatures. This was because the research project was also directed toward utilizing the collector as a supplemental heat source for the building during the cold winter months.

Excreta moisture content and mass were monitored under two conditions:

1. The wet, sloppy excreta with a rancid odor
2. The dried excreta, lower in odor and easier to handle.

Table 4.1 shows the environmental parameters which were recorded each

Table 4.1. Parameters recorded each one-half hour on the digital recorder.

Channel No.	Parameter Measured	Parameter Range	Instrument Used
1	Insolation	0-1000 langleys per day	Radiometer
2	Wind Direction	0-360°	Aerovane
3	Wind Speed	0-160 km/hr	Aerovane
4	Relative Humidity (outside)	10-100%	Electric Hygrometer
5	Dry Bulb Temperature (outside)	-34 to 38°C	Electric Hygrometer
6	Dry Bulb Temperature (solar heated air)	-18 to 60°C	Copper-Constantan Thermocouple
7	Dry Bulb Temperature (air exhausted from dryer)	-18 to 60°C	" "
8	Wet Bulb Temperature (air exhausted from dryer)	-18 to 60°C	" "
9-11	Dry Bulb Temperatures (in drying tunnel)	-18 to 60°C	" "
12-17	Dry Bulb Temperatures (in-house)	0 to 40°C	" "
18-23	Wet Bulb Temperatures (in-house)	0 to 40°C	" "
24-33	Dry Bulb Temperatures (collector plate and collector air)	-34 to 70°C	" "

half hour. The range of parameters encountered during the study and the instrument chosen to measure each parameter also appear. While 33 channels of information were recorded, only channels 1 through 8 were needed for this study.

Air velocity was only measured periodically with a portable hot wire anemometer and then included in the equations to calculate collector heat gain. Moisture content of the excreta samples was measured only once a day (14 samples) so hand calculation was used, and these values were not entered into the digital recording system. Excreta mass values were also independently recorded. Table 4.2 lists the parameters which were independently recorded, their range, and the instrument used to measure each.

Table 4.2. Parameters recorded independently.

No.	Parameter Measured	Parameter Range	Instrument Used
1	Air Velocity (in duct)	0 - 305 m/min	Hot Wire Anemometer
2	Mass (wet excreta)	0 - 680 kg	Platform Scale
3	Mass (dry excreta)	0 - 680 kg	Platform Scale
4	Mass (wet moisture samples)	50 - 250 g	Metler Balance
5	Mass (dry moisture samples)	10 - 250 g	Metler Balance

4.2 Instrument Selection

Among the considerations involved in the instrument selection process were:

1. Compatibility with the recording system
2. Performance under the environmental conditions involved
3. Accuracy of the instrument
4. Cost
5. Convenience

Table 4.3 shows the manufacturer's claimed accuracy for each instrument used in the study.

Table 4.3. Accuracy of instruments.

Instrument Used	To Measure	Manufacturer's Claimed Accuracy
Electric Hygrometer	Relative Humidity	3%
Electric Hygrometer	Dry Bulb Temperature	1.2°C
Copper-Constantan Thermocouple	Dry Bulb and Wet Bulb Temperatures	0.8°C
Hot Wire Anemometer	Air Velocity	1.5% of reading
Platform Scale	Mass	0.23 kg
Metler Balance	Mass	0.01 g
Radiometer	Insolation	1.5% of reading
Aerovane	Wind Speed	1.6 km/hr
Aerovane	Wind Direction	Unknown

4.3 Installation and Data Recording

By the beginning of the 1977 experimental period, all instruments were installed except the outside electric hygrometer. A wet bulb psychrometer was substituted. An Esterline Angus digital recorder monitored

28 channels of information, and printed the resulting millivolt reading as numerals on paper. These millivolt readings were converted to temperatures and hand written in tables for the period August 10 through August 17, 1977. The resulting values for the environmental parameters were not used in this report, however, as many of the values recorded by the instruments were questionable.

In 1978, all instruments were installed and calibrated prior to the July 21 start-up date. Thirty-three channels of information, including readings from the electric hygrometer were recorded. Two instruments malfunctioned soon after start-up. During the first weekend of operation, the reference junction circuit failed. It was not until three weeks later (August 17) that the faulty circuit could be replaced with a new unit. All thermocouple readings were lost during the period except for July 27, when a backup unit was installed and managed to function for a few hours. While the reference junction was inoperative, the ion-exchange cell of the electric hygrometer failed, causing a loss of relative humidity readings after August 3, 1978. A new cell was received, installed, and calibrated by August 28, 1978. After that date, the instrumentation functioned flawlessly.

The 1978 data were punched in binary code onto paper tape by a tape punching unit connected to the digital recorder. The tapes were fed into a digital computer, where the values were transferred to magnetic discs for easy manipulation. The paper tapes were kept as a permanent record of the data.

Thirty-minute recording intervals for data were used. Analog signals representing the various environmental parameters were sent as voltages from the primary sensors to the recorder, where they were converted to digital approximations.

5. RESULTS OF EXPERIMENT

5.1 Collector Performance

5.1.1 Sensible Heat Gain

Heat gain was the amount of solar heat picked up by the air passing through the collector. The half-hour heat gain values were summed to give the total cumulative heat gain for each day. Equation 5.1, Buelow (1956), was used in a computer program to calculate total daily heat gain.

$$q = \sum_{i=1}^{24} [mC(t - t_o)]_i \qquad (5.1)$$

where q = Heat gain, cal/day

m = Mass flow rate of air through the collector, g/30 min

C = Specific heat at constant pressure of air passing through the collector, cal/g-°C

t = Temperature of heated air, °C

t_o = Outside air temperature, °C

The resulting values were multiplied by the appropriate conversion factor to obtain the SI units Mega Joules (MJ)/day.

Instrument malfunctions caused a loss of heat gain data for the period July 24 through August 17, 1978. However, a linear regression analysis revealed a close relationship between the total daily heat gain of the collector air and the total daily insolation values recorded by the radiometer. The linear correlation coefficient for the two parameters over 28 days from August 21 to October 12, 1978, was 0.994.

Further analysis allowed the detection of a close linear relationship between the output of the radiometer at the collector site, a horizontally mounted radiometer at a nearby weather station. After a tilt angle correction factor was employed, the linear correlation coefficient was 0.991.

Table 5.1 displays the quantity of heat gained each day by the air passing through the collector, and total daily insolation on the collector. Values in the second and fourth columns were calculated from the data recorded at the collector site. The figures in the third and fifth columns are estimates based on the weather station data. The insolation data from the weather station were corrected to the 60 degree tilt angle of the collector and then substituted into Equations 5.2 and 5.3 in order to generate the heat gain and insolation estimates. These equations were the results of the regression analyses. Note that mixed engineering units appear in the equations.

$$Y_{ic} = 115.3 + 1.778X_{iw} \qquad (5.2)$$

where Y_{ic} = Estimated insolation on collector, 1000 BTU/day

X_{iw} = Insolation reported at weather station, langleys/day.

The resulting values were converted from 1000 BTU units to MJ units by multiplying by the appropriate conversion factor.

$$Y_{hg} = -140.6 + 0.676X_{ic} \qquad (5.3)$$

where Y_{hg} = Estimated daily heat gain of air passing through the collector, MJ/day

X_{ic} = Estimated insolation on collector, MJ/day.

The distribution of collector air heat gain can better be shown by a relative frequency histogram. Figure 5.1 illustrates how the collector

Table 5.1. Recorded and estimated daily heat gain and insolation on the 90.6 m^2 solar collector, during 1978.

