SOME EFFECTS OF ELECTROMAGNETIC ENERGY AND SUBATOMIC PARTICLES ON CERTAIN INSECTS WHICH INFEST WHEAT, FLOUR, AND BEANS

By

Vernon Hunter Baker

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

Year 1953

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AN ABSTRACT

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Approved D. E. Wiant

The destruction caused by harmful insects costs the American people about four billion dollars each year. Stored grains, flour, and cereal products are subject to attack by insects which cause at least $300,000,000 loss annually in the United States. Many chemicals are now used for the control of insects. Some of these chemicals may not be effective and may have residual effect on the product which would cause detrimental effects on human beings and livestock.

Insect control by energy in various parts of the electromagnetic spectrum has been the objective of many investigators. The effects of electromagnetic energy with frequencies up to a value equivalent to a wavelength of about 2880 Angstroms are mainly that which can be accomplished by heating. These frequencies include radio, microwave, infrared, and a portion of the ultraviolet spectrum. Far-ultraviolet, x-rays, and gamma rays can cause chemical changes in insects which cause lethal effects. Inefficiency of generation, penetration, and utilization of ultraviolet and x-rays would make these areas of the spectrum impractical for insect control.

Gamma radiation from radioactive isotopes offer possibilities of an effective means for killing insects in stored products as soon as shielding and conveying problems can be solved, together with the development of an economical source of radioisotope material.

Vernon Hunter Baker

The use of accelerated electrons or cathode rays for the control of insects in stored products offers advantages over gamma radiation. Accelerated electrons can be effectively applied to materials on a moving conveyor belt, and the shielding problem is not as great as with gamma radiation. The use of accelerated electrons present interesting possibilities for insect control and food preservation. It was found in this study that a dose of 10,000 rep would sterilize insect eggs and prevent adults from reproducing. Higher doses were required to kill adult insects. The installation and maintenance costs involved may limit the extent of use of accelerated electrons in the immediate future, but this fact should not stop research workers from investigating further the use of accelerated electrons or cathode rays in food processing.

In the final analysis, the application of electrical methods for destroying insects in stored products must be more effective than present mechanical methods of performing the same operation. One fact which must not be overlooked is that even if insects can be killed in stored products by electrical means, some mechanical method must be used to remove the insect fragments before the food can be lawfully sold for human consumption.

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candidate for the degree of

Doctor of Philosophy

Final examination: August 6, 1953, 10:00 A.M., Agricultural Engineering Conference Room

Dissertation: Some Effects of Electromagnetic Energy and Subatomic Particles on Certain Insects which Infest Wheat, Flour, and Beans

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INTRODUCTION

In the 1952 Yearbook of Agriculture it is stated that the destruction by harmful insects costs the American people about four billion dollars each year. Millions of dollars are spent each year on the control of insects with various degrees of success. Stored grains, flour, and cereal products are subject to attack by insects which, according to Cotton (1), cause at least $300,000,000 loss annually in the United States. Many chemicals are now widely used for the control of insects. Some of these chemicals may have a residual effect on the product and may be poisonous to human beings and livestock.

A few of the insects which attack wheat and beans are able to bore into the sound kernel and deposit their eggs in the kernel. When the eggs hatch, the young larvae consume practically the entire kernel. The granary weevil, *Sitophilus granarius* (L.), is one of the most damaging insects to grain. The adult weevil lives approximately 7½ months, each female laying between 300 and 400 eggs during this period (1). During warm weather the egg, larval, and pupal stages may be completed in less than 30 days.

The flour beetle, *Tribolium confusum* Duv., may be found in flour, prepared cereals and in grain. This insect is most commonly found in flour after it leaves the mill. The female may live for a year or more and lay 400 to 500 eggs. Under favorable conditions the development period from egg to adult may be as short as 30 days.

