INFLUENCE OF INFRARED ENERGY

ON EARLY GROWTH RATES OF POULTRY

BY

Ben

NOUREDDINE B. ABDALLAH

B.Sc. Texas A & M University, 1969

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in the Department of

Agricultural Engineering

We accept this thesis as conforming to the

required standard

THE UNIVERSITY OF BRITISH COLUMBIA
December, 1973.

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Agricultural Engineering

The University of British Columbia
Vancouver 8, Canada

Date December 17, 1973

ABSTRACT

The radiosity method of radiant interchange analysis of enclosures was used to predict the intensity and the uniformity of thermal radiation within a controlled environment chamber. The chamber was designed for testing the effects of infrared radiation on young broilers. The walls of the chamber were assumed to be grey and separated by a radiatively non-participating medium. Also the black globe thermometer method was used to calculate the incident radiation at different locations in the chamber. Then, the results obtained by the two mentioned methods, were compared.

Two separate experiments were designed for different purposes. The first experiment was to study the influence of infrared radiation on poultry. In this experiment, two levels of radiation were tested and the results were compared to those obtained by use of a conventional heat lamp brooding system. The second experiment was to compare a controlled temperature, warm air brooding system, to a conventional heat lamp brooding system. The relative effects in both sets of experiments were measured by use of the weekly growth rate index.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

APPENDIX A

LIST OF TABLES

APPENDIX B

LIST OF TABLES

APPENDIX C

LIST OF TABLES

APPENDIX D

LIST OF SYMBOLS

A_j = Surface area of an arbitrary surface 'j' of the chamber.

B_j = Radiosity of surface 'j' as defined by equation [1].

F = Kata factor supplied by the manufacturer of the Kata thermometer.

G_{j-i} = Configuration factor between surfaces 'j' and 'i'.

G_{g-i} = Configuration factor between the globe and surface 'i'.

I_j = Incident radiant energy on any surface 'j' of the chamber.

I_{gi} = Incident radiant energy on the globe due to surface 'i' of the chamber.

I_g = Total incident radiant energy on the globe from all surfaces of the chamber.

T_j = Absolute temperature of any surface 'j' of the chamber.

T_g = Absolute temperature of the black globe.

T_s = Absolute mean radiant temperature.

V = Air speed in the chamber as determined by the Kata thermometer.

a & b   Constants used in the Kata equation [17] depending upon the type of the instrument, the cooling range and the air speed range to be measured.

h_c = Convective heat transfer coefficient for the black globe thermometer depending upon the size of the globe.

q_c = Convective heat loss or gain by the globe.

q_r = Radiative heat loss or gain by the globe.

t_a = Dry bulb temperature of air in the chamber.

t_g = Black globe temperature.

t_s = Mean radiant temperature.

t_m = Mean temperature of the Kata thermometer depending upon the cooling range of the instrument.

$\emptyset$ = Cooling time of the Kata thermometer.

ε_j = Total hemispherical emissivity of surface 'j'.

ε_g = Total hemispherical emissivity of the black globe.

α_j = Total hemispherical absorptivity of surface 'j'.

ρ_j = Total hemispherical reflectivity of surface 'j'.

σ = Stefan-Boltzmann constant.

BGT = Black globe temperature $\rightleftharpoons$ t_g

MRT = Mean radiant temperature $\rightleftharpoons$ t_s

RHL = Radiant heat load $\rightleftharpoons$ I_g

ACKNOWLEDGEMENTS

INTRODUCTION

Reduction in the overall heating requirement of broiler houses can be accomplished by taking advantage of the thermal and optical properties of infrared radiation.

Due to the directional property of thermal radiation, the radiant energy can be transmitted directly from the source of radiation to the birds; thus eliminating the usual process of preheating large masses of air and the conveyance system associated with it.

By avoiding the necessity of heating the air in the broiler house a substantial reduction in conductive heat loss through the structure can be effected due to the decrease in the temperature gradient between the inside and outside air.

Another property of thermal radiation of primary importance is based on the fact that the exchange of radiant energy between two bodies is proportional to the difference of the fourth power of their respective absolute temperatures (Stefan-Boltzmann Law). Because of this fourth power law, the amount of energy that can be exchanged is increased significantly, with small differences in surface temperature. Instant heat is the other property of infrared radiation of practical importance compared to the relatively long period of time conventional warm air systems require to bring the temperature of the air in the building to a comfortable level for young chicks.

Even though infrared radiant heating systems would appear to be more economical than warm air systems, the effects of such radiation on biological systems and associated environmental parameters must be known before radiant heating systems can be widely adopted. Unfortunately, limited data are available about the effects of infrared radiation on the growth of birds and less about their thermal surface properties. Consequently, the purpose of this investigation was to study the effects of infrared radiation on broiler chicks, using growth rates as an index. The thermal radiation was from sources operating at temperatures of less than 200°F (93°C).

LITERATURE REVIEW

Researchers in the environmental aspects of poultry agree that the brooding phase, hatch to about three or four weeks of age, is the most important and most critical period in the life of the bird. The performance of the bird during its maturity is mainly dependent upon its brooding phase history.

Environmental factors which are important for the comfort of the chicks are not, as yet, fully defined. These factors may be classified, according to their nature, into thermal, physical and sociological.

In most instances, environmental factors that were found to influence the comfort of the birds were investigated separately, thus, ignoring interactions which may exist between the simple factors.

The effects of air speed, air composition, noise and radiation have received limited attention. Most of the available data are on the effects of dry-bulb temperature and relative humidity on growth rates of poultry (Staley et al. 1970).

Data on the effect of quality and quantity of light on broilers are negligible. McCluskey and Arscott (1967) have investigated the influence of incandescent and infrared lamps upon chicks. They found that body weights and feed conversion of birds, at 56 days of age, reared under continuous light

from 250 watt, clear glass, infrared heat lamps delivering a maximum of 600 foot candles (55.7 lux), were significantly (P < 0.05) lower than birds reared under continuous light from 250 watt, red glass, infrared heat lamps delivering a maximum light intensity of 62 foot candles (5.8 lux). Furthermore, the 8-week body weights of birds reared under continuous light from 60 watt incandescent lamps with a maximum intensity of 1.2 foot candles (.11 lux) were higher, though not statistically significant, than the 8-week body weights of birds reared under red glass heat lamps. Unfortunately, we cannot conclude that incandescent lamps are better than infrared lamps for the purpose of poultry rearing, because the lower body weight associated with the infrared heat lamp treatments was probably due to temperature difference rather than light since temperatures within the pens were neither controlled nor measured. These temperatures were obviously different because the energy input to the pens were different, 250 watts compared to 60 watts. Because of the nature of this experiment, it is probably safer to conclude that the red glass heat lamps are better than clear glass heat lamps for brooding chicks. This difference was due to the quality rather than the quantity of radiation. Longhouse and Garver (1964) found little difference between incandescent and fluorescent lights with respect to the physical conditions of broilers.

The influence of light intensity was investigated by Skoglund and Palmer (1962). They concluded that birds reared under a light intensity of 120 foot candles (11.1 lux) had significantly ($P < 0.05$) lower body weights than birds reared under 10, 5, 2 and 0.5 foot candles (.93, .46, .19, .05 lux). Also, they found no significant difference among the low light intensity treatments but there was a tendency to a small increase of body weight with a decrease in light intensity.

Some preliminary work was done on infrared radiation brooding by Baker and Bywaters (1951), Staley, Roberts and Crober (1967), Baxter, Maddox and Shirley (1970). All of the mentioned investigators have used in their experiments, industrial infrared heat lamps, high temperature sources of radiation. These heat lamps were purchased from different manufacturers with different intensity and quality of radiation.

Baker and Bywaters (1951) have concluded that the energy requirement for winter brooding was from 2 to 3 kWh per chick with continuous operation of the heat lamps for the first 8 weeks. They have also found that the mortality rate for infrared brooding was as low or lower than for other methods of brooding. No significant differences were found in body weight or degree of feathering between chicks brooded under infrared heat lamps and chicks brooded with other systems. Finally, these authors have found that pullets

reared with infrared radiation started to lay 2 to 3 weeks earlier than their sisters brooded with other systems.

Staley et al. (1967) have used a clear glass 250-watt heat lamp placed at 24 inches (61 cm) above the centre of the pen. The pen was divided into two radiation levels with approximate averages of 145 BTU/hr/sq ft (451 Wm^{-2}) and 185 BTU/hr/sq ft (583 Wm^{-2}) respectively. The resulting 2-in black globe thermometer readings were 76.5°F (24.8°C) and 82°F (27.8°C) respectively. They found significant differences ($P < 0.05$) in body weights in favour of the low radiation level.

Baxter et al. (1970) have established comfort zones for chicks at different ages by creating a heat gradient using three 375-watt industrial infrared heat lamps. The temperature gradient was divided into equal circular zones with known equivalent black globe temperatures, and using as criterion of comfort the number of birds resting in a specific zone. From the results of their experiments, the comfort equivalent globe temperature at one week of age was about 79°F (26°C) and at five seeks of age it was about 72°F (22°C).

EXPERIMENTAL DESIGN

The entire experiment consisted of six tests which may be divided into two categories or into two sub-experiments. The first sub-experiment was designed primarily to study the effect of thermal radiation on growth rate of young broiler chicks. This sub-experiment was composed of four tests. In these tests the independent variable of concern was the mean radiant temperature as calculated from the black globe thermometer data; while the dependent variable was the weekly growth rate as calculated from the weekly body weight data.

The first three tests consisted of three treatments each; a high level of radiation, a low level of radiation and a conventional brooding. The globe temperatures and the resulting radiant heat load as a function of the age of the birds in days from hatch are illustrated in Table 1. For the high level of radiation the starting globe temperature was 88°F (31.1°C) dropping at the rate of 3°F (1.7°C) every three days to a minimum of 70°F (21.1°C) on the nineteenth day of age. For the low level of radiation, the starting globe temperature was 82°F (27.8°C) dropping at the rate of 2°F (1.1°C) every three days to a minimum of 70°F (21.1°C) on the nineteenth day of age.

For both levels of radiation, the birds were removed from the controlled environment chambers on the twenty-first day and transferred to separate pens in the same house where

TABLE 1. Black globe temperature (BGT) and radiant heat load (RHL) as per treatment and brooding period for tests 1, 2 and 3.

	Brooding Period (days)						
	1-3	4-6	7-9	10-12	13-15	16-18	19-21
	High radiation level						
BGT (°F)	88	85	82	79	76	73	70
RHL (BTU hr^{-1} ft^{-2})	163	158	153	149	144	140	135
	Low radiation level						
BGT (°F)	82	80	78	76	74	72	70
RHL (BTU hr^{-1} ft^{-2})	151	148	145	143	140	137	135

the conventional brooding treatment was located since the start of the test. From the end of the third week to the termination of the test at the end of the seventh week, the three treatments were managed in the same manner.

TABLE 2.   Black globe temperature (BGT) and radiant heat load (RHL) as per brooding period for test 4.

	Brooding Period (days)		
	1-7	8-14	15-21
BGT (°F)	88	84	80
RHL (BTU/hr^{-1} ft^{-2})	163	156	151

The fourth test of this first experiment was designed to determine the effect of a lower rate of the black globe temperature drop as a function of the age of the birds. The final black globe temperature of 80°F (26.7°C) was chosen instead of the 70°F (21.1°C) used during the first three tests of the experiment.

Test 4 consisted of two treatments. One treatment starting at a globe temperature of 88°F (31.1°C) dropping 4°F (2.2°C) per week to 80°F (26.7°C) during the third week of growth in the chamber. The other treatment was a conventional floor brooding system using industrial heat lamps. The globe temperature and the RHL for test 4 as a function of the brooding period are illustrated in Table 2.

As mentioned earlier, the purpose of the previous

four tests, just described, was to determine the effect of thermal radiation on the rate of growth of young chicks. The second part of the experiment or sub-experiment number two, was designed for three major purposes:

1) To test the performance of a 300 cubic feet per min
     (8.5 m^3 min^{-1}) air conditioning unit made by AMINCO-
     AIRE and its adaptability in environmental control
     experimentation with poultry.

2) To compare infrared radiation brooding with warm air
     brooding.

3) To study the effect of the environmental chambers.

          The second part of this experiment consisted of two tests. In these tests the independent variable of concern was the dry bulb temperature, while the dependent variable was the same as before. Each test consisted of three treatments; chamber 1, chamber 2, and floor birds. The environmental conditions in the two chambers were kept as close as possible with the available facilities. The dry bulb temperature as a function of the age of the chicks in days from hatch, for test 5 and test 6, are shown in Table 3. For both tests the starting dry bulb temperature was 90°F (32.2°C) dropping at the rate of 3°F (1.6°C) every three days to a minimum of 78°F (25.6°C) on the thirteenth day for test 5 and to a minimum of 72°F (22.2°C) on the nineteenth day of age for test 6. Test 5 and test 6 were terminated on the

TABLE 3.   Dry-bulb temperature (°F) as per brooding

period for tests 5 and 6.   (Relative

humidity = 50%).

			Brooding Period (days)			
1-3	4-6	7-9	10-12	13-15	16-18	19-21
			Test 5			
90.0	87.0	84.0	81.0	78.0	78.0	78.0
			Test 6			
90.0	87.0	84.0	81.0	78.0	75.0	72.0

twenty-first day of age. During the entire investigation, the
floor birds were reared under industrial heat lamps using a
.conventional brooding system.