Date	Recorded Daily Heat Gain (MJ)	Estimated Daily Heat Gain (MJ)	Recorded Daily Insolation (MJ)	Estimated Daily Insolation (MJ)
July				
21		239.8		562.1
22		455.7		880.6
23		214.6		524.9
24		477.6		913.0
25		488.7		929.3
26		199.2		502.2
27	556.4	---	978.7	---
28		574.8		1061.1
29		613.8		1113.9
30		405.7		806.9
31		398.6		796.4
August				
01		418.6		826.0
02		170.1		459.3
03		---		---
04		---		---
05		588.7		1077.0
06		---		---
07		---		---
08		548.4		1017.5
09		487.3		927.3
10		556.2		1029.0
11		299.1		649.6
12		477.6		913.0
13		541.9		1007.7
14		521.7		977.9
15		449.2		871.1
16		385.0		776.2
17		583.1		1068.7
18		341.1		711.5
19		273.7		612.0
20		629.9		1137.6
21	548.3	590.5	1094.7	1079.5
22	604.0	589.5	1078.6	1077.9
23	568.1	559.5	993.3	1033.8
24	407.7	399.3	798.3	797.4
25		233.8		553.2
26		216.9		527.7
27		176.7		469.0
28	289.7	328.2	641.7	692.6
29	545.9	559.1	1046.1	1033.2
30		339.7		709.5
31		573.8		1055.0

Table 5.1. (cont'd.)

Date	Recorded Daily Heat Gain (MJ)	Estimated Daily Heat Gain (MJ)	Recorded Daily Insolation (MJ)	Estimated Daily Insolation (MJ)
Sept.				
01		596.8		1088.8
02		606.4		1103.0
03		539.0		1003.6
04		597.0		1088.9
05	483.6	481.4	923.1	918.5
06		530.3		990.7
07	574.3	559.4	1037.5	1033.7
08		451.4		874.2
09		268.2		603.9
10		494.1		937.3
11	471.0	477.6	888.2	912.9
12	56.6	4.6	262.3	214.9
13	68.8	52.3	310.5	285.5
14	113.2	146.4	407.0	424.4
15		496.3		940.5
16		611.9		1111.1
17		---		---
18	157.1	---	479.5	---
19	303.7	341.8	653.2	712.6
20	549.5	504.6	994.0	952.8
21	103.4	104.7	347.8	362.8
22		574.1		1055.5
23		604.5		1100.3
24		597.6		1090.0
25	652.2	619.6	1143.8	1122.4
26	653.2	606.0	1157.5	1102.4
27	279.2	281.8	621.9	623.9
28	750.3	705.7	1202.3	1249.6
29		558.3		1076.4
30		344.3		716.4

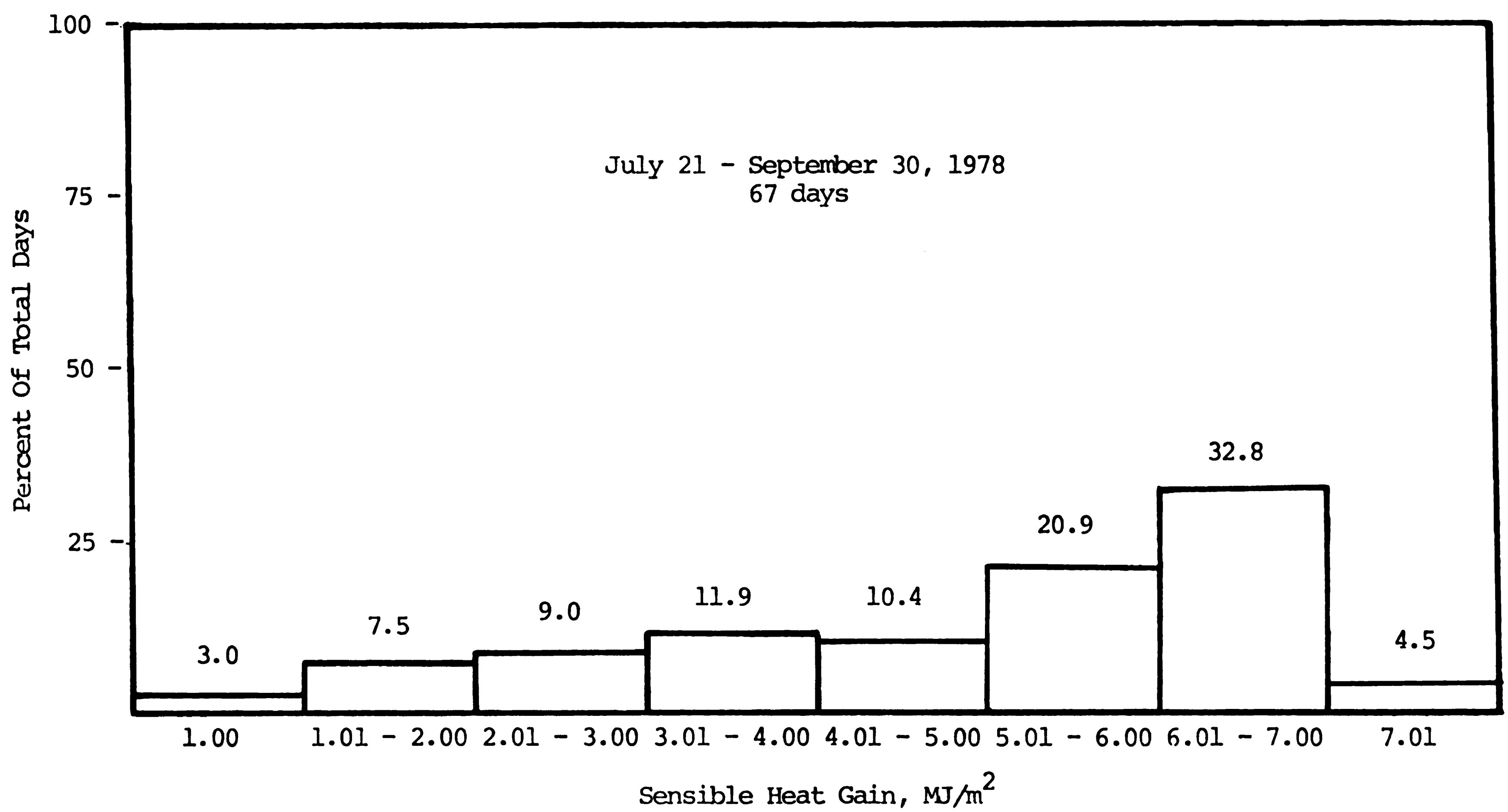

Figure 5.1 Distribution of total daily collector heat output.

heat output was distributed during a 67 day period in the summer of 1978. Mega Joule per square meter values appear in the figure.

5.1.2 Efficiency

Collector efficiency can be described in numerous ways. In this research the average daily efficiency was of interest. Table 5.2 displays average daily collector efficiencies for July 21 through September 30, 1978. Two methods of calculation were employed. The values appearing in the first column of efficiencies were calculated from Equation 5.4. The second column values came from Equation 5.5.

$$E_1 = \frac{100hg}{ic} \qquad (5.4)$$

$$E_2 = \frac{100hg}{tf \times ic} \qquad (5.5)$$

where hg = Total heat gain of air passing through collector, MJ/day

ic = Total insolation on collector at its 60 degree from horizontal tilt angle, MJ/day

tf = Tilt factor (additional heat energy theoretically available if collector was tilted normal to direct radiation).

Equation 5.5 gave lower collector efficiency values during the summer months than did Equation 5.4. As fall approached, the tilt factor diminished in value and the differences in efficiency became less. Seasonal variation was factored out of the Equation 5.4 efficiency values, because the heat gain was divided by the amount of energy actually available to the collector at its tilt angle.

The tilt factors appearing in Table 5.2 were derived from an extrapolation procedure described by Becker and Boyd (1956). When multiplied by the daily heat gain value, they represent the additional heat

Table 5.2. Average daily collector efficiency, tilt factor, and optimal tilt angle for date.