The bean weevil, *Acanthoscelides obtectus* (Say), is found where beans and peas are grown and stored. All kinds of beans and peas stored for seed or food, unless they are protected, are almost sure to be devoured or rendered useless by these hungry weevils. Breeding goes on steadily as long as there is any food left in the beans, either in the field or in storage, and the temperature is warm enough. The adults deposit eggs in or on the bean. The larval and pupal stages are passed inside the bean seed. The pupa develops into an adult and then eats its way out of the bean. Six or seven generations may be completed in a year, and as many as 28 weevils have been known to develop in one bean (2).

The object of trying to develop a means of controlling insects with electromagnetic energy and subatomic particles is to have an effective control without any residual affect on the product on which the insect lives.

Electromagnetic energy includes radiant energy of various wave lengths, such as radio or hertzian waves, infrared, visible and ultraviolet, x-rays, gamma and cosmic rays. Subatomic particles include electrons or beta particles, protons, neutrons, alpha particles or helium nuclei, mesons and positrons.

All matter, including insects, is made up of some of the basic elements. Each of these elements is composed of atoms and subatomic particles. The atom consists of a nucleus surrounded by negatively charged particles called electrons. The combination of the electrons and nucleus is often referred to as the atomic polar system, because it has been shown that electrons revolve about the nucleus, at relatively great distance from the nucleus, with a definite pattern.

Recent tests with the atomic bomb have shown that the energy contained within the atom is astounding. In the atomic bomb the atoms of uranium are broken apart and a tremendous amount of energy liberated. It has been demonstrated that an atom can be changed by less forceful means than with the atomic bomb explosion. Radiant energy (including electromagnetic energy and subatomic particles) may be used in various amounts and intensities to accomplish this. Radiant energy may be used to increase the natural vibration of atoms and molecules. This vibration of the atoms and molecules results in an increase in temperature of the material. Molecules also may be struck with enough energy to break off electrons and leave fragments called ions.

The physics involved in the application of electromagnetic energy and subatomic particles to biological materials is extremely complex. Very little is known about what gives life to a given arrangement of molecules in a living cell. Living organisms comprise such complicated patterns of molecules that scientists have not been able to devise techniques for analyzing the action of the various molecules within a living cell.

The science of atomic physics is progressing rapidly. The new knowledge from atomic research may help the scientist to investigate further the basic affects of radiant energy on living cells. The basic atomic knowledge that is known today should assist in forming some fundamental criteria for analyzing the possible effects of electromagnetic energy and subatomic particles on insects. When radiant energy is applied to an insect, it is difficult to determine which factors or combinations of factors cause death. Each type of radiation results in an effect on the molecule; some of these effects may be lethal to the cells of an insect while other effects may not cause damage to the organism.

Literature Cited

(1) Cotton, R. T., Insect Pests of Stored Grain and Grain Products, Burgess Publishing Co., Minneapolis, Minn. 1952, p. 1.

(2) Metcalf, C. L. and Flint, W. P., Destructive and Useful Insects, McGraw-Hill Book Co., New York, N.Y., 1939, p. 808-811.

OBJECTIVES

The objectives of this study are to:

1. Make an analytical study of the electromagnetic spectrum in order to predict that portion of the spectrum in which energy would likely cause a heating effect and that portion of the spectrum which would cause an ionization effect or chemical change in an insect.
2. Present a theory of electromagnetic radiation and develop equations which will give the relationships between the various factors involved when an insect on a plant is radiated with electromagnetic energy from a radiating source such an an antenna, black body radiation, x-ray, and gamma radiation.
3. Conduct a literature survey on radio frequency dielectric heat as a means of controlling insects and present a theory of dielectric heating.
4. Investigate the lethal effect of electromagnetic energy on insects in the following areas: (a) microwaves - 10-12 cm, (b) infrared, (c) ultraviolet, and (d) x-rays. Conduct literature survey and conduct as many tests as feasible in these areas using the flour beetle, granary weevil and bean weevil.
5. List the properties of the various subatomic particles and from the literature determine which particle has the

most possibilities for having lethal effects on living cells. Conduct tests with the particle that shows the most promise.