EXPERIMENTAL MATERIAL AND PROCEDURE

The experimental birds for the first test were University of British Columbia New Hampshires, a specific genetic line. This choice of experimental material was an attempt to reduce the experimental error thus increasing the sensitivity of the experiment to the environmental effect of concern.

During the following three tests, U.B.C. broilers, a less homogeneous genetic line than the New Hampshires, were used as experimental birds.

For the warm air experiment which included tests 5 and 6, the experimental birds were commercial broilers from J.J. Hambley Hatcheries (B.C.) Ltd., Abbotsford. The eggs were hatched at the U.B.C. poultry farm.

For each of the tests, one through four, 120 male chicks that hatched on the twenty-first day were randomly divided and assigned so that a total of 40 birds were in each of the three treatments. All chicks were completely dry on removal from the incubator and within two hours received a vaccination for Marek's disease.

After the vaccination and the assignment of the birds to their treatments, they were wing banded for identification, and weighed to the nearest gram. The subsequent weighings were randomized so that no one order could be

repeated on the next weighing. An antibiotic was mixed
with water for the first seven days of age. The birds were
fed *ad. libitum* a standard broiler ration containing about
23 percent protein, 3.5 percent fat and 5 percent fibre.

All birds were individually weighed every week up
to seven weeks of age. Individual weekly body weights were
punched on computer cards and the individual weekly growth
rates, the one to three week growth rate and the three to
seven week growth rate were calculated using the power func-
tion relationship given by Roberts (1964).

The individual growth rate (r) for the period
between times t_1 and t_2 was computed by the following
expression:

$$r = \frac{LOG\left(\frac{Y_2}{Y_1}\right)}{LOG\left(\frac{t_2}{t_1}\right)}$$

where Y_1 = body weight of bird at time t_1 from
              conception

          Y_2 = body weight of bird at time t_2 from
              conception

  t_1 and t_2 = age + 3 (on a weekly base)

Once the test was terminated, the birds were killed
and their sex verified by internal inspection. The females
were neglected from the anlysis along with the birds that
died during the seven weeks' test.

For test 5 and test 6, the same procedure was used with the following modifications: The birds were mixed instead of all males. The tests were terminated at the end of three weeks of age instead of seven weeks. And, for test 6 only, the density was reduced from 40 birds to 36 birds per treatment.

At the end of each test the birds were killed and sexed by internal inspection, then the males and females were analyzed separately.

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

1. Thermal Radiation Brooding Experiment

The experimental system may be divided into two major systems:

a) The controlled environment chambers and their radiant heat sources.

b) The air conditioning and conveying system.

Two controlled environment growth chambers of similar design were used during the entire investigation. Each chamber was constructed to house up to forty birds at three weeks of age. The overall inside dimensions of the chamber were 4X4 feet surface area by 3 feet high. The air entering the chambers was in the same condition for both chambers. This air was kept at the lowest dew-point temperature possible with the available air conditioning facilities. This was accom - plished by circulating the return air from the chambers over chilled water coils then passing it through a fine water spray at the same temperature as that of the cooling coils. The purpose of the spray chamber is twofold. One, to ensure saturation at a constant dew-point temperature; two, to partially clean the return air mixture from fine dust, ammonia and carbon dioxide gases (Figure 1).

Throughout the thermal radiation experiment, tests 1 through 4, the air leaving the air conditioning system and entering the growth chamber was saturated at a constant

FIGURE 1. SCHEMATIC OF THE AIR CONDITIONING SYSTEM USED WITH
THE INFRARED RADIATION EXPERIMENT.
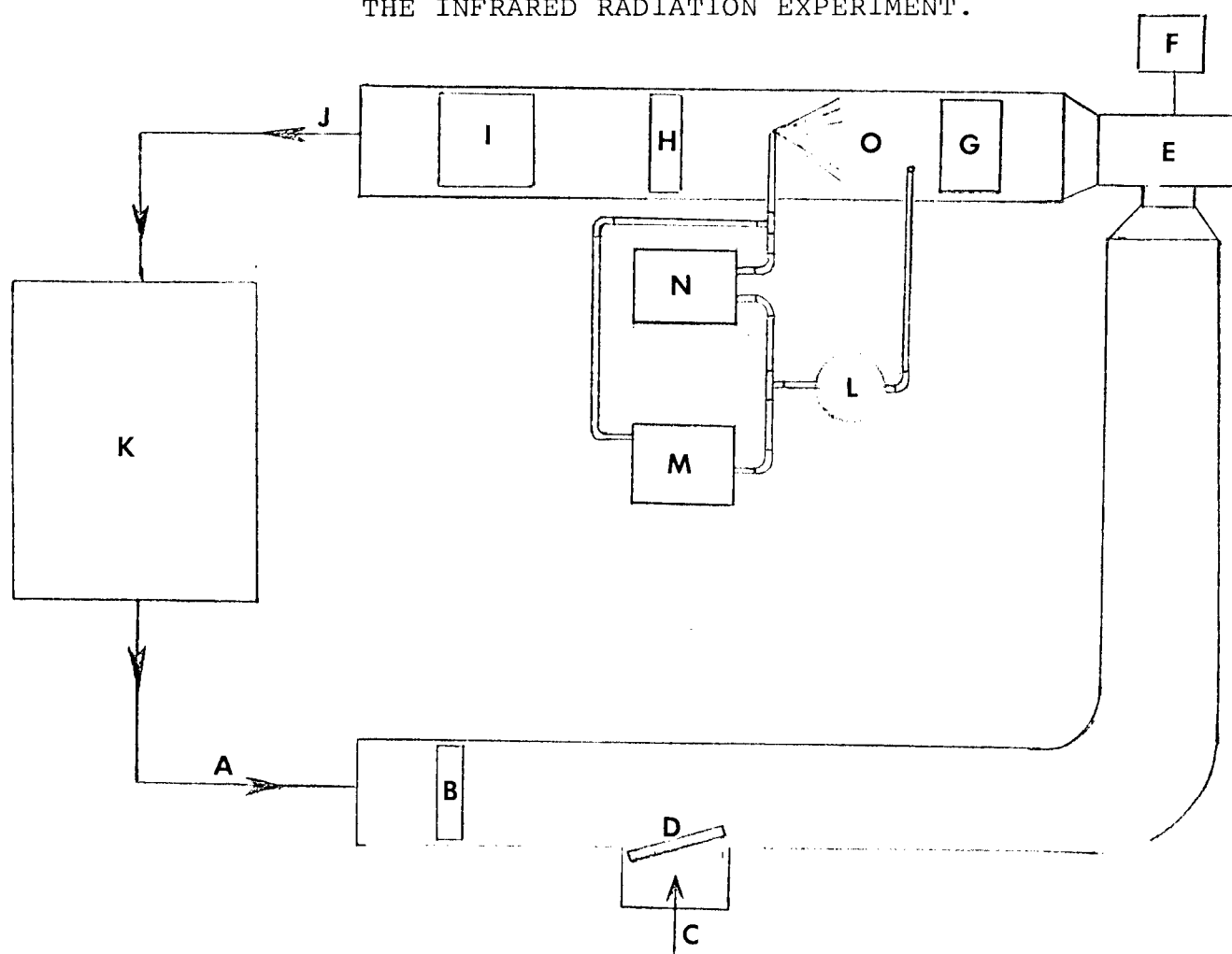
NOMENCLATURE

A: Recirculated air from chambers
B: Fibre glass filter
C: Make-up air intake
D: Damper for make-up air control
E: Centrifugal fan (3 speeds)
F: Fan electric motor
G: Chilled water cooling coil
H: Baffle
I: Hot water reheat coil
J: Conditioned air to chambers
K: Controlled environment chambers
L: Water recirculating pump
M: Water heater
N: Water chiller
O: Spray chamber

temperature of about 45°F (7.2°C).

This saturated air was conveyed to the growth chambers through flexible plastic ducts. The air entered the chambers near ceiling level and exhausted below floor level, then returned through flexible ducts to a fibre glass filter before passing over gas-filled wet and dry bulbs of a temperature recorder controller. The return air was then mixed with make up fresh air before entering a 3-speed fan to start a new cycle.

The use of the low saturation temperature of 45°F (7.2°C) was to make sure that the young birds got practically all their heat requirement from the radiant heat source. The radiant heat source was composed of 4 radiant heat panels of 750 watts capacity each, a total of 3 kilowatts per chamber. The radiant heat panels were located at about 18 inches (45.7 cm) high from the wire floor and provided almost full coverage of the ceiling surface area of the chambers.

2. Warm Air Brooding Experiment

The two controlled environment chambers used with the thermal radiation experiment were also used during this experiment, but with the radiant heat panels turned off. In order to keep the air in the chambers at some desired state a 300 cubic feet per min (8.5 m^3 min^{-1}) air conditioning unit was installed, replacing the air conditioning system used with the termal radiation experiment.

During this warm air brooding experiment, tests five and six, the air was kept at a constant relative humidity of 50 percent, while the dry bulb temperature was varying as specified in the experimental design section, Table 3.

Staley and Roberts (1969) described in detail the design and development of the controlled environment chambers used during the investigation.

DETERMINATION OF THE RADIANT HEAT LOAD
DISTRIBUTION IN THE CHAMBER

1.   Radiosity Method

Assumptions

In order to perform the radiant energy exchange
analysis among the different surfaces of the chamber, the
following assumptions are made:

1.   All the participating surfaces of the chamber are grey,
       that is the emittance of anyone of the surfaces is
       equal to its absorptance ($\varepsilon = \alpha$) for all wave-
       lengths for the range under study.

2.   Each of the participating surfaces is isothermal.

3.   The radiosity of any surface is uniform along that
       surface.

4.   The radiation emitted from any surface is diffuse.

5.   The radiation reflected from any surface is diffuse.

6.   The surfaces are separated by a non-absorbing, non-
       emitting and non-scattering medium.

Assumption number two may be achieved by subdivi-
ding non-isothermal surface into smaller surfaces. The
number of subdivisions will depend on the nature of the
problem and the degree of accuracy desired. The third
assumption is partially fulfilled by meeting assumption number
two, but in addition constant thermal properties of the sur-
face are required.

For the purpose of partially meeting the above mentioned assumptions, the walls of the chamber were divided into ten surfaces, each one of which is assumed isothermal. The development of the chamber and the identification number of the different surfaces are shown in Figure 2.

Theory

Let surface 'j' be any arbitrary surface of the participating surfaces. Surface 'j' is receiving radiation from all surfaces of the chamber including itself if surface 'j' is concave. Let this total incident radiation on surface 'j' be I_j. Part of this incident radiation is reflected from surface 'j' at a rate of $\rho_j I_j$. The remaining incident radiant energy is absorbed by surface 'j' at a rate $\alpha_j I_j$. A portion of the absorbed radiation is emitted back at a rate $\varepsilon_j \sigma T_j^4$ and the remainder is lost by conduction through the chamber walls and by convection to the air stream. Therefore, the total radiant energy leaving a surface 'j' per unit surface area per unit time is termed radiosity. Radiosity (B) is the sum of the reflected energy and the emitted energy. In equation form, the radiosity of a surface 'j' may be stated as:

$$B_j = \varepsilon_j \sigma T_j^4 + \rho_j I_j \qquad [1]$$

and for a grey-body ($\varepsilon = \alpha$).

Therefore $\rho_j = 1 - \varepsilon_j$ [2]

and equation [1] becomes,

Globe locations

40"

HEAT PANEL

①

②

⑦ ⑤ ③ ⑨

⑧ ⑥ ④ ⑩

A   B   C

1   2   3

6" 14" 14" 6"
40"

6" 14" 14" 6"

13"

29"