Date	Tilt Factor	Average Daily Efficiency $E = \frac{100hg}{ic}$ (%)	Average Daily Efficiency $E = \frac{100hg}{tf \times ic}$ (%)	Optimum Collector Tilt Angle for Date
July				
21	2.02	43	21	23°
22	2.01	52	26	
23	2.00	41	20	
24	1.98	52	26	
25	1.97	53	27	
26	1.96	40	20	
27	1.95	57	29	
28	1.93	54	28	25°
29	1.92	55	29	
30	1.91	50	26	
31	1.90	50	26	
August				
01	1.89	51	27	
02	1.87	37	20	
03	---	---	---	
04	---	---	---	
05	1.84	55	30	
06	---	---	---	
07	---	---	---	
08	1.81	54	30	
09	1.80	53	29	
10	1.79	54	30	
11	1.78	46	26	
12	1.77	52	30	
13	1.76	54	31	
14	1.75	53	30	30°
15	1.74	52	30	
16	1.73	50	29	
17	1.72	55	32	
18	1.71	48	28	
19	1.70	45	26	
20	1.69	55	33	
21	1.69	50	30	
22	1.68	56	33	
23	1.66	57	34	
24	1.64	51	31	
25	1.63	42	26	
26	1.61	41	26	
27	1.59	38	24	
28	1.58	45	29	
29	1.56	52	33	35°
30	1.55	48	31	
31	1.53	54	36	

Table 5.2. (cont'd.).

Date	Tilt Factor	Average Daily Efficiency $E = \frac{100hg}{ic}$	Average Daily Efficiency $E = \frac{100hg}{tf \times ic}$	Optimum Collector Tilt Angle for Date
		(%)	(%)	
Sept.				
01	1.52	55	36	
02	1.50	55	37	
03	1.49	54	36	
04	1.47	55	37	
05	1.46	52	36	
06	1.44	54	37	
07	1.43	55	39	
08	1.42	52	36	
09	1.40	44	32	
10	1.39	53	38	
11	1.38	53	38	
12	1.37	22	16	40°
13	1.35	22	16	
14	1.34	28	21	
15	1.33	53	40	
16	1.32	55	42	
17	1.31	--	--	
18	1.30	33	25	
19	1.28	46	36	
20	1.27	55	44	
21	1.26	30	24	
22	1.25	54	44	
23	1.24	55	44	
24	1.23	55	45	
25	1.22	57	47	
26	1.21	56	47	
27	1.20	45	37	
28	1.19	62	52	45°
29	1.18	52	44	
30	1.17	48	41	

energy which theoretically would have been available to the collector, had it been tilted normal to direct radiation. For example, on July 22, 1978, 2.01 times as much heat energy (an additional 460 MJ), could have been provided by the collector, had it been tilted at an angle of 23 degrees from the horizontal.

The last column of Table 5.2 shows how the optimal tilt angle for the collector changed with the seasons.

Once seasonal variation was factored out, collector efficiency was found to vary with the amount of insolation received. A plot of average collector efficiency versus total insolation received by the collector daily appears in Figure 5.2. A curve was fitted to the data by the least squares method. The resulting correlation coefficient was 0.977 on 20 observations. The standard error of the estimate was 2.78. The equation of the curve was:

$$Y_e = -1.44 + 8.69X_{ic} - 0.32X_{ic}^2$$

where Y_e = Estimated average daily collector efficiency, %

X_{ic} = Total insolation for the day, on the collector surface, MJ/m^2.

5.2 Total Mass of Moisture Evaporated from Excreta During Drying

The mass of excreta loaded onto and off from the drying belt was measured daily. The resulting mass values were used to determine the mass of water evaporated from the excreta after 24 hours on the drying belt. Table 5.3 shows the estimated total mass of water in the excreta as freshly excreted, the estimated mass of water evaporated by ventilation air in the poultry house, the recorded mass of water evaporated on the drying belt and the mass of moisture remaining in the excreta.

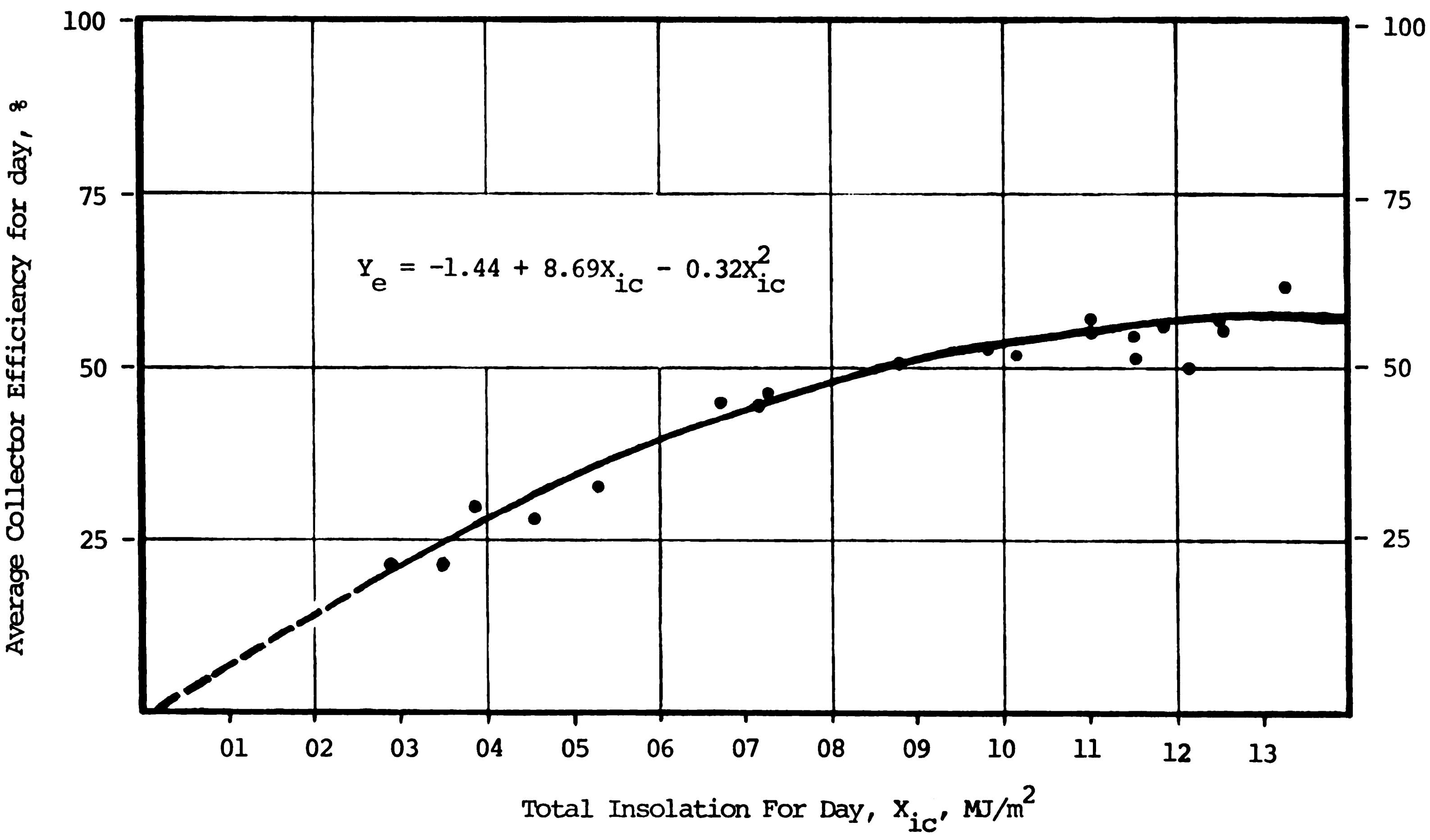

Figure 5.2 Collector efficiency versus total insolation received.

Table 5.3. Mass of moisture evaporated from excreta.

1977 Date	Total Mass of Moisture in Excreta (kg)	Mass of Moisture Removed in House (kg)	Mass of Moisture Removed on Belt (kg)	Mass of Moisture Remaining in Excreta (kg)
August				
10	375	-20	76	317
14	516	151	146	220
15	412	119	35	266
16	487	58	147	282
17	421	74	130	216
21	469	116	145	209
22	452	167	113	171
23	380	122	123	135
24	556	183	148	224
28	490	108	107	275
29	422	112	166	144
30	329	84	119	126
31	449	101	97	250
September				
05	510	93	139	279
06	444	53	140	251
07	533	79	147	307
11	464	147	116	200
12	415	101	66	249
13	467	91	140	236
14	837	135	69	433
18	560	114	108	338
19	568	235	72	261
20	460	86	85	289
21	453	84	100	268
26	413	110	83	220

Table 5.3. (cont'd.).