PART I

THEORY OF ELECTROMAGNETIC RADIATION

The Electromagnetic Spectrum

Classical theory in physics points out that all electromagnetic waves are similar, differing only in frequency or wavelength, regardless of the method of generation. In the use of electromagnetic energy the engineer will more than likely be concerned with electromagnetic energy from some particular source and thus should be interested in the source which generates this energy. For this reason this discussion will be devoted to the energy in electromagnetic waves from different sources of electromagnetic radiation with various wavelengths, and the absorption of various wavelengths by different materials.

An electromagnetic wave may be considered to consist of a component of an electrical field and a component of a magnetic field. A field is defined as a region in which a particular kind of force is exerted. These two components in a polarized wave in free space are at right angles to each other in a plane perpendicular to the direction of travel, and the energy is divided between the magnetic field component and the electric field component (Fig. 1).

The electric field or lines of force is considered to begin on a plus charge and end on a minus charge. These

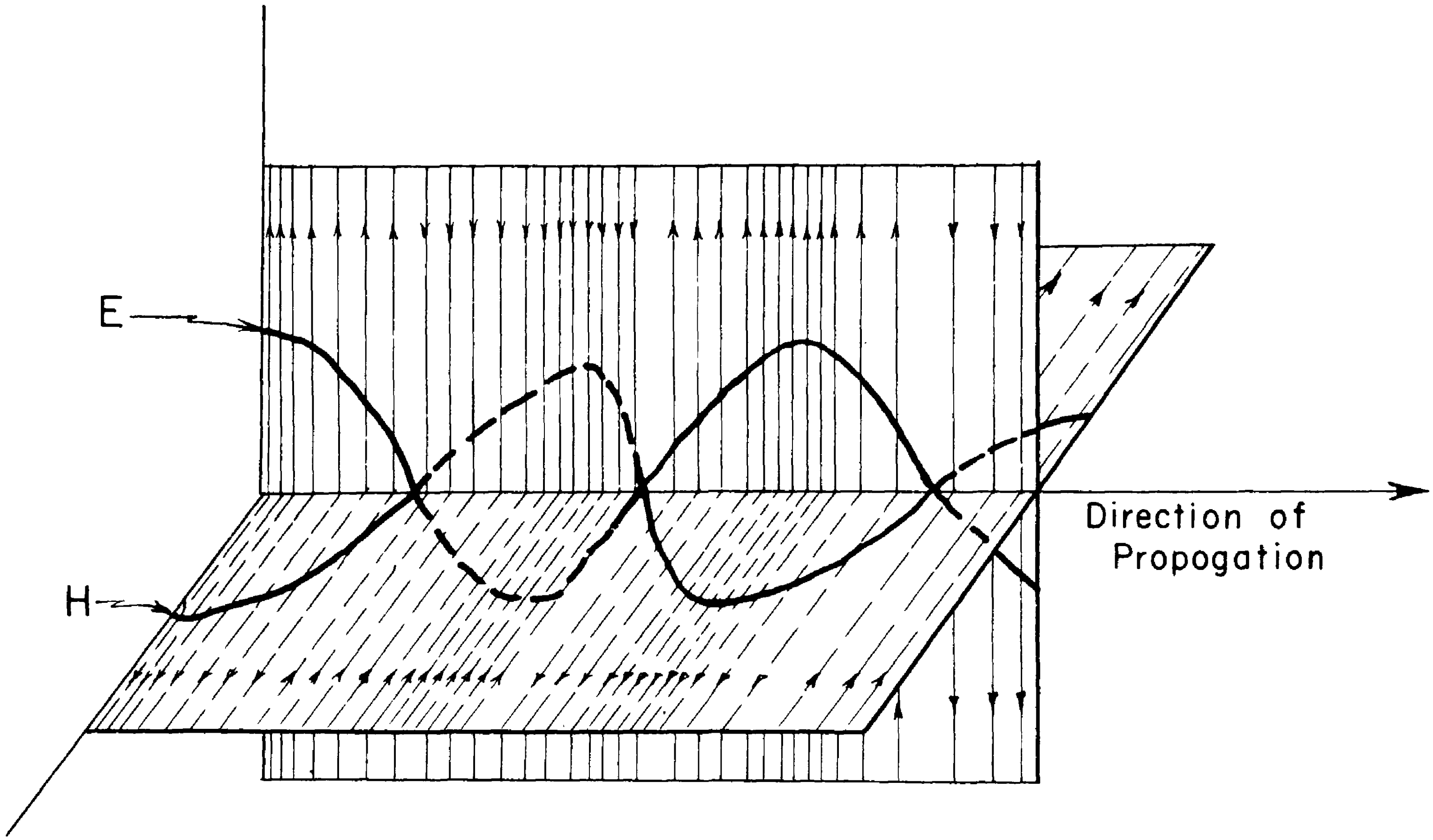

Fig. I Sketch of a plane polarized electromagnetic wave in space lines of force or flux do not form a closed loop. An electrostatic field can be only static. The electric field may generally be referred to as static or dynamic. The divergence of the electrostatic induction of any point in a medium, where the charge density is finite, is equal to the charge density of that point. At points in a medium where the charge density is zero, the divergence of the electrostatic induction is zero.

If free magnetic poles exist the conditions of the magnetostatic field are identical with those of an electrostatic field. If, as generally believed, no free magnetic poles exist, then all lines of force in a magnetic field are continuous, i.e., they form a complete loop, and the divergence of magnetic induction is zero. A magnetic field can be static or dynamic with respect to change in direction.