40"
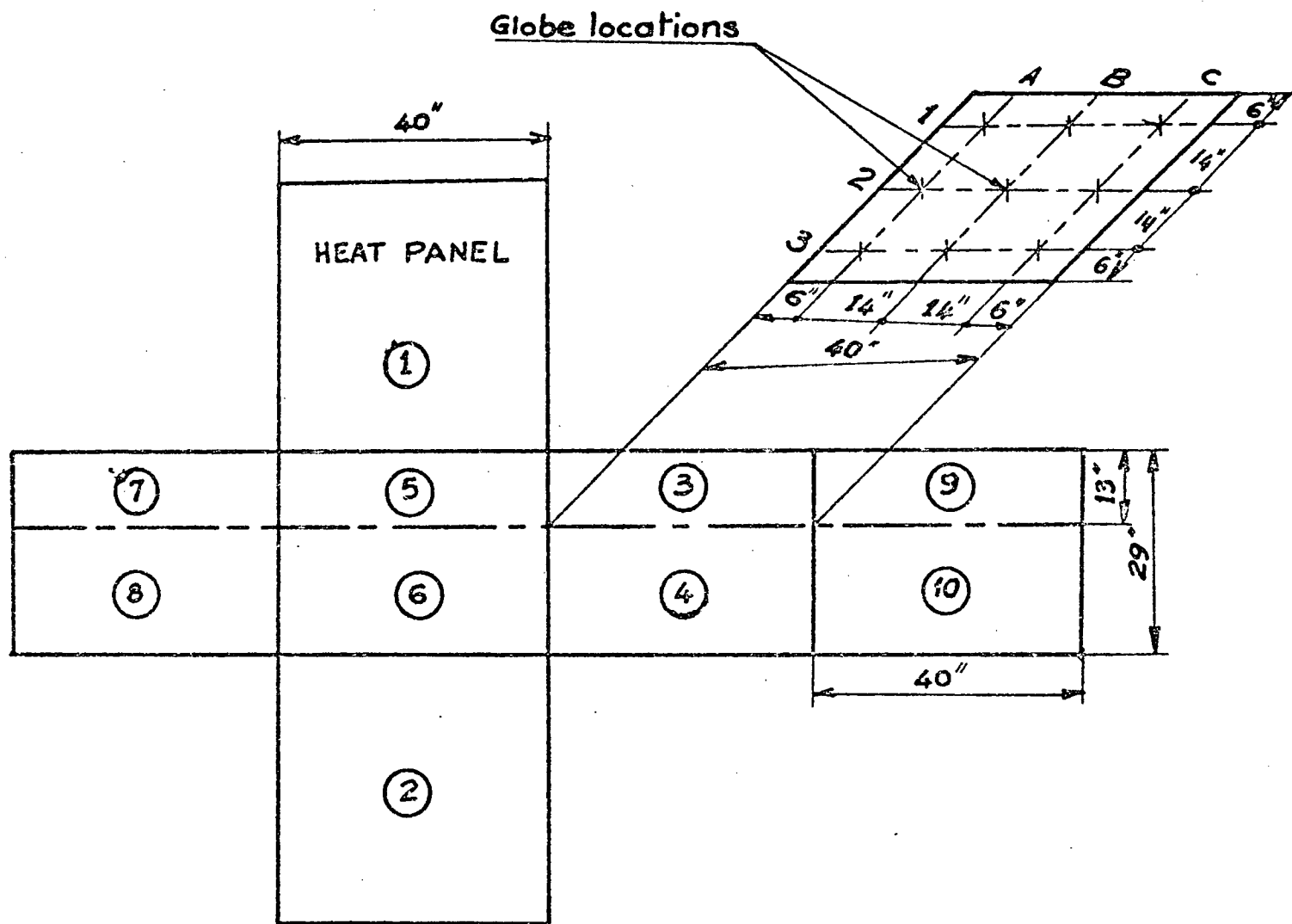
FIGURE 2. Development of the chamber showing surface
identification number and the 9 locations of
the globe.

$$B_j = \varepsilon_j \sigma T_j^4 + (1 - \varepsilon_j) I_j \qquad [3]$$

But, I_j, the total incident radiation on surface 'j' is the sum of the radiant energy, reflected and emitted, leaving every one of the participating surfaces of the chamber that is reaching surface 'j'. Or in equation form,

$$I_j = \sum_{i=1}^{n} B_i \, G_{j-i} \qquad [4]$$

where, G_{j-i} is the configuration factor between the arbitrary surface 'j' and the surface 'i'.

n = number of participating surfaces making up the enclosure.

By inserting the value of I_j into the general radiosity equation [1], we get,

$$B_j = \varepsilon_j \sigma T_j^4 + \rho_j \sum_{i=1}^{n} B_i \, G_{j-i}. \qquad [5]$$

From the above discussion it is clear that there are as many radiosities as surfaces. Therefore, an equation of the form of equation [5] may be written for each surface. Thus, we obtain a system of 'n' linear non-homogeneous algebraic equations with 'n' unknown radiosities.

Solution and Results

This sytem of linear algebraic equations may be written in simple matrix form:

$$A X = b \qquad [6]$$

where   A = matrix of coefficients,

          b = column vector of constants,

and X = column vector of unknowns.

Our problem is to find the column vector of unknowns which represents the radiosities, given the column vector of constants and the matrix of coefficients.

With some simple algebraic manipulation, equation [5] may be changed to the matrix form:

$$(1-\rho_1 G_{1-1})\, B_1 - \rho_1 G_{1-2} B_2 - \rho_1 G_{1-3} B_3 - \cdots - \rho_1 G_{1-10} B_{10} = \varepsilon_1 \sigma T_1^4$$

$$-\rho_2 G_{2-1} B_1 + (1-\rho_2 G_{2-2}) B_2 - \rho_2 G_{2-3} B_3 - \cdots - \rho_2 G_{2-10} B_{10} = \varepsilon_2 \sigma T_2^4$$

$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots$$

$$-\rho_{10} G_{10-1} B_1 - \rho_{10} G_{10-2} B_2 - \rho_{10} G_{10-3} B_3 \cdots + (1-\rho_{10} G_{10-10}) B_{10} = \varepsilon_{10} \sigma T_{10}^4$$

To solve the system of linear algebraic equations for the ten unknown radiosities, the surface temperatures as well as the configuration factor between each pair of surfaces in the chamber must be known. A minimum of three temperatures at different locations on each surface of the chamber were measured. The mean of the three or more measurements is taken as the temperature of that specific surface. These means are included in Appendix A, Table A1 along with the surface area, the material and the assumed emittance of each surface.

The configuration factors for a rectangular enclosure are easy to calculate since only two basic types of configuration are present:

1. Opposite and equal parallel rectangles, and

2. Perpendicular rectangles with a common edge.

Equations, tables and graphs used to determine the configuration factors for these two common geometries are available in most radiation heat transfer text books. The two equations used in this paper are given by Siegel and Howell (1972).

For the two equal, parallel, directly opposed rectangles,

$$
* \ G_{1-2} = \frac{2}{\pi XY} \left[\ln \left[\frac{(1+X^2)(1+Y^2)}{1+X^2+Y^2} \right]^{1/2} + X \sqrt{1+Y^2} \arctan \frac{X}{\sqrt{1+Y^2}} \right.
$$

$$
\left. + Y \sqrt{1+X^2} \arctan \frac{Y}{\sqrt{1+X^2}} - (X \arctan X) - (Y \arctan Y) \right] \quad [7]
$$

where X = a/c and Y = b/c. For the two finite rectangles of the same length, having one common edge, and perpendicular to each other

$$
** \ G_{1-2} = \frac{1}{\pi X} \left[X \arctan \frac{1}{X} + Y \arctan \frac{1}{Y} - \sqrt{X^2+Y^2} \arctan \frac{1}{\sqrt{X^2+Y^2}} \right.
$$

$$
\left. + \frac{1}{4} \ln \left\{ \left[\frac{(1+X^2)(1+Y^2)}{(1+X^2+Y^2)} \right] \left[\frac{X^2(1+X^2+Y^2)}{(1+X^2)(X^2+Y^2)} \right]^{X^2} \left[\frac{Y^2(1+X^2+Y^2)}{(1+Y^2)(X^2+Y^2)} \right]^{Y^2} \right\} \right] \quad [8]
$$

* For definition of terms refer to Figure 3a

** For definition of terms refer to Figure 3b
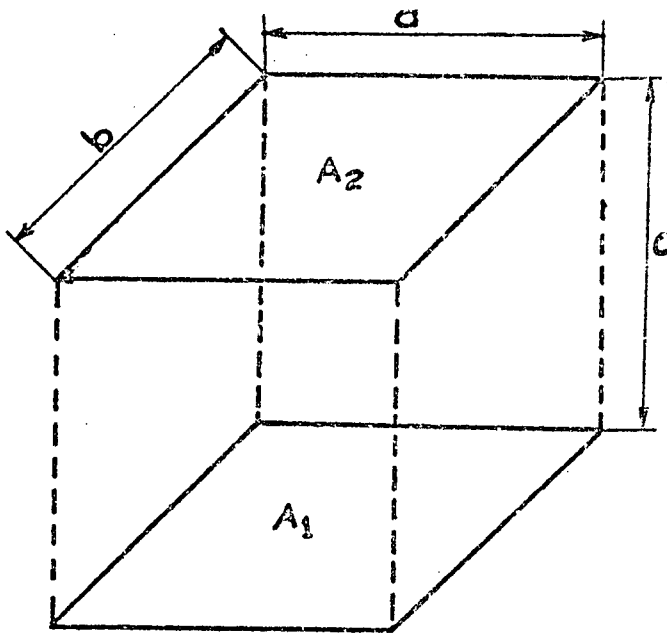
FIG. 3a

X = a/c

Y = b/c
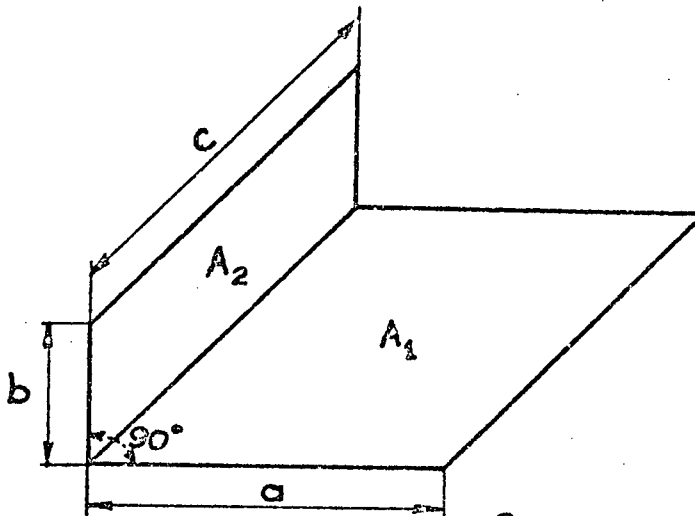
FIG. 3b

X = a/c

Y = b/c
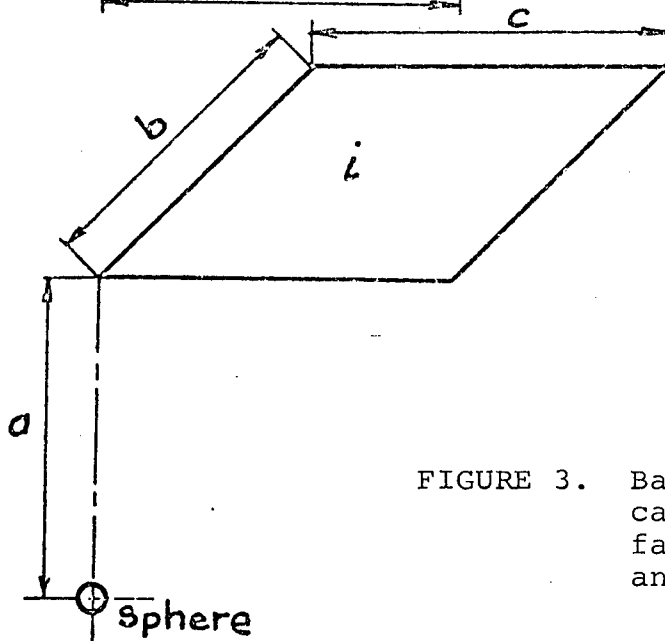
FIG. 3c

X = b/a

Y = c/a

FIGURE 3. Basic geometry used to
calculate the configuration
factors by equations 7, 8
and 18.

With the use of equations [7] and [8] along with the symmetry relations, the flux-algebra or angle-factor algebra, and the configuration factor reciprocity rule; all the one hundred configuration factors required can easily be determined.

The configuration factor reciprocity rule is

$$A_i G_{i-j} = A_j G_{j-i} \qquad [9]$$

The calculations for configuration factors use the flux algebra method which has been explained by Sparrow and Cess (1970). Using the dimensions of Figure 2 and the above equations and rules, the configuration factors were calculated and the results are shown in Appendix A, Table A2.

The sum of all the configuration factors from any surface 'j' to all the surfaces making up the enclosure must equal unity, or in equation form:

$$\sum_{i=1}^{n} G_{j-i} = 1.0. \qquad [10]$$

This sum is also shown in Table A2 as a check for errors in calculating configuration factors.

With these configuration factors and the surface temperatures, the system of linear nonhomogeneous equations can be solved on the digital computer.

The matrix of coefficients and the column vector of constants are shown in Appendix A, Table A3.

The solution of the matrix was obtained by using the Gaussian elimination method with partial pivoting. The results are summarized in Table 4.

TABLE 4.   Computer output for the value of the radiosity
           (B) in BTU hr^{-1} ft^{-2} for the 10 surfaces of the
           chamber as specified in Figure 2.

Surface	Radiosity	Surface	Radiosity
1	210.96	6	166.07
2	152.66	7	151.38
3	172.84	8	166.85
4	165.58	9	174.48
5	173.44	10	166.29

2.   Black Globe Thermometer Method

Temperature of radiant heat panels

Temperature regulation of the radiant heat panels
was critical because of the fourth power law of radiation
($q_r \propto T^4$).   An on-off Honeywell controller was tested first;
it was found that there were fluctuations up to 7°F (4°C)
in the surface temperatures of the heat panels.   In order to
minimize these fluctuations, the on-off controller was
replaced by an electronic proportional controller with
resistance type temperature sensor cemented to the surface
of the radiant heat panel.   With this proportional controller
a maximum fluctuation of 4°F (2.2°C) was encountered.

The location of the temperature sensor on the heat panel was determined by measuring the temperature on its surface at nine locations simultaneously. The measured difference in temperature between locations were within 2°F (1°C). Since these differences were well within the temperature fluctuation range, the location of the sensor on the heat panel was immaterial.

Mean Radiant Temperature (MRT), Radiant Heat Load (RHL) and Black Globe Temperature (BGT).

The MRT, like the effective temperature, the equivalent temperature and similar terms, is an environmental index rather than a real temperature. Therefore, like other thermal environmental indices, it can not be measured directly.

The MRT is a measure of the combined effects of three of the main environmental factors, namely ambient air temperature, air velocity and thermal radiation. The MRT can only be computed from the black globe thermometer data. Few papers have been written on the theory of the black globe thermometer and its application to thermal environmental studies in agriculture and other fields. Among these, Bedford and Warner (1934), Bond and Kelly (1955), Pereira et al. (1966) and Parker et al. (1967) are notable examples.