1978 Date	Total Mass of Moisture in Excreta (kg)	Mass of Moisture Removed in House (kg)	Mass of Moisture Removed on Belt (next day) (kg)	Mass of Moisture Remaining in Excreta (kg)
July				
23	496	298	94	104
24	660	407	79	174
25	658	403	75	180
26	604	313	102	189
30	430	244	60	126
31	471	317	74	80
August				
01	452	299	37	116
02	442	220	71	151
06	423	278	53	92
07	413	243	74	96
08	417	256	66	95
09	396	230	63	103
13	425	238	84	103
14	428	271	68	89
16	407	234	73	100
20	388	202	124	62
21	250	160	57	33
22	213	111	64	38
23	352	147	90	115
27	431	175	77	179
28	378	137	103	138
29	388	181	90	117
30	422	218	97	107
September				
04	516	249	134	161
05	478	225	130	123
06	424	209	114	101
10	365	127	110	128
12	424	177	49	198
13	383	136	63	184
17	424	136	73	215
18	426	123	68	235
19	426	81	--	---

The estimates for total water mass and mass of water evaporated in the poultry house were based on an assumed moisture content of 80 percent wet basis for the fresh droppings. While this assumption was verified for the 1978 flock of birds, the 1977 flock was not tested. The 1977 flock was a different strain than that of 1978. It was affected by disease during the experimental period, while the 1978 flock was not. Since some of the 1977 excreta samples contained more than 80 percent moisture after in-house drying, it might be that those birds were voiding excreta of more than 80 percent moisture. If so, the amount of in-house drying during 1977 was underestimated.

Figures 5.3 and 5.4 graphically depict the percentage of the total mass of water remaining in the excreta, after evaporation in the poultry house and on the drying belt. Figure 5.3 shows 1977 results, while Figure 5.4 represents 1978 data. Note the higher amount of in-house drying which occurred in 1978. Also note the division between the tent system and perforated tube system of air delivery.

After three days of drying on weekends, an average 26% of total moisture was evaporated from the excreta under the tent system, 40% under the perforated tube system in 1978, and 44% under the perforated tube system in 1977. Table 5.4 shows the amount of drying which occurred on weekends.

5.3 Energy Utilization Efficiency

The sensible heat energy of the solar heated air came from three sources:

1. Sensible heat of the outside climatic air
2. Solar energy supplied by the collector
3. Energy added by the air delivery fan and its drive motor.

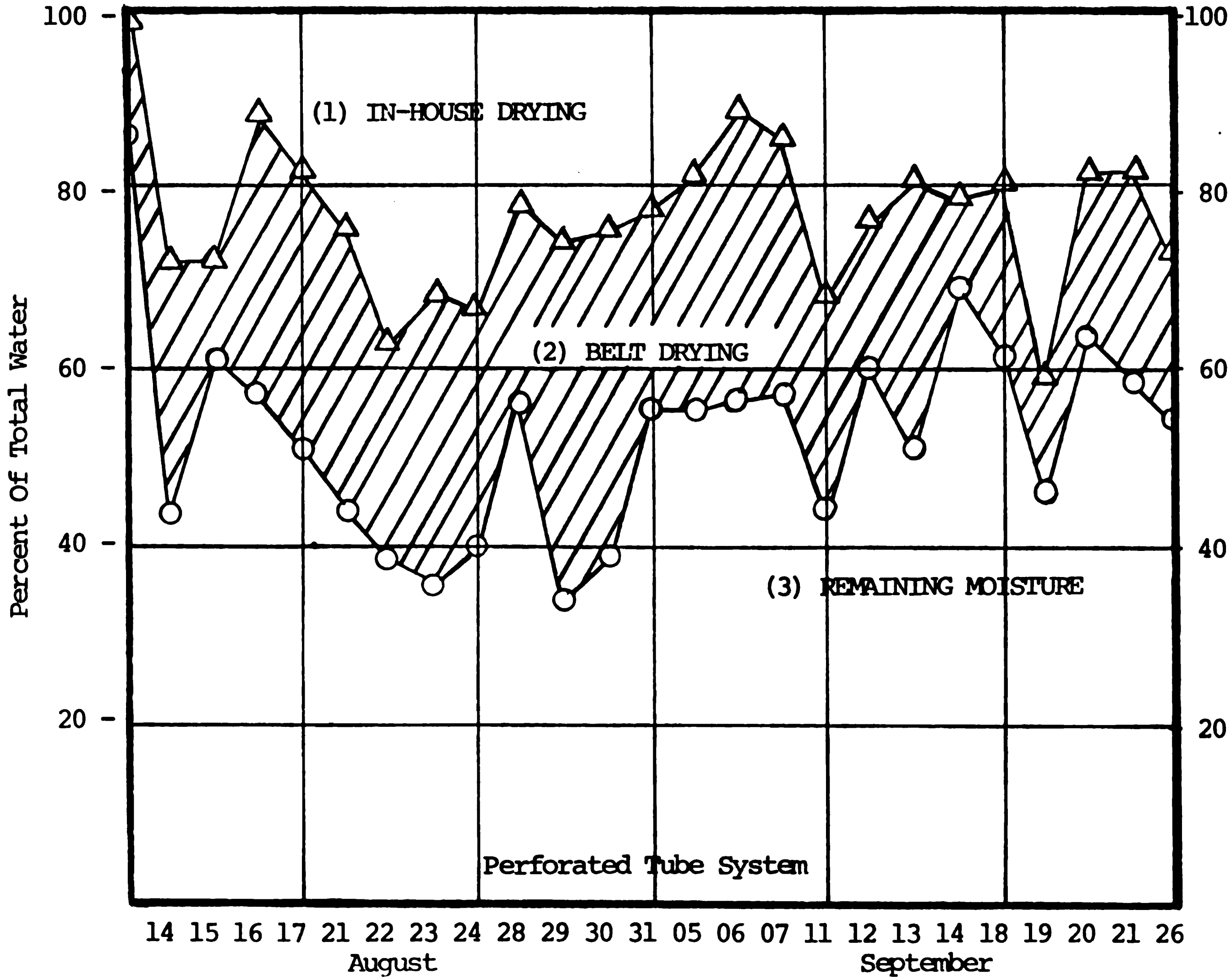

Figure 5.3 Portion of excreta water remaining after in-house and belt drying, 1977.