An electromagnetic wave thus contains a component of electric lines of force, and a component of magnetic lines of force which form a closed loop, and the varying electric field produces a changing magnetic field. Each component vibrates with the same frequency, and in free space, the two components are in equal phase, Fig. 1. The two components are at right angles to each other and are perpendicular to the direction of propagation.

Radio and Hertzian waves including far infrared differ from other forms of electromagnetic radiation, such as light and x-rays, in their wavelength, the manner in which they are generated and detected. As previously mentioned, the properties of radiations of various wavelengths are identical and are independent of the method of production; only the frequency is important in determining their properties (1). In this presentation a theory will be presented dividing the spectrum on the method of generation. This first discussion will be devoted to that part of the spectrum which can be obtained with electronic tubes and resonant circuits of inductance and capacitance.

The wavelength spectrum of Hertzian or radio waves, Figs. 2A and 2B and Table 1, is greater than either visible light or x-rays and ranges from 30,000 meters to less than one centimeter. This corresponds to a frequency range of about 10,000 cycles to 3,000,000 megacycles. Electromagnetic radio waves travel at the same velocity as light waves, i.e., about 186,000 miles per second in free space, and can be reflected, refracted, and diffracted. These properties will not be discussed here. Further information may be found in almost any practical or classical physics book. Before discussing further the properties of electromagnetic waves, a mathematical expression for the energy in an electromagnetic wave will be presented in order to have some basis as a criterion for determining the lethal effects of electromagnetic waves on insects when the insects are irradiated by energy from an antenna.