The basic black globe thermometer consisted of a temperature sensor placed at the centre of a hollow, blackened, copper sphere. Pereira et al. (1966) considered using a table tennis ball as a black globe thermometer; they found that the response time of the black globe thermometer made of a table tennis ball was considerably faster than that of the copper black globe thermometer.

The selection of the size of the sphere, the type and size of the temperature sensor is dependent on the application and the response time desired. The effect of the diameter of the sphere on the black globe temperature was discussed by Bond and Kelly (1955) and Bedford and Warner (1934).

Parker et al. (1967) discussed the effect of thermo-couple wire size on the black globe thermometer reading; they also estimated the percent error due to heat conduction for various wire sizes.

The size of the globe was selected using the surface area to volume ratio criterion. For young chicks, the surface area to volume ratio decreases with age from about 2.6 at hatch to 0.8 at 7 weeks of age. When the equivalent diameter of the bird is taken as the diameter of the sphere having the same surface area, the 2 inch (5 cm) diameter globe will have approximately the same surface area to volume ratio as a hatching bird. Therefore, the 2 inch (5 cm) diameter black globe thermometer, painted with two coats of flat black lacquer, was chosen as the standard to correlate the growth

rate of young broilers to the BGT.

Iron-constantan thermocouples were used to measure the air and globe temperatures. The size of the thermocouples (24 gauge) in this experiment was not critical because of the steady-state condition of the environmental chambers.

For a better understanding of how the MRT is related to the black globe temperature, it is helpful to examine the final result of the theory of the black globe thermometer. If it is assumed that the globe is at equilibrium with its surroundings and it is under steady state conditions, and if conduction through the thermocouple wires and the support is neglected, then the heat loss or gain by radiation must equal the heat loss or gain by convection, $(q_r = q_c)$, thus

$$h_c \sqrt{\overline{V}} \, (t_g - t_a) = \varepsilon_g \, \sigma \, (T_s{}^4 - T_g{}^4) \qquad [11]$$

Solving the above equation for the mean radiant temperature, T_s, in degrees Rankine, we get,

$$T_s = 100 \left[\frac{h_c}{\sigma \varepsilon_g} V^{0.5} (t_g - t_a) + (\frac{T_g}{100})^4 \right]^{0.25} \qquad [12]$$

and in degrees Farhenheit

$$MRT = T_s - 459.69.$$

In the above equations, the convective heat transfer coefficient (h_c) for different diameters of the globe are given by the ASHVE Research Technical Advisory Committee on

Instruments (1942). For the 2 inch diameter globe, they suggest the value of 0.202. Also, in the above equations, the emmissivity of the black globe may be taken as that of the flat black lacquer paint (ε_g = .95). By equation [12] it may be seen that in order to compute the MRT, measured values of the globe temperature, the air temperature and the air velocity near the globe are required. Also, it may be seen from equation [12] that the MRT approaches the BGT if the difference between BGT and air temperature approaches zero or the velocity of the air approaches zero (calm environmental conditions). In either case equation [12] becomes

$$\varepsilon_g \, \sigma \, (T_s^4 - T_g^4) \cong 0 \qquad\qquad [13]$$

which implies that,

$$T_s \cong T_g.$$

The MRT is a measure of the equivalent temperature of the surrounding surfaces with which the animals are exchanging radiant energy. Also, the MRT is a direct indicator of the radiant energy incident on the animals. This incident radiation, referred to as radiant heat load (RHL) by Bond and Kelly (1955), is proportional to the fourth power of the MRT, or

$$RHL = \sigma \, T_s^4. \qquad\qquad [14]$$

The MRT may be calculated using equation [12] or read directly from the nomograph, Figure 4.

DIFFERENCE BETWEEN GLOBE AND AIR TEMPERATURE $(t_g - t_a)$, °F.

Air Velocity (fpm)

Globe Temp (°F)

$t_g - t_a = 10°F$

$Velocity = 10 fpm$

$t_g = 85°F$

$Read: MRT = 91 °F$

$\varepsilon = 0.95$

$h_c = 0.202$

FIGURE 4.

MEAN RADIANT TEMPERATURE NOMOGRAPH FOR 2-IN DIAMETER
BLACK GLOBE THERMOMETER

MEAN RADIANT TEMPERATURE, °F.

32.

In order to check the variations in RHL inside the chamber the MRT was determined at nine locations* of the floor surface area. The centre of the globe was kept at about 13 inches (33 cm) from the heat panels during all the nine measurements. The air temperature was measured at about 2 inches (5 cm) from the globe by a shielded iron-constantan thermocouple.

The cooling rate of a Kata thermometer was used to determine the air velocity near the black globe at each location. The Kata thermometer was chosen because of the low velocity range encountered in the chamber. The equation used to relate the cooling time to the air velocity was given by Bruce (1960) as,

$$V = \left[\left\{ \frac{F/\emptyset}{(t_m - t_a)} - a \right\} /b \right]^2 \qquad [15]$$

where V = air velocity in fpm

         F = Kata factor

         $\emptyset$ = average cooling time in secs

         t_m = mean temperature of the Kata thermometer in °F

         t_a = air temperature in °F

a and b = constants.

The Kata factor F is supplied with each thermometer by the manufacturer. The F factor for the non-silvered thermometer employed in this experiment was 473 (cooling range 100 - 95°F).

The values of a and b as well as the mean temperature, t_m, are given by Bruce (1960) for low velocities

*   Refer to Figure 2, on page 21.

(< 180 fpm). In this experiment the velocity equation

$$V = \left[\frac{\frac{473/\emptyset}{(97.7-t_a)} - 0.111}{0.0158} \right]^2 \qquad [16]$$

was used.

Results

The computed air velocities, mean radiant temperatures, and radiant heat loads for the nine locations are tabulated in Appendix A, Table A6, along with the measured air temperatures and globe temperatures for a constant heat panel temperature of 136°F (58°C).

A correction was required to account for the size of the globe. Bond and Kelly (1955) have shown that there is an increase in globe temperature with increase in globe size. They also indicated that the 6 and 8 inch (15.2-20.3 cm) globes gave the closest values to the spherical radiometer readings. A maximum temperature difference of 7°F (3.8°C) between the 2 and 6 inch globe thermometer was reported.

The equivalent radiant heat load values corrected to the standard 6 inch (15.2 cm) diameter black globe thermometer are shown in the last row of Table A6.

3. Comparison of Radiant Heat Load Results Obtained by the Radiosity Method and the Black Globe Thermometer Method

In order to compare the results of the two methods it is necessary to calculate the incident radiation (RHL) on the globe using the predicted radiosities of the chamber

walls and heat panels. This incident radiation is the sum of the radiation streaming away from each surface of the chamber that is reaching the globe.

Let this incident radiant energy be termed I_g, then in equation form,

$$I_g = \sum_{i=1}^{n} G_i G_{g-i} \quad (n = 10) \tag{17}$$

where

$$\sum_{i=1}^{n} G_{g-i} = 1$$

G_{g-i} = configuration factor between the globe and surface 'i' of the chamber.

The configuration factors between the globe and the ten surfaces of chamber for each of the nine locations* of the globe were determined by the use of equation [18], along with the symmetry relations and flux-algebra.

$$G_{g-i}^{**} = \frac{1}{4\pi} \arcsin \frac{XY}{\sqrt{1+X^2+Y^2+X^2Y^2}} \tag{18}$$

The configuration factors for the globe at any location (A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3) to any of the ten surfaces of the chamber are tabulated in Appendix A, Table A4.

Using equation [17] and the configuration factors of Table A4, the theoretical incident radiation on the globe at each location may be calculated. The results are shown in

* Appendix A
** For definition of terms refer to Figure 3c.

Appendix A, Table A5.

For the purpose of comparison, the predicted and experimental radiant heat load values for the nine locations of the globe in the chamber, are reproduced in Table 5. The experimental values of the incident radiant energy of the globe (RHL), using the black globe thermometer method, are taken from Table A6*; and the predicted values using the radiosity method are taken from Table A5*.

Table 5 shows that the predicted mean radiant heat load in the chamber was 8.8 BTU hr^{-1} ft^{-2} (27.75 Wm^{-2}) higher than the experimental mean value. This implies, if the radiosity method was to be used to design such environmental chambers for a specific radiant heat load on certain surface of the enclosure, then the actual mean radiant heat load, as determined by the black globe thermometer would be about 5 percent lower than the required value. For most design purposes, this error is acceptable; therefore, the radiosity method is a valuable design tool, if a digital computer is accessible.

The main advantage of the radiosity method is probably the ability to change the properties of the surfaces as well as the shape of the structure, in order to obtain an even radiant energy distribution with the most efficient radiant energy utilization.

In the present experiment the predicted maxiumum difference in radiant heat load between locations, at the floor level of the chamber, was 4.0 BTU hr^{-1} ft^{-2} (12.6 Wm^{-2}), as compared to the measured maxiumum value of 6.1 BTU hr^{-1} ft^{-2} (19.2 Wm^{-2}).

* Appendix A

TABLE 5.   Predicted and experimental RHL (BTU hr^{-1} ft^{-2}) distribution in the environmental chamber.

	Location of the globe in the chamber								
	A1	A2	A3	B1	B2	B3	C1	C2	C3
Predicted	170.9	171.6	171.0	174.0	174.9	174.2	173.3	174.4	173.5
Experimental	163.8	161.8	166.2	162.7	163.3	167.9	163.6	163.3	166.3
Difference	7.1	9.8	4.8	11.3	11.6	6.3	9.7	11.1	7.2
% Error	4.3	6.0	2.8	6.9	7.1	3.7	5.9	6.7	4.3

Predicted mean RHL in the chamber = 173.1 BTU hr^{-1} ft^{-2}
= 545.88 Wm^{-2}

Experimental mean RHL in the chamber = 164.3 BTU hr^{-1} ft^{-2}
= 518.13 Wm^{-2}

Predicted maximum difference between locations in the chamber
= 4.0 BTU hr^{-1} ft^{-2}
(12.6 Wm^{-2})

Experimental maximum difference between locations in the chamber
= 6.1 BTU hr^{-1} ft^{-2}
(19.2 Wm^{-2})

Maximum difference between experimental and predicted RHL

= 11.6 BTU hr^{-1} ft^{-2} (36.58 Wm^{-2})

Mean difference between experimental and predicted RHL

= 8.8 BTU hr^{-1} ft^{-2} (27.75 Wm^{-2})

Mean percent error

= $\frac{173.1 - 164.3}{164.3}$ X 100 = 5.3%

DATA ANALYSIS

1. General Models

(a) Analysis of variance of the experimental data

The weekly body weights and growth rates were analyzed using the following statistical model:

$$Y_{ij} = \mu + d_i + \varepsilon_{ij} \qquad [19]$$

where,

Y_{ij} = the weekly body weight or growth rate of bird 'j' in treatment 'i',

μ = the true population mean,

d_i = the fixed effect of treatment 'i',

ε_{ij} = independent random normal deviates with mean zero and variance σ_e^2,

i = treatments = 1-3 for all tests except for test 4, where $i = 1, 2$

and j = $1 - n_i$ = individuals within treatments.

In order to perform the analysis of the data for the case of unequal number of observations per treatment, a Fortran program was written following the procedure of analysis outlined by Brownlee (1960), chapter 10. For the single degree of freedom contrasts, and the estimation of the confidence intervals, the Scheffé's method was used, Brownlee (1960).

The confidence interval for any contrast θ, where

$$\theta = \sum_{i=1}^{k} C_i \hat{\mu}_i \qquad [20]$$

with an estimated variance

$$\hat{V}[\theta] = \sigma_e^2 \sum_{i=1}^{k} (C_i/n_i) \qquad [21]$$

and with the restriction, $\sum\limits_{i=1}^{k} C_i = 0.$ [22]

Then, the Scheffé's limits for the contrast are

$$\pm \; S \; (\hat{V} \, [\theta])^{0.5} \qquad\qquad [23]$$

where, $S^2 = (k-1) \; F_{1-\alpha} \; (k-1, \, \nu)$ [24]

       k = number of treatments,

       ν = degrees of freedom for the error term.

(b) <u>Regression analysis of the experimental data</u>

Multiple linear regression was used to determine the coefficient of determination, R^2. Three mathematical models were fitted to the infrared brooding experimental data. These models are:

i) $Y = a_o + b_1 \, X_1 + b_2 \, X_2 + b_3 \, X_3$ [25]

where,

       Y = 3-week body weight in grams,

       X_1 = 1-week body weight in grams,

       X_2 = 1-2 week growth rate,

       X_3 = 2-3 week growth rate

and a_o, b_1, b_2 and b_3 are multiple linear regression coefficients.

ii) $Y' = a_o' + b_1' \, X_1 + b_4' \, X_4$ [26]

where,

       Y' = 3-week body weight in grams,

       X_1 = 1-week body weight in grams,

       X_4 = 1-3 week growth rate,

and a_o', b_1' and b_4' are multiple linear regression coefficients.

$$\text{iii)} \quad Y'' = a_0'' + b_1'' X_1 + b_2'' X_2 + b_3'' X_5 \qquad [27]$$

where,

$$Y'' = \text{7-week body weight in grams,}$$

$$X_1 = \text{1-week body weight in grams,}$$

$$X_2 = \text{1-3 week growth rate,}$$

$$X_5 = \text{3-7 week growth rate,}$$

and a_0'', b_1'', b_2'' and b_3'' are multiple linear regression coefficients.

For the warm air brooding experimental data, only the first two models were used, since the experiment was terminated at three weeks of age rather than seven weeks.