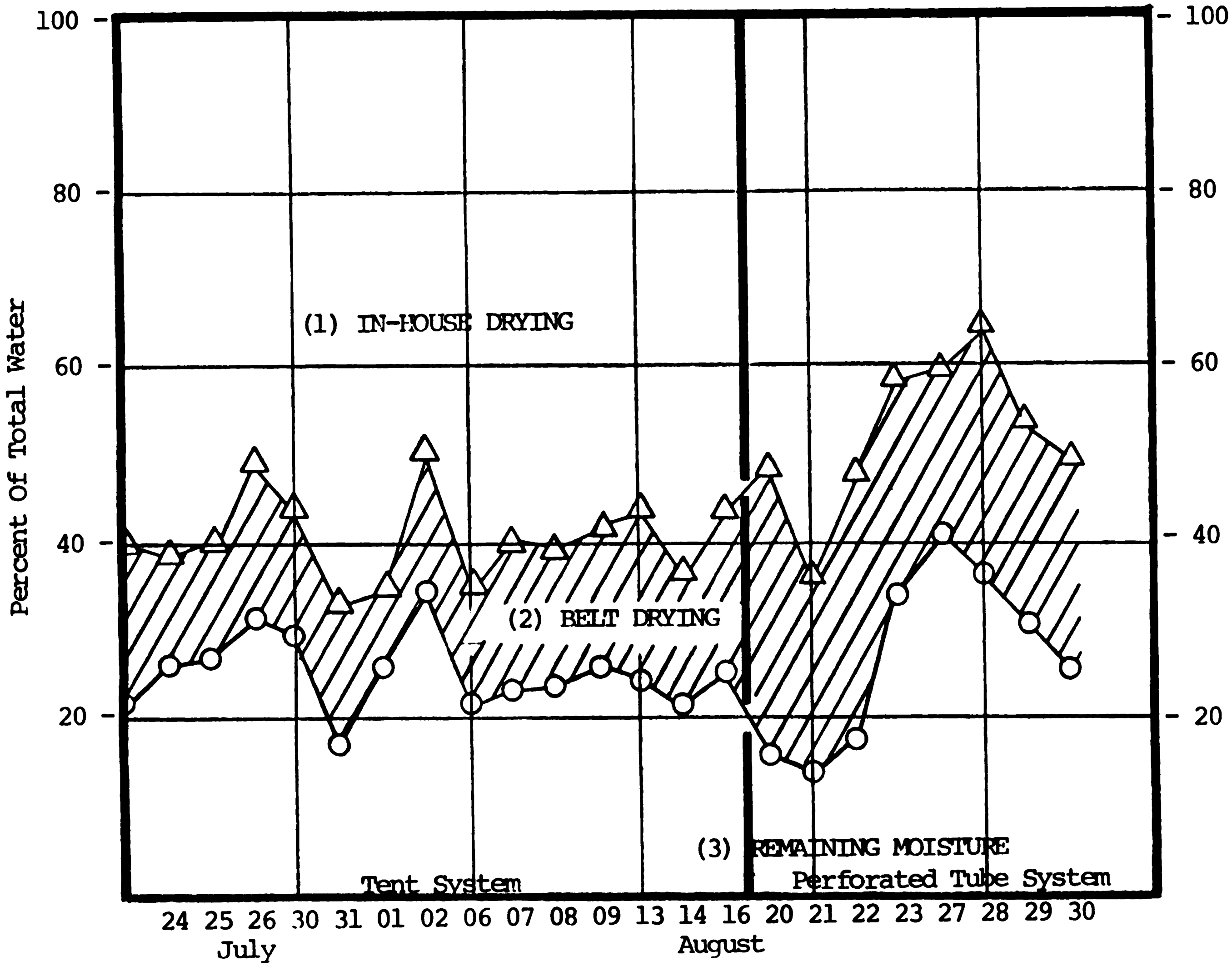

Figure 5.4 Portion of excreta water remaining after in-house and belt drying, 1978.

Table 5.4. Mass of moisture evaporated from excreta on weekends.

Weekend	Total Mass of Moisture in Excreta	Mass of Moisture Removed in House	Mass of Moisture Removed on Belt	Mass of Moisture Remaining in Excreta
	(kg)	(kg)	(kg)	(kg)
1977				
August				
12–15	487	141	177	169
19–22	334	97	220	17
26–29	392	127	221	44
September				
02–06	360	59	228	73
09–12	560	181	329	50
16–19	436	71	196	169
23–26	455	74	210	171
1978 -- Tent System				
July				
28–31	633	423	147	63
August				
04–07	424	272	113	39
11–13	408	248	112	48
1978 -- Perforated Tube System				
August				
18–21	413	221	128	64
25–28	371	165	137	69
September				
01–04	388	182	182	24
08–11	445	209	187	49
15–17	452	131	200	121

Thermocouple readings indicated that the amount of heat added by the fan was approximately equal to the amount of heat lost through the insulated ducting between the collector and the drying tunnel. The thermocouple output also revealed that the air exhausted from the drying tunnel was always higher in dry bulb temperature than outside air. Thus, no sensible heat from the outside air contributed to belt drying. For these reasons. it was assumed that all drying energy supplied to the tent system came from the collector. In the case of the perforated tube system, drying energy came from both the collector and the unutilized heat from the poultry house exhaust ventilation air.

As collector efficiency may be expressed in many ways, so may the efficiency with which the heat energy was used in drying. Esmay et al. (1976) described excreta dryer efficiency as the ratio of energy needed to evaporate water versus total energy input, or:

$$E_d = \frac{100\ M'\lambda}{Q_i} \tag{5.6}$$

where E_d = Efficiency of dryer, %

λ = Latent heat of evaporation, 2.46 MJ/kg at 16°C and 100,000 Pa

M' = Mass of water evaporated in dryer, kg

Q_i = Heat energy input to dryer, MJ

Table 5.5 lists average daily energy utilization efficiencies where the collector heat gain values were used as Q_i in Equation 5.6. These efficiency values varied widely, from as low as 23 to as high as 174%. Efficiencies of more than 100% would not be possible without another heat source, so the unaccounted for heat source (exhausted ventilation air) must have provided at least that portion of drying over 100%. The highest efficiency values generally occurred on cloudy days when little

Table 5.5. Energy utilization efficiency.

1978 Date	Collector Heat Gain	Moisture Evaporated on Drying Belt	Energy Utilization Efficiency
	(MJ)	(kg)	(%)
		Tent System	
July			
24	477.6	94.3	49
25	488.7	79.4	40
26	199.2	74.8	92
27	556.4	102.1	45
31	398.6	59.9	37
August			
01	418.6	74.4	44
02	170.1	36.7	53
08	548.4	74.4	33
09	487.3	66.7	33
10	556.2	63.0	29
14	521.7	84.4	40
15	449.2	68.5	38
17	583.1	72.5	31
		Perforated Tube	
21	548.3	124.6	56
22	604.0	57.2	23
23	568.1	64.0	28
24	408.3	91.2	55
28	290.4	78.2	66
29	546.7	103.4	46
September			
05	484.6	134.3	68
07	574.3	112.9	49
11	470.7	110.0	58
13	69.2	49.3	174
14	113.1	63.1	136

solar heat was available. The lowest two values were for days when only a small amount of excreta was placed on the drying belt, due to a scraper malfunction, but much solar heat was available.

5.4 Parametric Inference for Mass of Moisture Removed

In order to determine if daily water removal on the belt was significantly correlated to any other parameter or combination of parameters, a series of correlation analyses were conducted. It was hoped that an equation could be found to describe daily moisture removal as a function of environmental factors.

A simple linear regression equation relating the mass of moisture evaporated each day to the daily collector heat gain held quite well for days of similar outside temperatures and excreta loading mass. The outside air temperatures and the excreta loading mass were not constant, however. The loading mass was found to vary greatly from day to day, and from year to year. The daily variations occurred because of differences in the amount of in-house drying, due to varying outside weather conditions. Yearly variations were due to differences in flock breed, and disease problems of the 1977 flock. Heat gain of the air passing through the collector actually increased during the late summer and early fall, due to an increase of solar radiation incidence on the collector surface. The total mass of moisture removed decreased as fall approached, so a more complicated analysis was required to explain all of the factors affecting the amount of drying obtained.

Several multiple regression analyses were performed with the aid of a computer. Every combination of average daily outside dry bulb temperature, outside relative humidity, mass of excreta to be dried, collector heat gain, and temperature of the heated air were tested for their ability to predict the mass of water evaporated on the drying belt. An instrument malfunction caused a loss of relative humidity information. The values of that parameter were only available for seven days.

The highest correlation coefficient obtained in the analyses was 0.987, and resulted from the multiple linear regression equation 5.7.

$$M_{wr} = 76.47 + 1.40T_{ca} + 0.20M_m - 1.37RH \qquad (5.7)$$

where M_{wr} = Estimated mass of water removed, kg

T_{ca} = Average daily temperature of heated air from collector, °C

M_m = Total mass of excreta to be loaded on belt, kg

RH = Average relative humidity of outside air for day

The standard error of the estimate was 7.0, but sample size was only seven. With only seven observations and a multiple regression equation with four variables, it was understood that the results of the analysis were of limited significance. However, because of the high correlation coefficient, the results were included in this report.

Table 5.6 shows the predicted values for mass of moisture removed on the drying belt, and the values of the parameters used in the analysis for seven days of August and September, 1978. The ranges of the parameters involved in the analysis appear.

5.5 Moisture Content of the Dried Excreta

During the two summers of operation, 1,219 excreta samples were collected and oven dried. Mass of the samples was measured before and after drying. Moisture content was determined from the recorded mass values using Equation 5.8, Henderson and Perry (1976).

$$m = \frac{100\ M_m}{M_m + M_d} \qquad (5.8)$$

Table 5.6. Parameters for predicting mass of water evaporated.