Ohm, Faraday, Henry, Lenz, Kirchoff, and Gauss presented

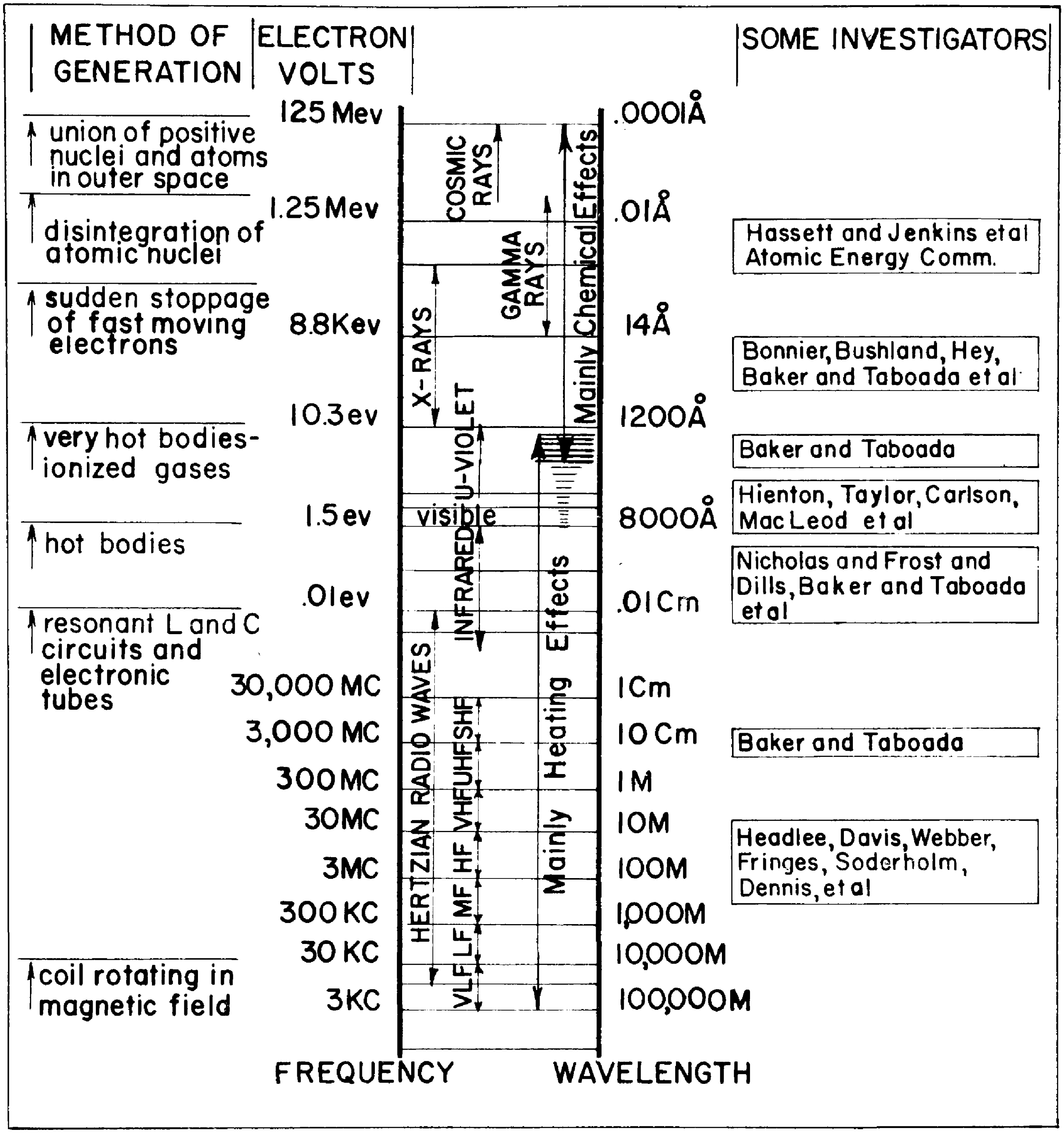

Fig 2A. The electromagnetic spectrum with method of generation and a partial list of investigators of the lethal effects on certain insects