2. Results and Discussion of the Analyses of Variance

a) Infrared brooding experiment

TEST 1: New Hampshires

The average weekly body weights and their analyses of variance are included in Appendix B, Table B1. The average weekly growth rates as well as the average growth rates for the 1 to 3-week period and the 3 to 7-week period with their analyses of variance are included in Appendix B, Table B2. In the above mentioned two tables, the treatments were as follows:

Floor (conventional heat lamp brooding).

Chamber 1 (low radiation level brooding).

Chamber 2 (high radiation level brooding).

The analyses of variance of average weekly body weights (Table B1 (b)) show that for the first three weeks of age, the average weekly body weights of birds reared in the two chambers

were significantly higher (probably < 0.01) than the average
weekly body weights of birds reared on the floor. Table B1,
also indicates that there was no significant difference in
average weekly body weights between birds brooded under the
high level of thermal radiation (chamber 2) and birds brooded
under the low level of radiation (chamber 1). However, the
average 7-week body weight of birds brooded in the high
radiation level chamber was 25 grams higher (though
statistically non-significant) than that of birds brooded in
the low radiation level chamber. The failure of the analysis
to detect the above difference was due to the random
variations which accounted for more than 98 percent of the
total sums of squares. Furthermore, the analyses of variance
of average weekly body weights (Table B1 (b)) indicates that
the difference in average weekly body weights, between birds
brooded in chambers and birds brooded on the floor, became
non-significant during the later weeks of the test (4 to 7
weeks), when the chicks reared in the chamber for the first
three weeks of age were transferred to the floor. The failure
of the birds brooded in the chambers to maintain their
advantage in body weights over the floor birds, implies that
they suffered a depression in growth rate. This depression
started as early as the second week of growth as indicated
by the analyses of variance of average growth rates (Table
B2 (b)).

It is important to notice the highly significant average difference in the first week growth rate in favour of the chicks reared in the chambers. The average first week growth rates were 2.62 and 1.95 for chambers and for floor birds, respectively (Table B2). But, during the growth periods (1 to 3) and (3 to 7) weeks, the floor birds had significantly higher (probability < 0.01) growth rates than the corresponding growth rates for birds reared in the chambers. Even though the average growth rate of birds brooded in the chambers was 2.77 compared to 3.08 for floor birds for the same period, the birds reared in chambers finished with a highly significant average 3-week body weight over floor birds. The highest decline in growth rate for birds in the chambers was during the 3 to 4-week period. This period corresponded to the transfer of the young chicks from the chambers to the floor. The average growth rates for the 3 to 4-week period were 2.38 and 2.67 for chamber and floor birds, respectively. The cause of the reduction in growth rate during the 3 to 4-week period was due to the sudden environmental change from chambers to floor. However, it seems that after a period of acclimatization of one week, the birds, which have been transferred from the chambers to the floor, adjusted to the new environment. This adjustment to the new environment is indicated by the equal average weekly growth rates during the growth period between 4 and 7 weeks, (Table B2). The equality of weekly growth rates during the 4 to 7-weeks period implies that the significance of the difference in the 3 to 7-week period

growth rate in favour of the floor birds, was mainly due to the significant difference in the 3 to 4-week growth rate. The high reduction in growth rate during the 3 to 4-week period is an indication that the transfer of birds from the chambers to the floor was critical. In the subsequent tests, care was taken to minimize physical and environmental stresses during the transfer period. The cause of the low growth rate, during the second and third week of growth of birds in the two chambers compared to floor birds (Table B2), remains to be investigated.

The confidence interval for the contrast, chamber 1 and chamber 2 birds versus floor birds may be estimated during Scheffé's method. In equation form the contrast may be expressed as,

$$\theta = \hat{\mu}_1 + \hat{\mu}_2 - 2\hat{\mu}_3$$

where,

$\hat{\mu}_1$, $\hat{\mu}_2$, and $\hat{\mu}_3$ are estimates of the true mean of chamber 1, chamber 2, and floor birds respectively.

For the 1-week body weight, we have

$$\theta = 89 + 89 - 2(74) = 30 \text{ grams,}$$

with an estimated variance $\hat{V}(\theta)$,

$$\hat{V}[\theta] = \frac{89.8}{33} [(1)^2 + (1)^2 + (-2)^2] = 16.33$$

By equation [24],

$$s^2 = 6.24;$$

then, by equation [23], the 95 percent confidence limits are:

$$\theta = 30 \pm 10 \text{ grams.}$$

Similarly for the 2-week body weight we get,

$$\Theta = 36 \pm 21 \text{ grams,}$$

and, for the 3-week body weight,

$$\Theta = 35 \pm 33 \text{ grams.}$$

The 95 percent confidence level limits for the difference in weekly body weights between the high radiation level (chamber 2) and the conventional brooding (floor) treatments, may be calculated in a similar manner. We have the contrast,

$$\Theta = \hat{\mu}_2 - \hat{\mu}_3.$$

For the 1-week body weight,

$$\Theta = 15 \pm 6 \text{ grams.}$$

For the 2-week body weight,

$$\Theta = 20 \pm 9 \text{ grams.}$$

And for the 3-week body weight,

$$\Theta = 20 \pm 11 \text{ grams.}$$

TEST 2: U.B.C. Broilers

The average weekly body weights and their analyses of variance are shown in Appendix B, Table B3. The average weekly growth rates as well as the average growth rates for the 1 to 3-week period and the 3 to 7-week period and their analyses of variance are shown in Appendix B, Table B4. In these two tables, the treatments were as follows:

Floor   (conventional pen brooding).

Chamber 1   (high radiation level brooding).

Chamber 2   (low radiation level brooding).

The analysis of variance of the average first week body weights indicated that chicks brooded in the two chambers were significantly superior (probability < 0.01) than chicks brooded with the conventional system. This is in agreement with the results of test 2. But, unlike test 1, there was a highly significant difference (11 grams) in 1-week body weight between the two levels of thermal radiation in favour of the high level (chamber 1).

During the following weeks of the test, there was a steady decline in growth rates of birds reared in the chambers, as indicated by the average weekly growth rate analyses of variance (Table B4). This decline in growth rates, starting during the second week of growth, was mainly due to a disease (porosis) which was observed, in the chambers only, early during the second week of growth. Dead and visibly diseased birds were neglected from the reported analyses.

Using Scheffé's method, the 95 percent confidence level limits for the contrast between chicks brooded in the chambers and chicks brooded on the floor, may be calculated. We have the contrast,

$$\theta = \hat{\mu}_1 + \hat{\mu}_2 - 2\hat{\mu}_3.$$

For the 1-week body weight,

$$\theta = 75 \pm 17 \text{ grams}.$$

For the 2-week body weight,

$$\theta = 28 \pm 34 \text{ grams}.$$

And for the 3-week body weight,

$$\theta = -44 \pm 53 \text{ grams.}$$

Similarly, the 95 percent confidence level limits for the difference in weekly body weights, between high level of radiation (chamber 1) and floor treatments may be constructed. We have the contrast,

$$\theta = \hat{\mu}_1 - \hat{\mu}_3.$$

For the 1-week body weight,

$$\theta = 43 \pm 10 \text{ grams.}$$

For the 2-week body weight,

$$\theta = 19 \pm 20 \text{ grams.}$$

And for the 3-week body weight,

$$\theta = -8 \pm 31 \text{ grams.}$$

TEST 3: U.B.C. Broilers

The average weekly body weights with their analyses of variance are shown in Appendix B, Table B5. The average weekly growth rates as well as the average 1 to 3-week period and the average 3 to 7-week period growth rates are included in Appendix B, Table B6. In these tables the treatments are as follows:

Floor (conventional heat lamp brooding).

Chamber 1 (low radiation level brooding).

Chamber 2 (high radiation level brooding).

From the weekly body weight analyses of variance, Table B5, we can conclude:

First, on the average, week one and week two body
weights of the chicks brooded in the two chambers were
significantly higher (probability < 0.01) than the corres-
ponding body weights of birds brooded under heat lamps.

Second, from week three to week seven, there was no
significant difference between the average value of weekly
body weights of the birds in the chambers and the floor birds.

Third, from week two to week five, the weekly body
weights for birds brooded under high thermal radiation level
(chamber 2) were significantly higher (probability < 0.01)
than the weekly body weights for birds brooded under low
radiation level (chamber 1).

The Scheffé's limits at the 95 percent level of
confidence for the contrast

$$\Theta = \hat{\mu}_1 + \hat{\mu}_2 - 2\hat{\mu}_3$$

are, for the 1-week body weight,

$$\Theta = 19 \pm 13 \text{ grams.}$$

For the 2-week body weight,

$$\Theta = 26 \pm 24 \text{ grams.}$$

For the 3-week body weight,

$$\Theta = 22 \pm 40 \text{ grams.}$$

For the 4-week body weight,

$$\Theta = -5 \pm 57 \text{ grams.}$$

And, for the 5-week body weight,

$$\Theta = 21 \pm 77 \text{ grams.}$$

Similarly, the Scheffé's limits for the difference in weekly body weights, between the high level of thermal radiation (chamber 2) and floor treatments, are:

$$\Theta = \hat{\mu}_2 - \hat{\mu}_3$$

for the 1-week body weight,

$$\Theta = 8 \pm 7 \text{ grams.}$$

For the 2-week body weight,

$$\Theta = 20 \pm 14 \text{ grams.}$$

For the 3-week body weight,

$$\Theta = 31 \pm 23 \text{ grams.}$$

For the 4-week body weight,

$$\Theta = 24 \pm 33 \text{ grams.}$$

And for the 5-week body weight,

$$\Theta = 38 \pm 45 \text{ grams.}$$

The analyses of variance of the mean weekly growth rates for the first three week period of growth, indicated the same trend as the previous two tests. On the average, the hatch to 1-week growth rate of birds reared in the two chambers, was higher compared to the growth rate for the same period of their contemporaries reared on the floor. However, the situation was reversed during the following two weeks of growth (Table B6).

It is of importance to mention that the same disease as in test 2 was observed again within the birds in the chambers, but to a lesser degree.

TEST 4: U.B.C. Broilers

The average weekly body weights and their analyses of variance are shown in Appendix B, Table B7. The average weekly growth rates, the 1 to 3-week and the 3 to 7-week growth rates and their analyses of variance are shown in Appendix B, Table B8. In these tables, the two treatments are as follows:

Floor (conventional heat lamp brooding).

Chamber 2 (high radiation level, the same starting black globe temperature as in the previous tests, but the final globe temperature was increased from 70°F (21°C) to 80°F (26.7°C)).

The average weekly growth rate analyses of variance show an alternating trend of significance and non-significance. This trend is unique to this test, and it is probably a result of the modified rate of black globe temperature drop.

In the previous tests, the average hatch to 1-week growth rate of birds brooded in the chambers was significantly higher than that of birds brooded on the floor, while in this test the situation was reversed. Therefore, maintaining a black globe temperature of 88°F (31.1°C), Table 2, for the whole first week of the test had an adverse effect on growth rate of chamber birds. The reverse situation occurred again during the second week of growth. The chamber birds had a superior 1 to 2-week growth rate to floor birds, while in the previous tests, the opposite situation occurred. Therefore, during the second week of growth, a black globe

temperature of 84°F (28.9°C), Table 2, was better for growth than a black globe temperature of 82°F (27.8°C) dropping to 76°F (24.4°C) during the later part of the week, Table 1. Finally, the present test indicated no significant difference in the 2 to 3-week growth rate between chamber and floor birds, while previous tests showed a superior growth rate during the third week of growth in favour of floor birds. Therefore, a black globe temperature of 80°F (26.7°C) during the third week gave slightly better results than a globe temperature of 73°F (22.8°C) dropping to 70°F (21°C).

b) Warm Air Brooding Experiment: Commercial Broilers

TESTS: 5 and 6

The mean weekly body weight with their analyses of variance for test 5 and for test 6, females and males, are included in Appendix C, Tables C1, C3, C5 and C7, respectively. The average weekly growth rates as well as the 1 to 3-week growth rates with their analyses of variance are also included in Appendix C, Tables C2, C4, C6 and C8, respectively.

The body weight analyses of variance indicated a significant difference in the 1-week body weights in favour of the birds reared in the chambers compared to birds reared on the floor. This difference was present in both tests and for both sexes. But, during the following two weeks, the difference in body weights remained significant for females only.

It is important to note the significant difference in 3-week body weight between the two chambers. This difference was in favour of birds in chamber 1. It is also important to note that the above trend was consistently present in both tests and for both sexes. The analyses of variance tables for growth rates (Appendix C) indicated that the growth rate of birds in chamber 2 started to fall behind that of birds in chamber 1 during the second week of growth. Also, these tables indicated that the difference in growth rates of the two chambers become highly significant during the third week. During this period, the growth rates of the male birds in test 5 were 3.39 and 3.12 for chamber 1 and chamber 2, respectively; and, in test 6, they were 3.19 and 2.86 for chamber 1 and chamber 2, respectively. The cause of the difference in growth rates could not be environmental, since the two chambers were practically at the same environmental conditions. The cause of this difference was due to the fact that the feeder in chamber 2 was smaller than the feeder in chamber 1. Obviously, the capacity of the feeder did not influence the birds during the early stage of growth but, as the feed consumption increased, the feeder capacity became a factor.