Date	Average Temp. Solar Heated Air	Mass of Excreta to Be Dried	Average R.H. of Outside Air	Mass Moisture Removed	Predicted Mass Removed
	(°C)	(kg)	(%)	(kg)	(kg)
August					
29	34.5	335	70.8	102.5	94.3
September					
05	37.1	396	55.7	134.3	130.9
07	40.7	321	56.7	113.4	119.5
11	37.2	329	60.2	110.2	111.4
13	14.7	353	86.6	48.5	48.5
14	24.7	343	85.7	62.6	61.7
18	26.5	394	82.5	73.5	78.8

For Parameter Ranges: 14.7 to 40.7 °C
329 to 396 kg
55.7 to 86.6%

where m = Moisture content, % wet basis

M_m = Mass of moisture, g

M_d = Mass of oven dried material, g

5.5.1 Fresh Samples

Forty-four random samples of freshly excreted droppings were measured for moisture content during the 1978 operational period. The mean moisture content of these samples was 80.0 and the standard deviation was 5.5. A 95% confidence interval for the fresh excreta mean moisture content was (78.3, 81.7). This sampling verified that the 1978 flock was typical when compared with flock measurements reported by Zindel et al. (1977). Unfortunately, no fresh samples were collected from the 1977 flock of birds, so the fresh excreta moisture content was unknown.

5.5.2 Dried In House Samples

Four samples, one from each cage row, were collected to determine the amount of in-house drying which occurred during the 24-hour period that excreta accumulated on the dropping boards. Figure 5.5 shows 95% confidence intervals for the mean moisture content, based on the samples taken daily at each of the 14 sampling stations. One set of confidence intervals was made for the entire 1977 operational period. The 1978 data were divided into two sections, one for the tent system and one for the perforated tube system. The intervals were carefully drawn so that it is possible to detect any significant differences in moisture contents simply by locating non-overlapping confidence intervals.

The excreta at sampling station 1 was found significantly dryer than that at stations 2, 3, or 4 during the 1977 period. Station 1 excreta was significantly dryer than that of station 3 or 4, during

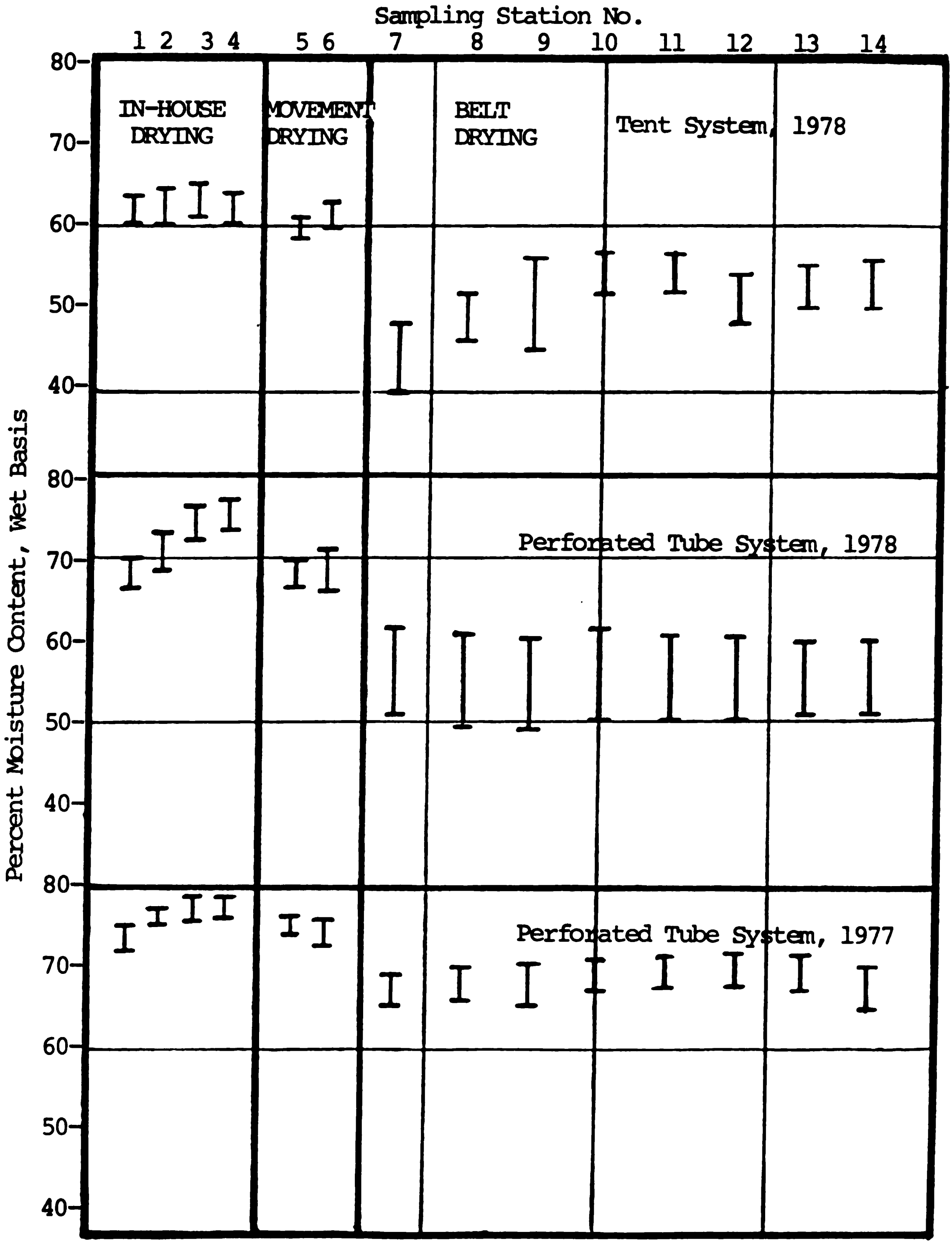

Figure 5.5 95% confidence intervals for the mean moisture content (daily drying).

the perforated tube system operation in 1978. No significant difference was detected between in-house sampling stations during the 1978 tent system operation. The differences in in-house drying between stations can be explained by the following. Outside air entered the house near cage row 1 and passed through to cage row 4, picking up moisture. As the air became more saturated, it had less drying potential, and thus the differences in excreta moisture content.

The absence of significant differences in in-house drying between sampling stations during the tent system operation was due to the time of year. The tent system was operated earlier in the summer, when outside air temperatures were higher. A much greater ventilation rate was required to lower the in-house temperature. With the greater ventilation rate, the ventilation air did not become greatly saturated, and thus its drying potential was nearly the same across the house.

5.5.3 Movement Drying

Two moisture samples were taken daily from pre-specified locations along the drying belt immediately after loading. Figure 5.5 displays 95% confidence intervals for the moisture content of these samples. While the excreta was being transported, some mixing occurred. The moisture content of the excreta after being transported onto the belt was not found significantly lower than that of all of the in-house stations. For these reasons, the data do not strongly support the hypothesis of Muiruri (1976), that the excreta is dried significantly by the transportation process. When a single mean value was determined for samples 1 through 4, and a single mean value determined for samples 5 and 6, the latter value was always less than the former, but not significantly so. Perhaps a larger number of observations would have allowed the detection of a significant difference resulting from excreta movement. These three tests were based on 33 observations for 1977, 20 observations for the tent system period of 1978, and 26 observations per sampling station for the perforated tube system operation in 1978.

5.5.4 Solar Assisted Belt Drying

In order to determine the moisture content of the excreta after 24 hours of drying, and to detect any gradiation in drying along the length of the belt, eight moisture samples were collected daily (one every 3 m of belt length). Figure 5.5 shows 95% confidence intervals for the mean moisture content at each of the eight sampling stations.

No significant difference in moisture content was discovered between any of the eight stations during the perforated tube system operation in 1977 or 1978. When the tent system sample values were statistically tested, however, it was found that sample 7 was significantly dryer than samples 10, 11, 12, 13, and 14. Sample 8 was found significantly dryer than samples 10 and 11. The statistical analysis of the tent system was based on 20 observations per station.