3. Results of the Linear Multiple Regression Analyses

    a) Infrared brooding experiment

The simple and multiple coefficients of determination (R^2) for the 3-week body weight with 1-week body weight,

1 to 2-week growth rate, 2 to 3-week growth rate and 1 to 3-week growth rate, are shown in Appendix D (Table D1). For all treatments, the 1-week body weight alone explained between 70%-85%, 26%-59%, 41%-62% and 47%-54% of the variability in the 3-week body weight for test 1, 2, 3 and 4 respectively. The simple correlation coefficients between the 3-week body weight and each one of the three growth rates listed above, were generally low and non-significant. It is interesting to note that only the following two traits, 1-week body weight and 1 to 3-week growth rate, were needed to account for almost 100 percent of the variability in the 3-week body weight.

The coefficients of determination for the 7-week body weight with 1-week body weight, 1 to 3-week growth rate and 3 to 7-week growth rate are included in Appendix D (Table D2). It is of interest to note that for all treatments the correlations between the 7-week body weight and 1-week body weight (Table D2) were lower than the correlations between 3-week body weight and 1-week body weight (Table D1). As was expected, the combination of the three traits, 1-week body weight, 1 to 3-week growth rate and 3 to 7-week growth rate, explained most of the variability in the 7-week body weight.

b)   Warm Air Brooding Experiment

The coefficients of determination for the 3-week body weight with 1-week body weight, 1 to 2-week growth rate,

2 to 3-week growth rate and 1 to 3-week growth rate are
tabulated in Appendix D (Table D3) for test 5 and (Table D4)
for test 6.

The regression analyses for the two tests indicated
that the 1-week body weight explained between 44 and 76 per-
cent (a significant amount) of the variation associated with
the 3-week body weight, assuming all other independent
variables were kept constant. The other simple coefficients
of determination were generally low. As in the infrared
brooding experiment, the following two traits, 1-week body
weight and 1 to 3-week growth rate explained almost all the
variability in the 3-week body weight.

4. Infrared and Warm Air Brooding: A Comparison

For the purpose of comparison, Table 5 was constructed
which represents a summary of the results for the brooding
period, hatch to three weeks of age. Test 1 was neglected,
because New Hampshires were   used as experimental material
instead of broilers;   therefore, no comparison could be made
between test 1 and other tests of the experiment.

Table 5 shows the average weekly body weights in
grams and their resulting average weekly growth rates. The
actual treatments with their identifications are listed below
the table. As the table indicates, some of the treatments were
replicated once or more.

It is of interest to note the growth rate trend of
each treatment. During all the tests, the growth rates of the

TABLE 6. Average weekly body weights in grams and average weekly growth rates as by treatment, for tests 2, 3, 4, 5 and 6 (males).

	Test No	Treat-ment	Age (weeks)				Growth period			
			H	1	2	3	H-1	1-2	2-3	n
Floor	2	E	43	98	294	543	2.87	4.95	3.37	22
	3	E	45	127	283	511	3.65	3.57	3.25	30
	4	E	47	124	278	500	3.34	3.63	3.22	37
	5	E	46	115	290	542	3.14	4.15	3.43	24
	6	E	41	116	268	497	3.60	3.74	3.40	23
Chamber 1	2	A	43	141	313	535	4.08	3.60	2.93	20
	3	C	44	138	289	502	3.95	3.33	3.03	25
	5	D	48	126	301	559	3.36	3.91	3.39	14
	6	D	42	124	277	496	3.77	3.60	3.19	18
Chamber 2	2	C	42	130	303	507	3.89	3.81	2.82	25
	3	A	44	135	303	542	3.88	3.64	3.18	27
	4	B	47	120	288	519	3.28	3.92	3.22	26
	5	D	48	125	297	525	3.34	3.90	3.12	18
	6	D	41	125	269	452	3.89	3.42	2.86	11

Nomenclature below:

A: High radiation level brooding, final BGT of 70°F (21.1°C)

B: High radiation level brooding, final BGT of 80°F (26.7°C)

C: Low radiation level brooding, final BGT of 70°F (21.1°C)

D: Warm air brooding, relative humdity = 50%

E: Heat lamps brooding.

H: Hatch

n: Number of birds

TABLE 7. Scheffé's limits at the 95% confidence level for the specified contrasts for tests 2, 3, 5 and 6 (males).

| | | | AGE | |
	Contrast *	Test No.	Week 1	Week 2	Week 3
$\Theta = \hat{\mu}_1 + \hat{\mu}_2 - 2\hat{\mu}_3$		2	75 ± 17	28 ± 34	-44 ± 53
		3	19 ± 13	26 ± 24	22 ± 40
		5	21 ± 17	18 ± 37	0 ± 60
		6	17 ± 15	10 ± 35	-46 ± 60
$\Theta = \hat{\mu}_1 - \hat{\mu}_3$		2	43 ± 10	19 ± 20	-8 ± 31
$\Theta = \hat{\mu}_2 - \hat{\mu}_3$		3	8 ± 7	20 ± 14	31 ± 23
$\Theta = \hat{\mu}_1 - \hat{\mu}_3$		5	11 ± 10	11 ± 23	17 ± 37
$\Theta \quad \hat{\mu}_1 - \hat{\mu}_3$		6	8 ± 8	9 ± 19	-1 ± 33

*

$\hat{\mu}_1$ = estimated mean of chamber 1 birds

$\hat{\mu}_2$ = estimated mean of chamber 2 birds

$\hat{\mu}_3$ = estimated mean of floor birds

floor birds indicated a low-high-low trend. The low hatch to 1-week growth rate indicated the birds were stressed during their first week of growth. This stress was due to either a recovery from hatching effect and/or an environmental effect. The same growth rate trend occurred during test 4, in chamber 2, with the high radiation level and high final black globe temperature treatment. However, during tests 2 and 3, in chambers 1 and 2, with the high level of radiation and low final black globe temperature treatment, the growth rates showed a decreasing trend with age. These growth rate trends indicated the importance of the rate of change of the black globe temperature with time.

Furthermore, a table of confidence intervals is included for a better appreciation of the difference between some of the treatment means of Table 5. These confidence limits at the 95 percent level, for some selected contrasts, are shown in Table 6. The largest treatment difference of 43 $\pm$ 10 grams occurred during test 2. This difference was between the high level thermal radiation and the floor treatments.

CONCLUSIONS

The intensity and uniformity of thermal radiation within the controlled environment chambers were studied using the following two methods:

a)   The radiosity method.

b)   The black globe thermometer method.

The incident radiant energy was determined at nine different locations within the chamber, and it was found that:

a)   The variations between locations were small.

b)   For all locations, the radiosity method predicted about

   5 percent higher values of incident radiation than

   values determined by the black globe thermometer.

A first experiment was designed to study the effects of infrared energy on poultry. A total of 311 young male chicks, 99 New Hampshires, and 212 U.B.C. broilers were used in the experiment. This experiment consisted of four tests, with three treatments in each test; a high radiation level, a low radiation level and a conventional heat lamp brooding system. It was found that:

a)   On the average, the weekly body weights, for the first

   three of growth, of birds brooded under the low and

   high levels of radiation were significantly higher

   than the corresponding body weights of birds reared

   under heat lamps.

b)   Birds brooded under the high level of radiation were

   superior to birds brooded under the low level of

   radiation.

A second experiment was designed to compare warm air brooding to heat lamp brooding. A total of 212 mixed sex commercial broilers were used in the experiment. This experiment consisted of two tests, with the treatments in each test; chamber 1, chamber 2 and floor (heat lamp brooding). The two chambers were maintained at the same environmental conditions for each test. It was found that:

a) On the average, the weekly body weights of birds with warm air were higher than the weekly body weights of birds brooded under heat lamps.

b) There was a significant chamber effect, during the third week of growth, in favour of chamber 1.

When the high level of thermal radiation of the first experiment was compared to the warm air experiment, the weekly body weights of the former treatment were higher or at least equal to the weekly body weights of the latter treatment.

LIST OF REFERENCES

1. ASHVE Research Technical Advisory Committee on Instruments. "Measurement of physical properties of the thermal environment", Heating, Piping and Air Conditioning, 14: 382-385, 1942.

2. Baker, V.H. and J.H. Bywaters. "Brooding Poultry with Infrared Energy". Agr. Eng. 42: 316-320, June 1951.

3. Baxter, D.O., T.E. Maddox and H.V. Shirley. "Temperature preferences of chicks". Trnasactions of the ASAE, Vol. 13, No. 6, pp. 788-791, 1970.

4. Bedford, T. and C.G. Warner. "The globe thermometer in studies of heating and ventilating". Journal of Hygiene, 34: 458, 1934.

5. Bond, T.E. and C.E. Kelly. "The globe thermometer in agricultural research". Agr. Eng. 36: 251-255, April, 1955.

6. Brownlee, K.A. Statistical Theory and Methodology in Science and Engineering. John Wiley & Sons, N.Y. 1960.

7. Bruce, W. Man and His Thermal Environment. Technical Paper No. 84, Division of Building Research, National Research Council of Canada, Ottawa, NRC 5514, pp. 123-126, February 1960.

8. Longhouse, A.D. and H.L. Garver. "Poultry environments".
    ASHRAE Journal, 68-74, July 1964.

9. McCluskey, W.H. and G.H. Arscott. "The influence of
    incandescent and infrared light upon chicks".
    Poultry Science, 46: 528-29, 1967.

10. Parker, B.F., E.M. Smith and B.P. Verma. "Black sphere
    thermal radiometry". Transactions of the ASAE 10:
    780-783, 1967.

11. Pereira, N., T.E. Bond and S.R. Morrison. "Thermal
    characteristics of a table-tennis-ball used as a
    black-globe thermometer". ASAE paper No.66-328,
    1966.

12. Roberts, C.W. "Estimation of early growth rate in the
    chicken". Poultry Science, 43: 238-252, January,
    1964.

13. Siegel, R. and J.R. Howell. Thermal Radiation Heat
    Transfer. McGraw-Hill Book Company, N.Y., 1972.

14. Skoglund, W.C. and D.H. Palmer. "Light intensity studies
    with broilers". Poultry Science, 41: 1839-1842,
    1962.

15. Sparrow, E.M. and R.D. Cess. Radiation Heat Transfer.
    Brooks/Cole Publishing Company, Belmont, California,
    1970.

16. Staley, L.M., C.W. Roberts and D.C. Crober. "The effect
    of thermal radiation on early growth of the New
    Hampshire chicken". Can. Agr. Eng. 9: 39-42,
    January, 1967.

17. Staley, L.M. and C.W. Roberts. "Design and development of controlled environment brooders for poultry". Can. Agr. Eng. 11: 71-73, November 1969.

18. Staley, L.M., C.W. Roberts and S. Paulson. "Improved growth of poultry utilizing controlled environments". Can. Agr. Eng. 12: 76-79, November 1970.

APPENDIX   A

TABLE A1

AVERAGE SURFACE TEMPERATURE EMITTANCE AND SURFACE AREA OF THE SURFACES OF THE CHAMBER.

Surface No.	Material	Surface Size (in.)	Emittance	Average Temperature (°F)
1	white paint	40 x 40	0.90	136
2	wood	40 x 40	0.85	82
3	oxidized alum.	40 x 13	0.20	74
4	"	40 x 16	0.20	68
5	"	40 x 13	0.20	82
6	"	40 x 16	0.20	70
7	plexiglass	40 x 13	0.90	82
8	oxidized Al	40 x 16	0.20	70
9	"	40 x 13	0.20	87
10	"	40 x 16	0.20	72

TABLE A2

CONFIGURATION FACTORS BETWEEN THE SURFACES OF THE
CHAMBER.

i	F_{1-i}	F_{2-i}	F_{3-i}	F_{4-i}	F_{5-i}	F_{6-i}	F_{7-i}	F_{8-i}	F_{9-i}	F_{10-i}
1	0	0.293	0.329	0.175	0.329	0.175	0.329	0.175	0.329	0.175
2	0.293	0	0.160	0.312	0.160	0.312	0.160	0.312	0.160	0.312
3	0.107	0.052	0	0	0.125	0.048	0.070	0.065	0.125	0.048
4	0.070	0.125	0	0	0.060	0.139	0.080	0.096	0.060	0.139
5	0.107	0.052	0.125	0.049	0	0	0.125	0.048	0.070	0.065
6	0.070	0.125	0.060	0.139	0	0	0.060	0.139	0.080	0.096
7	0.107	0.052	0.070	0.065	0.125	0.049	0	0	0.125	0.048
8	0.070	0.125	0.080	0.096	0.060	0.139	0	0	0.060	0.139
9	0.107	0.052	0.125	0.049	0.070	0.065	0.125	0.049	0	0
10	0.070	0.125	0.060	0.139	0.080	0.096	0.060	0.139	0	0
Total	1.001	1.001	1.009	1.025	1.009	1.023	1.009	1.023	1.009	1.022

TABLE A3

THE MATRIX OF COEFFICIENTS AND THE COLUMN VECTOR OF CONSTANTS FOR THE
SOLUTION OF THE SYSTEM OF LINEAR NONHOMOGENEOUS EQUATIONS ON DIGITAL COMPUTERS

+1.0	-0.0293	-0.0107	-0.0070	-0.0107	-0.0070	-0.0107	-0.0070	-0.0107	-0.0070	B_1	194.64
-0.0439	+1.0	-0.0078	-0.0187	-0.0078	-0.0187	-0.0078	-0.0187	-0.0078	-0.0187	B_2	125.73
-0.2632	-0.1280	+1.0	0.0	-0.1000	-0.0480	-0.0560	-0.0640	-0.1000	-0.0480	B_3	27.87
-0.1400	-0.2497	0.0	+1.0	-0.0392	-0.1112	-0.0520	-0.0768	-0.0392	-0.1112	B_4	26.64
-0.2632	-0.1280	-0.1000	-0.0480	+1.0	0.0	-0.1000	-0.0480	-0.0560	-0.0640	B_5	29.58
-0.1400	-0.2496	-0.0384	-0.1112	0.0	+1.0	-0.0392	-0.1112	-0.0520	-0.0768	B_6	27.05
-0.0329	-0.0160	-0.0070	-0.0080	-0.0125	-0.0060	+1.0	0.0	-0.0125	-0.0060	B_7	133.12
-0.1400	-0.2496	-0.052	-0.0768	-0.0384	-0.1112	0.0	+1.0	-0.0392	-0.1112	B_8	27.05
-0.2632	-0.128	-0.1000	-0.0480	-0.0560	-0.0640	-0.1000	-0.0480	+1.0	0.0	B_9	30.69
-0.1400	-0.2496	-0.0384	-0.1112	-0.0520	-0.0768	-0.0384	-0.1112	0.0	+1.0	B_{10}	27.46

TABLE A4

CONFIGURATION FACTOR BETWEEN THE SPHERE AT DIFFERENT
LOCATIONS AND THE WALLS OF THE CHAMBER.

Surface	LOCATION OF GLOBE IN CHAMBER								
	A1	A2	A3	B1	B2	B3	C1	C2	C3
1	0.162	0.203	0.162	0.203	0.248	0.203	0.162	0.203	0.162
2	0.138	0.168	0.138	0.168	0.208	0.168	0.138	0.168	0.138
3	0.025	0.029	0.025	0.051	0.063	0.051	0.144	0.168	0.144
4	0.030	0.035	0.030	0.059	0.073	0.059	0.151	0.177	0.151
5	0.144	0.051	0.025	0.168	0.063	0.029	0.144	0.051	0.025
6	0.151	0.059	0.030	0.177	0.073	0.035	0.151	0.059	0.030
7	0.144	0.168	0.144	0.051	0.063	0.051	0.025	0.029	0.025
8	0.151	0.177	0.151	0.059	0.073	0.059	0.030	0.035	0.030
9	0.025	0.051	0.144	0.029	0.063	0.168	0.025	0.051	0.144
10	0.030	0.059	0.151	0.035	0.073	0.177	0.030	0.059	0.151
$\sum_{i=1}^{10} F_{g-i}$	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

TABLE A5

INCIDENT RATIATION*ON THE GLOBE FOR THE 9 LOCATIONS

Surface No.	LOCATION OF GLOBE ON THE CHAMBER								
	A1	A2	A3	B1	B2	B3	C1	C2	C3
1	34.18	42.82	34.18	42.82	52.32	42.82	34.18	42.82	34.18
2	21.08	25.65	21.08	25.65	31.75	25.65	21.08	25.65	21.08
3	4.32	5.01	4.32	8.81	10.89	8.81	24.89	29.04	24.89
4	4.97	5.80	4.97	9.77	12.09	9.77	25.00	29.31	25.00
5	24.96	8.85	4.34	29.14	10.93	5.03	24.96	8.85	4.34
6	25.08	9.80	4.98	29.39	12.12	5.81	25.08	9.80	4.98
7	21.80	25.43	21.80	7.72	9.54	7.72	3.78	4.39	3.78
8	25.19	29.53	25.19	9.84	12.18	9.84	5.00	5.84	5.00
9	4.36	8.90	25.12	5.06	11.00	29.31	4.36	8.90	25.12
10	4.99	9.81	25.11	5.82	12.14	29.43	4.99	9.81	25.11
Total	170.93	171.60	171.09	174.02	174.96	174.19	173.32	174.41	173.48

* Units: BTU hr^{-1} ft^{-2}

TABLE A6

AIR VELOCITY, AIR TEMPERATURE, GLOBE TEMPERATURE AND RESULTING MEAN
RADIANT TEMPERATURE OF THE GLOBE FOR THE 9 LOCATIONS (heat panel
temperature = 136°F = 58°C)

	LOCATION OF GLOBE IN THE CHAMBER									
	A1	A2	A3	B1	B2	B3	C1	C2	C3	Mean
Air velocity (FPM)	7.0	3.2	4.3	7.0	3.6	7.6	20.0	24.7	14.8	10.2
Air temperature (°F)	74.0	74.0	75.0	69.5	78.0	74.0	65.5	68.0	73.0	72.3
Globe temperature (°F)	80.2	80.6	83.1	78.0	82.4	82.4	73.6	74.0	79.3	79.3
MRT (°F)	83.5	82.9	86.3	82.5	85.1	86.8	80.8	79.8	84.0	83.5
RHL (BTU hr^{-1} ft^{-2})	150.9	150.3	153.1	149.9	152.7	154.7	147.9	146.9	151.6	150.9
RHL (corrected to the standard 6 in black globe)	163.8	161.8	166.2	162.7	163.3	167.9	163.6	163.3	166.3	164.3

APPENDIX   B

TABLE B1

a) Average weekly body weights[a] of test 1 as by treatment.

Treatment	(n)	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Floor	(33)	42	74	148	256	386	535	719	923
Chamber 1	(33)	41	89	164	271	391	539	720	926
Chamber 2	(33)	42	89	168	276	399	554	740	951
Mean	(99)	42	84	160	268	392	543	726	933

b) Weekly body weight analyses of variance in percentage of total sums of squares
    of test 1 for treatment effect.

S.V.	d.f.	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Treatments	2	1.2	37.3**	16.2**	7.3**	1.3	1.6	1.6	1.9
-Chambers vs floor	1	-	37.3**	15.7**	6.9**	0.9	0.7	0.4	0.6
-Chamber 1 vs Chamber 2	1	-	0.0	0.5	0.4	0.4	0.9	1.2	1.3
Error	96	98.8	62.7	83.8	92.7	98.7	98.4	98.4	98.1
Total	98	1,031	13,756	47,548	101,729	210,241	376,566	555,727	771,999

** Highly significant (P $\leq$ 0.01)

*   Significant   (P $\leq$ 0.05)

a   in grams

TABLE B2

a) Average growth rates of test 1 as by treatment.

Treatment	(n)	Growth Period								
		H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Floor	(33)	1.95	3.13	3.01	2.67	2.46	2.51	2.38	3.08	2.52
Chamber 1	(33)	2.64	2.74	2.76	2.39	2.41	2.47	2.39	2.75	2.41
Chamber 2	(33)	2.60	2.84	2.73	2.38	2.45	2.47	2.39	2.79	2.42
Mean	99	2.40	2.90	2.83	2.48	2.44	2.48	2.39	2.87	2.45

b) Growth rate analyses of variance in percentage of total sums of squares
    of test 1 for treatment effect.

S.V.	d.f.	Growth Period								
		H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Treatments	2	37.4**	32.21**	25.6**	34.0**	2.21	0.8	0.1	49.7**	14.7**
-Chambers vs floor	1	37.3**	30.3**	25.3**	34.0**	0.7	0.8	0.1	49.0**	14.6**
-Chamber 1 vs Chamber 2	1	0.1	1.9	0.3	0.0	1.5	0.0	0.0	0.7	0.1
Error	96	62.6	67.8	74.4	66.0	97.8	99.2	99.9	50.3	85.3
Total	98	26.92	8.50	6.19	5.26	2.08	4.31	3.43	4.28	1.52

** Highly significant ($P \leq 0.01$)

*   Significant   ($P \leq 0.05$)

a) Average weekly body weights[a] of test 2 as by treatment.

Treatment	(n)	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Floor	(22)	43	98	294	543	812	1108	1469	1826
Chamber 1	(20)	43	141	313	535	800	1117	1458	1814
Chamber 2	(25)	42	130	303	507	771	1083	1428	1795
Mean	(67)	43	123	303	528	794	1103	1452	1812

b) Weekly body weight analyses of variance in percentage of total sums of squares of test 2 for treatment.

S.V.	d.f.	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Treatments	2	2.5	67.4**	7.7	13.4*	7.4	2.8	2.6	0.8
-Chambers vs floor	1		63.1**	5.3	6.5*	4.2	0.3	1.4	0.5
-Chamber 1 vs Chamber 2			4.3**	2.4	6.8*	3.2	2.5	1.2	0.3
Error	64	97.5	32.6	92.3	86.6	92.6	97.2	97.4	99.2
Total	66	514	32,075	49,291	123,264	284,484	492,960	852,416	1,423,984

** Highly significant (P ≤ 0.01)

* Significant (P ≤ 0.05)

a in grams

a) Average growth rates of test 2 as by treatment.

		Growth Period								
Treatment	(n)	H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Floor	(22)	2.87	4.95	3.37	2.62	2.33	2.40	2.06	4.24	2.38
Chamber 1	(20)	4.08	3.60	2.93	2.61	2.50	2.26	2.06	3.30	2.39
Chamber 2	(25)	3.89	3.81	2.82	2.72	2.55	2.34	2.17	3.36	2.48
Mean	(67)	3.61	4.12	3.04	2.65	2.46	2.33	2.10	3.63	2.42

b) Growth rate analyses of variance in percentage of total sums of squares of test 2 for treatment effect.

		Growth Period								
S.V.	d.f.	H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Treatments	2	67.2**	67.3**	51.0**	7.9	23.0**	11.1*	5.7	81.8**	15.8**
-Chambers vs floor	1	65.8**	65.8**	49.4**	1.9	21.9**	7.0*	1.6	81.6**	5.8*
-Chamber 1 vs Chamber 2	1	1.4	1.5	1.6	6.0*	1.1	4.1	4.1	0.2	10.0**
Error	64	32.8	32.7	49.0	92.1	77.0	88.9	94.3	18.2	84.2
Total	66	27.64	33.98	7.59	2.26	2.75	2.06	3.45	14.62	0.89

** Highly significant ($P \leq 0.01$)

* Significant ($P \leq 0.05$)

TABLE B5

a) Average weekly body weights[a] of test 3 as by treatment.

Treatment	(n)	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Floor	(30)	45	127	283	511	776	1086	1435	1792
Chamber 1	(25)	44	138	289	502	747	1069	1420	1781
Chamber 2	(27)	44	135	303	542	800	1124	1466	1815
Mean	(82)	44	133	292	518	774	1093	1440	1796

b) Weekly body weight analyses of variance in percentage of total sums of squares of test 3 for treatment effect.

S.V.	d.f.	AGE							
		Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Treatments	2	0.5	13.3**	15.2**	18.8**	15.4**	10.4*	4.3	1.5
-Chambers vs floor	1	-	12.6**	9.0**	2.2	0.0	0.6	0.3	0.1
-Chamber 1 vs Chamber 2	1	-	0.7	6.2*	16.6**	15.4**	9.8**	4.0	1.4
Error	79	99.5	86.7	84.8	81.2	84.6	89.6	95.7	98.5
Total	81	784	11,612	42,029	121,692	231,120	402,368	285,216	1,050,640

** Highly significant (P ≤ 0.01)

* Significant   (P ≤ 0.05)

a   in grams

a)   Average growth rates of test 3 as by treatment.

Treatment	(n)	Growth Period								
		H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Floor	(30)	3.65	3.57	3.25	2.72	2.52	2.36	2.11	3.43	2.46
Chamber 1	(25)	3.95	3.33	3.03	2.58	2.68	2.41	2.15	3.20	2.48
Chamber 2	(27)	3.88	3.64	3.18	2.53	2.55	2.26	2.03	3.43	2.37
Mean	(82)	3.83	3.51	3.15	2.61	2.58	2.34	2.10	3.35	2.44

b)   Growth rate analyses of variance in percentage of total sums of squares
     of test 3 for treatment effect.

S.V.	d.f.	Growth Period								
		H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Treatments	2	15.4**	29.1**	29.4**	16.4**	18.3**	13.3**	7.7*	33.6**	16.4**
-Chambers vs floor	1	14.7**	2.2	21.9**	15.7**	7.9**	0.7	0.5	7.8**	2.4
-Chamber 1 vs Chamber 2	1	0.7	26.9**	7.5**	0.7	10.4**	12.6**	7.2*	25.8**	14.0**
Error	79	84.6	70.9	70.6	83.6	81.7	86.7	92.3	66.4	83.6
Total	(81)	9.34	4.09	3.88	3.26	2.13	2.56	2.70	2.81	1.08

**   Highly significant (P $\leq$ 0.01)

*   Significant   (P $\leq$ 0.05)

TABLE B7

a) Average weekly body weights[a] of test 4 as by treatment.

Treatment	(n)	Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
					A G E				
Floor	(37)	47	124	278	500	765	1082	1438	1799
Chamber 2	(26)	47	120	288	519	775	1087	1411	1770
Mean	(63)	47	122	283	510	770	1085	1425	1785

b) Weekly body weight analyses of variance in percentage of total sums of squares of test 4 for treatment.

S.V.	d.f.	Hatch	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
					A G E				
Chamber 2 vs floor	1	0.6	2.0	4.7	4.9	0.6	0.1	1.5	1.1
Error	61	99.4	98.0	95.3	95.1	99.4	99.9	98.5	98.9
Total	62	762	8,261	36,109	114,451	252,304	446,016	744,592	1,190,896

** Highly significant (P ≤ 0.01)

* Significant (P ≤ 0.05)

a in grams

TABLE B8

a) Average growth rates of test 4 as by treatment.