5.5.5 Belt Drying (Weekends)

As described in the experimental procedure, the excreta was weighed onto the belt on Friday mornings and left until Monday mornings to be weighed off. This procedure tripled the residence time of the excreta on the drying belt, and extended the effects of weather conditions on drying over a period of four days. Figure 5.6 shows 95% confidence intervals for the mean moisture content at each sampling station after drying on the belt for three days. Three different sets of confidence intervals appear. One for the entire 1977 operations

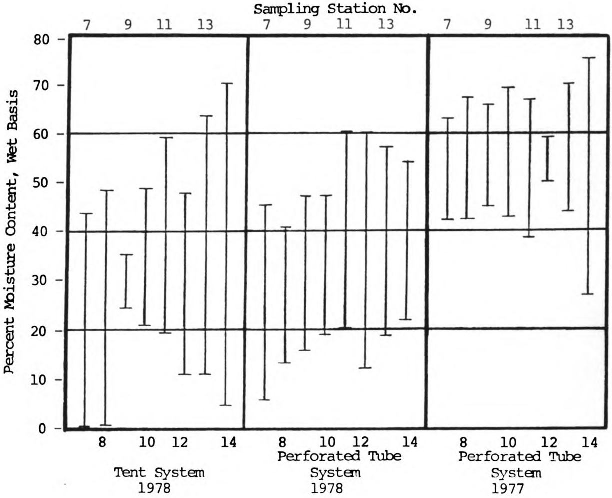

Figure 5.6 95% confidence intervals for the mean moisture content (weekends).

and one for the tent and perforated tube system operations of 1978.

6. DISCUSSION

6.1 Comparison of Results

Muiruri (1976) used recirculation fans to direct exhausted ventilation air over excreta on the drying belt involved in this study. He found that 24% of the total excreta water was removed after 24 hours on the drying belt. When in-house and movement drying were considered, Muiruri managed to reduce the amount of water in the excreta by 73% in the months of October, November, December, and January, without supplemental heat.

With the addition of supplemental solar heat, an average 15% of the total excreta moisture was removed daily under the tent, an average 25% was removed under the perforated tube system in 1977, and 23% in 1978. While Muiruri's results are not directly comparable to the results of this study (because the number of observations, the variance between observations, and the mass of excreta involved were not included in his report) it would seem that the system designs could be improved to make better use of the heat available from the solar collector. The following discussion considers some of the factors which affected the amount of energy available from the collector and the energy utilization efficiency of the drying approaches.

6.2 Factors Affecting Ability of Collector to Provide Sensible Heat

6.2.1 Tilt Factor

Becker and Boyd (1956) covered the effects of season, orientation latitude, altitude, and cloudiness on the availability of solar energy. While one has little control over most of these factors, collector tilt angle can be regulated by the system designer. The collector involved in this research was constructed with a tilt angle optimal for maximum efficiency on December 21. Using this tilt angle in the summer months resulted in low efficiencies. As pointed out in Section 5.1.2, more than twice as much heat energy could have been provided by the collector had it been normal to direct radiation in July.

6.2.2 Collector Area

The solar collector in this study was sized according to the supplemental heat requirement for raising the in-house temperature from 12°C to 21°C in the winter months. A heat and moisture balance was performed, and it was found that an average 43.6 MJ/hr of supplemental heat would be required. From weather data it was found that 105 langleys per day were available to a horizontal surface in an eight-hour day, December 21. It was estimated that twice as much insolation would be available at the 60 degrees from horizontal collector tilt angle in the winter months. It was determined that 39.8 m^2 of collector area would be required at 100% efficiency. A 44% efficiency was assumed, and the net collector area was set at 90.6 m^2. Summertime use of the collector for drying poultry excreta was not considered in the original size determination.

A similar process should be employed to calculate the required collector area for the summertime excreta drying use. Data recorded in this investigation could be used to help determine optimal design specifications. An example of how this might be done is now offered.

The heat requirement of a dryer depends upon the design goal for the final moisture content of the excreta. For this example, 30% wet basis will be used (doing so will simplify the design process, as all drying would take place at the initial constant rate). The mass of water in the excreta after in-house drying was sharply lower in 1978 than in 1977. The 1978 values seem to be more typical, however. A 99% upper error bound for the mass of water remaining in the excreta after in-house drying was therefore taken from 1978 data. The resulting value was 250 kg. The mass of dry matter in the excreta averaged about 115 kg over the experiment. About 50 kg of water may remain in the 115 kg of dry matter at the 30% moisture content. This leaves 200 kg of water which must be evaporated from the excreta on the drying belt. The latent heat of vaporization for water is 2.46 MJ/kg, so 492 MJ of heat energy would be required to reach the design goal, if the dryer was 100% efficient in using collector heat.

Dryer efficiency was found to vary widely (section 5.3). Moisture removed was found to be more dependent upon the quantity of excreta to be dried, and upon temperature of the heated air, than upon the collector heat gain. For this analysis an estimate of dryer efficiency was needed, so the extreme values were discarded and an assumption was made that the drying system would be capable of utilizing 35% of the collector heat energy. This would require 2.9 times as much heat output from the collector, or 1427 MJ.

From the distribution of collector heat output (Figure 5.1), there seems to be a natural break at 4 MJ/m^2/day. More than 4 MJ/m^2/day was obtained 69% of the time, so this value will be used, and a system capable of drying excreta to at least 30% wet basis on 69% of the summer days will be designed. As the collector delivered 4 MJ/m^2, the 1427 MJ heat requirement could be divided by 4 to obtain 357 m^2 of collector area necessary to reach the design goal. If utilization efficiency could be increased, less collector area would be required.

6.2.3 Miscellaneous Considerations

Collector efficiency could be improved by increasing air flow rate, insulation value, and the number of glazings, or by reducing the distance from the collector to dryer. The problem is one of minimizing cost, while meeting the other design constraints. A linear optimization program could be developed to find the least cost alternative, given existing price coefficients.

6.3 Factors Affecting Ability of the Drying Systems to Convert Sensible Heat to Latent Heat

The excreta handling system used in this research was originally designed as part of a poultry excreta dehydration and utilization project. The purpose of the project was to reduce pollution by drying the excreta in a mechanical dryer and refeeding the resulting anaphage. The drying belt was designed first to transport the excreta from the house to the mechanical dryer, and second to allow exhausted ventilation air to pass over the excreta and thus increase the belt drying rate. Changes in the drying tunnel design would be suggested if maximum use of the solar energy available for drying was to be made. The following discussion describes possible changes and their effects on drying.

6.3.1 Drying Air Velocity

Wells (1972) found that free stream air velocity affects constant rate drying through its hydrodynamic effects on heat and mass transfer. For laminar flow, he found it to be a function of the square root of the velocity. In such a case, an increase in velocity by four times would double the drying rate. An increase in velocity of the air passing through the collector would improve collector efficiency. More electrical energy would be required to operate the fan at the higher mass flow rate, however. Higher velocities would also result in lower air temperatures, and thus less wet bulb depression. In this research, fan speed was held constant. Air flow rate was also constant at about 0.94 m^3/sec.

6.3.2 Drying Body Geometry

The geometry of the drying body has been found to have a dramatic effect on the drying rate. Wells (1972) doubled the rate of moisture removal and decreased the critical moisture ratio of three samples of poultry excreta simply by doubling the surface area exposed to the drying air. He found that drying time varied approximately inversely as the layer thickness. Wells dried samples of less than 1 cm thickness.

The layer thickness of the manure on the drying belt in this study was about 10 cm. Spreading the excreta 5 cm thick on a belt twice as wide might have doubled the amount of drying, according to Wells. The drying rate per unit surface area would remain constant, but twice as much surface area would be available.

6.3.3 Miscellaneous Factors

As pointed out in Chapter 2, holes were made in the plastic covering of the tent system in order to facilitate moisture sampling. As much as 1/3 of the solar heated air leaked through these holes before reaching the end of the drying belt. The degree of saturation of the leaking air was not determined, but it was assumed that some sensible heat was lost.

The direction of air flow inside the tent was opposite that of the ventilation air exiting the poultry house by way of the drying tunnel. The effect was similar to that of a counter-flow heat exchanger through the plastic. Insulation might have helped to reduce the sensible heat loss to this phenomenon.