		Growth Period								
Treatment	(n)	H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
Floor	(37)	3.34	3.63	3.22	2.76	2.59	2.42	2.13	3.44	2.51
Chamber 2	(26)	3.28	3.92	3.22	2.61	2.53	2.22	2.15	3.61	2.40
Mean	(63)	3.31	3.78	3.22	2.69	2.56	2.32	2.14	3.53	2.46

b) Growth rate analyses of variance in percentage of total sums of squares
   of test 4 for treatment effect.

		Growth Period								
S.V.	d.f.	H-1	1-2	2-3	3-4	4-5	5-6	6-7	1-3	3-7
-Chamber 2 vs floor	1	1.0	30.8**	0.0	18.3**	1.8	29.9**	0.3	16.8**	17.2**
Error	61	99.0	69.2	100.0	81.7	98.2	70.1	99.7	83.2	82.8
Total	62	7.12	4.20	2.16	2.00	3.05	2.08	3.12	2.31	0.96

** Highly significant (P ≤ 0.01)

* Significant   (P ≤ 0.05)

APPENDIX   C

TABLE C1

a) Average weekly body weights in grams of test 5 (males)·
by treatment

Treatment	(n)	Hatch	Weeks of Age 1	2	3
Floor	(24)	46	115	290	542
Chamber 1	(14)	48	126	301	559
Chamber 2	(18)	48	125	297	525
Mean	(56)	47	122	296	542

b) Weekly body weight analyses of variance in percentage sums
of squares of test 5 (males) for treatment effect.

S.V.	d.f.	Weeks of Age 1	2	3
Treatments	2	16.3**	3.1	8.4
- Chambers vs floor	1	16.3**	2.8	0.0
- Chamber 1 vs Chamber 2	1	0.0	0.3	8.4*
Error	53	83.7	96.9	91.6
Total	55	9,595	39,659	110,637

** Highly significant (P $\leq$ 0.01)

* significant (P $\leq$ 0.05)

TABLE C2

a)   Average growth rates of test 5 (males) by treatment.

Treatment	(n)	Growth Period			
		H-1	1-2	2-3	1-3
Floor	(24)	3.14	4.15	3.43	3.83
Chamber 1	(14)	3.36	3.91	3.39	3.68
Chamber 2	(18)	3.34	3.90	3.12	3.55
Mean	(56)	3.28	3.99	3.31	3.69

b)   Growth rate analyses of variance in percentage sums of
     squares of test 5 (males) for treatment effect.

S.V.	d.f.	Growth Period			
		H-1	1-2	2-3	1-3
Treatments	2	10.4	18.7**	33.5**	34.8**
- Chambers vs floor	1	10.4*	18.7**	15.8**	29.3**
- Chamber 1 vs Chamber 2	1	0.0	0.0	17.7**	5.5*
Error	53	89.6	81.3	66.5	65.2
Total	55	5.661	4.415	3.224	2.343

** Highly significant (P ≤ 0.01)

* Significant   (P ≤ 0.05)

TABLE C3

a) Average weekly body weights in grams of test 5 (females).
    by treatment.

Treatment	(n)	Weeks of Age			
		Hatch	1	2	3
Floor	(16)	47	109	265	469
Chamber 1	(25)	47	125	285	505
Chamber 2	(20)	46	120	276	480
Mean	(61)	47	118	275	485

b) Weekly body weight analyses of variance in percentage sums
    of squares of test 5 (females) for treatment effect.

S.V.	d.f	Weeks of Age		
		1	2	3
Treatments	2	22.1**	9.4	12.4*
- Chambers vs floor	1	19.5**	7.4*	6.1
- Chamber 1 vs Chamber 2	1	2.6	2.0	6.3*
Error	58	77.9	90.6	87.6
Total	60	10,557	42,084	117,353

** highly significant $(P \leq 0.01)$

*   significant $(P \leq 0.05)$

TABLE C4

a) Average growth rates of test 5 (females) by treatment.

Treatment	(n)	Growth Period			
		H - 1	1 - 2	2 - 3	1 - 3
Floor	(16)	2.93	3.95	3.15	3.59
Chamber 1	(25)	3.40	3.70	3.15	3.45
Chamber 2	(20)	3.34	3.75	3.04	3.43
Mean	(61)	3.22	3.80	3.11	3.49

b) Growth rate analyses of variance in percentage sums of squares of test 5 (females) for treatment effect.

S.V.	d.f.	Growth Period			
		H - 1	1 - 2	2 - 3	1 - 3
Treatments	2	23.2**	19.3**	10.6*	16.7**
- Chambers vs floor	1	22.8**	18.5**	1.8	16.2**
- Chamber 1 vs Chamber 2	1	0.4	0.8	8.8*	0.5
Error	58	76.8	80.7	89.4	83.3
Total	60	10.358	3.322	1.705	1.657

** highly significant ($P \leq 0.01$)

* significant ($P \leq 0.05$)

TABLE C5

a) Average weekly body weights in grams of test 6 (males).
    by treatment

Treatment	(n)	Weeks of Age			
		Hatch	1	2	3
Floor	(23)	41	116	268	497
Chamber 1	(18)	42	124	277	496
Chamber 2	(11)	41	125	269	452
Mean	(52)	41	122	271	482

b) Weekly body weight analyses of variance in percentage sums
    of squares of test 6 (males) for treatment effect.

S.V.	d.f.	Weeks of Age		
		1	2	3
Treatments	2	13.8*	2.9	17.2*
- Chambers vs floor	1	13.7**	1.5	4.3
- Chamber 1 vs Chamber 2	1	0.1	1.4	12.9**
Error	49	86.2	97.1	82.8
Total	51	6,101	30,384	102,778

** highly significant (P $\leq$ 0.01)

* significant (P < 0.05)

TABLE C6

a) Average growth rates of test 6 (males) by treatment .

Treatment	(n)	Growth Period			
		H-1	1-2	2-3	1-3
Floor	(23)	3.60	3.74	3.40	3.58
Chamber 1	(18)	3.77	3.60	3.19	3.42
Chamber 2	(11)	3.89	3.42	2.86	3.17
Mean	(52)	3.75	3.59	3.15	3.39

b) Growth rate analyses of variance in percentage sums of squares of test 6 (males) for treatment effect.

S.V.	d.f.	Growth Period			
		H-1	1-2	2-3	1-3
Treatments	2	14.7*	19.8**	50.6**	59.5**
- Chambers vs floor	1	12.5**	11.8**	32.6**	40.1**
- Chamber 1 vs Chamber 2	1	2.2	8.0*	18.0**	19.4**
Error	49	85.3	80.2	49.4	40.5
Total	51	5.000	2.802	4.329	2.238

** Highly significant ($P \leq 0.01$)

* Significant ($P \leq 0.05$)

TABLE C7

a) Average weekly body weights in grams at test 6 (females).
by treatment

Treatment	(n)	Weeks of Age			
		Hatch	1	2	3
Floor	(10)	40	103	229	405
Chamber 1	(13)	41	114	251	446
Chamber 2	(20)	40	120	256	433
Mean	(43)	40	112	245	428

b) Weekly body weight analyses of variance in percentage sums of squares of test 6 (females) for treatment effect.

S.V.	d.f.	Weeks of Age		
		1	2	3
Treatments	2	37.6**	20.4*	13.7
- Chambers vs floor	1	31.7**	19.5**	12.0*
- Chamber 1 vs Chamber 2	1	5.9	0.9	1.7
Error	40	62.4	79.6	86.3
Total	42	5,470	23,492	73,524

** Highly significant ($P \leq 0.01$)

*   Significant   ($P \leq 0.05$)

TABLE C8

a) Average growth rates of test 6 (females) by treatment.

Treatment	(n)	Growth Period			
		H-1	1-2	2-3	1-3
Floor	(10)	3.32	3.58	3.11	3.37
Chamber 1	(13)	3.56	3.53	3.16	3.37
Chamber 2	(20)	3.84	3.38	2.88	3.15
Mean	(43)	2.57	2.50	3.05	3.30

b) Growth rate analyses of variance in percentage sums of
    squares of test 6 (females) for treatment effect.

S.V.	d.f.	Growth Period			
		H-1	1-2	2-3	1-3
Treatments	2	41.4**	15.8*	39.7**	35.8**
- Chambers vs floor	1	27.9**	7.3[a]	5.5[a]	10.0*
- Chamber 1 vs Chamber 2	1	13.5**	8.5[a]	34.2**	25.8**
Error	40	58.6	84.2	60.3	64.2
Total	42	4.738	2.239	1.864	1.375

** Highly significant (P $\leq$ 0.01)

* Significant   (P $\leq$ 0.05)

a Approaching significance

APPENDIX   D

TABLE D1

Multiple linear regression analyses for
tests 1 to 4, with 3-week body weight
as dependent variable.

Treatment	Dependent variables				R^2 for test			
	X_1	X_2	X_3	X_4	1	2	3	4
Floor	*				70.7	25.9	61.6	47.4
		*			1.0	19.9	2.8	3.3
			*		1.0	32.0	0.3	8.4
				*	0.0	6.7	1.9	7.6
	*	*			88.4	89.3	83.0	83.7
	*		*		88.9	46.9	81.5	83.6
	*			*	99.5	99.2	99.8	99.8
	*	*	*		99.5	99.4	99.8	99.8
Chamber 1	*				85.6	30.6	42.9	
		*			48.7	0.8	9.5	
			*		4.0	15.8	0.0	
				*	25.7	1.5	5.4	
	*	*			93.7	59.6	77.1	
	*		*		88.7	49.0	61.1	
	*			*	99.5	99.3	99.6	
	*	*	*		99.7	99.3	99.6	
Chamber 2	*				70.0	58.5	40.8	53.9
		*			20.4	0.0	0.0	2.0
			*		1.4	15.0	5.8	0.0
				*	19.3	6.3	1.0	1.1
	*	*			92.3	87.3	81.9	90.7
	*		*		70.1	58.5	77.0	77.2
	*			*	99.8	99.8	99.4	98.4
	*	*	*		99.8	99.8	99.4	98.5

X_1 = 1-week body weight.
X_2 = 1-2 week growth rate.
X_3 = 2-3 week growth rate.
X_4 = 1-3 week growth rate.

TABLE D2

Multiple linear regression analyses for
tests 1 to 4, with 7-week body weight as
dependent variable.

| Treatment | Dependent variables | | | R^2 for test | | | |
	X_1	X_2	X_3	1	2	3	4
Floor	*			19.2	17.2	16.2	28.4
		*		11.4	8.4	4.9	9.9
			*	0.6	0.3	10.4	2.0
	*	*		66.6	82.7	40.4	74.5
	*		*	54.9	20.1	53.5	41.6
	*	*	*	98.3	99.4	99.7	99.5
Chamber 1	*			71.1	14.0	25.3	
		*		24.9	1.5	1.5	
			*	11.2	54.3	22.6	
	*	*		85.3	52.6	51.6	
	*		*	79.5	69.9	54.4	
	*	*	*	99.3	99.5	99.6	
Chamber 2	*			63.0	38.3	4.8	7.4
		*		11.2	0.9	7.7	12.0
			*	0.0	5.6	6.0	8.4
	*	*		82.0	54.4	41.0	47.1
	*		*	68.4	57.4	24.7	42.8
	*	*	*	99.5	99.7	98.9	97.4

X_1 = 1-week body weight.
X_2 = 1-3 week growth rate.
X_3 = 3-7 week growth rate.

TABLE D3

Multiple regression analyses for test 5,
with 3-week body weight as dependent variable.

Treatment	X_1	X_2	X_3	X_4	R^2 (males)	R^2 (females
Floor	*				54.8	70.6
		*			26.0	21.2
			*		10.2	1.7
				*	4.4	12.3
	*	*			92.3	93.4
	*		*		67.6	76.6
	*	*	*		99.8	99.7
	*			*	99.8	99.7
Chamber 1	*				43.6	60.8
		*			2.9	0.4
			*		14.4	0.5
				*	11.6	0.6
	*	*			79.1	84.8
	*		*		63.4	75.5
	*	*	*		99.8	99.6
	*			*	99.7	99.6
Chamber 2	*				74.0	62.4
		*			12.3	1.0
			*		2.6	1.0
				*	16.0	1.0
	*	*			81.7	91.6
	*		*		77.2	83.4
	*	*	*		99.2	99.5
	*			*	98.3	99.5

X_1 = 1-week body weight.
X_2 = 1-2 week growth rate.
X_3 = 2-3 week growth rate.
X_4 = 1-3 week growth rate.

TABLE D4

Multiple regression analyses for test 6,
with 3-week body weight as dependent variable.

Treatment	X_1	X_2	X_3	X_4	R^2 (males)	R^2 (females)
Floor	*				65.0	75.5
		*			1.3	55.0
			*		4.5	6.6
				*	12.3	52.7
	*	*			69.5	94.5
	*		*		82.4	86.6
	*	*	*		84.6	99.9
	*			*	99.7	99.9
Chamber 1	*				58.5	55.2
		*			3.1	5.4
			*		8.0	6.4
				*	8.5	1.0
	*	*			81.7	90.2
	*		*		80.2	56.8
	*	*	*		99.7	99.7
	*			*	99.7	99.6
Chamber 2	*				68.4	52.3
		*			22.9	14.6
			*		5.8	27.9
				*	9.6	33.8
	*	*			86.4	87.8
	*		*		71.1	77.2
	*	*	*		99.8	99.6
	*			*	99.7	99.6

X_1 = 1-week body weight.
X_2 = 1-2 week growth rate.
X_3 = 2-3 week growth rate.
X_4 = 1-3 week growth rate.