7. SUMMARY AND CONCLUSIONS

7.1 Summary

Sensible heat energy from an air medium solar collector was used to increase the amount of drying in a poultry excreta drying system. The excreta handling-drying system was built for previous research. It was designed to make use of any drying potential left in ventilation air exhausted from the poultry house, by passing it over wet excreta on a conveyor belt. Heated air from a solar collector was incorporated into the drying system by also directing it over the wet excreta on the belt.

A 90.6 m^2 flat plate, single air pass solar collector provided the heated air. It was designed to provide supplemental heat to the poultry house during the cold winter months, but it was hoped that the collector could also be used on a year-round basis for drying excreta in the warm summer months.

Two different systems were employed for delivering the heated air from the solar collector over the excreta on the drying belt. The tent system forced the heated air over the length of the drying belt, before exhausting out the opposite end. The perforated tube system (positioned 15 cm above the excreta surface) provided clearance for exhausted ventilation air to mix with the solar heated air and aid in drying.

Results of the experiment showed an average 15% of the total excreta moisture was evaporated on the drying belt each 24 hours with the tent system approach, while 25% was removed with the perforated tube system in 1977, and 23% in 1978.

The collector delivered more than 400 MJ of heat energy on 65% of the summer test days. Dryer efficiency in utilizing this heat varied with the amount of excreta to be dried. About 35% average efficiency was obtained form the tent system, while around 45% efficiency was obtained from the perforated tube system.

Moisture content of the excreta after drying was uniform along the length of the belt when the perforated tube heated air delivery system was used. A gradiation in moisture content developed under the tent system of air delivery. Final moisture content of the solar dried excreta average 67% during 1977, 50% for the tent system of 1978, and 55% for the perforated tube system in 1978. Initial moisture contents were 76%, 62%, and 70% wet basis respectively. The average mass of moisture evaporated on the drying belt for each of the three systems was 113 kg, 72 kg, and 90 kg respectively.

Equations were found to describe the performance of the systems. One equation predicted the heat output of the collector, given total daily insolation. Another equation predicted collector efficiency, given total daily insolation. A third predicted the amount of drying obtainable from the perforated tube system, given outside relative humidity, temperature of heated air, and mass of excreta to be dried. These equations were specific to the systems involved and limited to the range of parameters involved in the analysis, but seemed to describe system performance quite satisfactorily.

7.2 Conclusions

The following five conclusions were reached regarding the use of solar heated air to dry poultry excreta:

1. Heat energy from the collector surpassed 4 MJ/m^2 on 69% of the summer days, and 5 MJ/m^2 on 58% of the test days.
2. Average daily efficiency of the collector was dependent upon the amount of insolation received, and varied with the season. The seasonal variation was explained by the tilt factors appearing in Table 5.2. When the seasonal variation was factored out, collector efficiency was found to vary as:

   $$Y_e = -1.44 + 8.69X_{ic} - 0.32X_{ic}^2$$

   where Y_e = Estimated average daily collector efficiency, %

   X_{ic} = Total insolation for the day, on the collector surface, MJ/m^2
3. The tent-type air distribution system operated at about 35% efficiency, and evaporated on a daily basis about 15% of the total water in the excreta. The average mass of moisture evaporated was 72 kg.
4. The perforated tube system obtained efficiencies of about 45% and evaporated on a daily basis an average 25% of the total water in the excreta in 1977, 23% in 1978. The average mass of moisture evaporated was 113 kg in 1977, and 90 kg during 1978.
5. Based on results from previous research by Muiruri (1976) it would seem that the design of these drying systems could be improved to make better use of the available solar heat. Muiruri reported nearly the same amount of drying for a system which used only exhausted ventilation air in drying. His results are not directly comparable, however, because the mass of excreta involved, the number of observations made, and the variance between observations were not included in his report.

8. RECOMMENDATIONS

The following recommendations are made concerning the incorporation of heated air from a solar collector into poultry excreta handling systems.

1. A larger drying surface area to volume ratio (thinner excreta layer) than used in this study is suggested. A device to reduce excreta layer thickness would be required.
2. Velocity of the solar heated air over the excreta surface should be maximized. The aerodynamic characteristics of the air delivery system should be such that maximum velocity of drying air over the excreta surface would occur.
3. Optimal collector design should be determined by developing a linear optimization program to find the best alternative, given existing cost coefficients. The problem would be one of minimizing cost, while meeting the other design constraints.
4. Reducing the distance between collector and drying tunnel, sealing the air leaks and providing insulation over the plastic heated-air distribution ducts would reduce sensible heat loss. This should improve drying performance.

LIST OF REFERENCES

LIST OF REFERENCES

ASHRAE Handbook of Fundamentals, 1972. Published by American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 345 East 47th Street, New York, New York.

Becker, C. F. and J. S. Boyd, 1956. Solar radiation availability on surfaces in the United States as affected by season, orientation, latitude, altitude and cloudiness. Michigan Agricultural Experiment Station Journal Article No. 1978.

Brown, W. H. and R. E. Forbes, 1976. Poultry house heating and manure drying utilizing solar energy. Proceedings of Symposium on Use of Solar Energy for Poultry and Livestock Production, Auburn University, Auburn, Alabama.

Buelow, F. H., 1956. The effect of various parameters on the design of solar air heaters. Thesis for the degree of Ph.D., Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

DeBaerdemaeker, J. and B. C. Horsefield, 1976. Drying animal wastes with solar energy. Proceedings of Symposium on Use of Solar Energy for Poultry and Livestock Production, Auburn University, Auburn, Alabama.

Dhingra, P. D., 1979. Economic evaluation and analysis of the impact of a solar collector on the environment of a poultry house. Unpublished report for Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

Dixon, J. E., G. D. Wells, and M. L. Esmay, 1977. Convective heat transfer coefficient for poultry excreta. ASAE Paper No. 76-4511, American Society of Agricultural Engineers, St. Joseph, Michigan.

Dixon, J. E., 1979. Maximizing poultry excreta dehydration with ventilating air using a simulation model. Ph.D. Dissertation, Michigan State University, Agricultural Engineering Department, East Lansing, Michigan.

Esmay, J. L., C. J. Flegal, J. B. Gerrish, J. E. Dixon, C. C. Sheppard, H. C. Zindel, T. S. Chang, 1976. In-house handling and dehydration of poultry manure from a caged layer operation: A project review. Journal Article No. 7202, Michigan Agricultural Experiment Station, East Lansing, Michigan.

Esmay, M. L., 1978. Principles of Animal Environment. AVI Publishing Company, Westport, Connecticut.

Henderson, S. M. and R. L. Perry, 1976. Agricultural Process Engineering, third edition. AVI Publishing Company, Westport, Connecticut.

Henry, Z. A., 1975. Instrumentation and Measurement for Environmental Sciences. Published by American Society of Agricultural Engineers, St. Joseph, Michigan.

Kays, W. M., 1966. Convective Heat and Mass Transfer. McGraw-Hill Book Company, New York, New York.

Muiruri, J. K., 1976. The use of ventilation air to minimize the energy utilized in the production of anaphage. Thesis for the degree of M.S., Poultry Science Department, Michigan State University, East Lansing, Michigan.

Perry, R. H., and Cecil H. Chilton, 1963. Chemical Engineers Handbook, fourth edition. McGraw-Hill Book Company, New York, New York.

Sobel, A. T., 1969. Removal of water from animal manures. Animal Waste Management, Proceedings of the Cornell University Conference on Agricultural Waste Management.

Structures and Environment Handbook, 1976. Published by Midwest Plan Service, Iowa State University, Ames, Iowa.

Wells, G. D., 1972. Simulation of in-house drying of chicken excreta. Thesis for the degree of Ph.D., Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

Zindel, H. C., T. S. Chang, C. J. Flegal, D. Polin, C. C. Sheppard, B. A. Stout, J. E. Dixon, M. L. Esmay, and J. B. Gerrish, 1977. Poultry excreta dehydration and utilization: System development and demonstration. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia, Report No. EPA-600/2-77-221.

MICHIGAN STATE UNIV. LIBRARIES
31293100643745