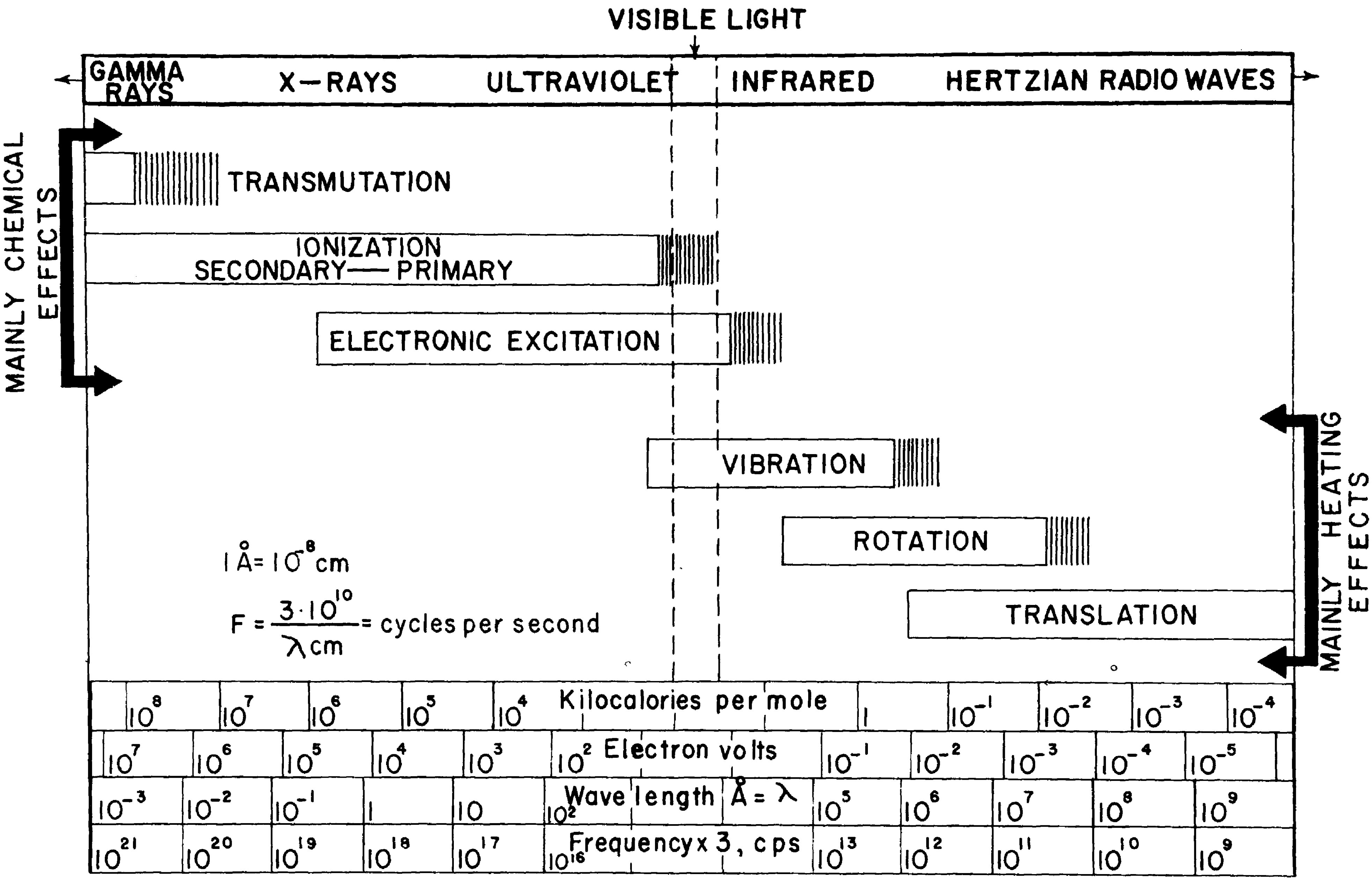

Fig 2B. The primary processes of the reaction of electromagnetic energy with matter – adapted from a chart released by Brookhaven National Laboratory under contract with the United States Atomic Energy Cmmission.

Type of Radiation	Cycles per Sec. Frequency	Wavelength-(cm)*
Electric waves	$0-10^{4}$	$0-3 \times 10^{6}$
Radio waves	$10^{4} - 10^{11}$	$3 \times 10^{6} - 0.3$
Infrared	$10^{11} - 4 \times 10^{14}$	$0.3 - 7.6 \times 10^{-5}$
Visible	$4 \times 10^{14} - 7.5 \times 10^{14}$	$7.6 \times 10^{-5} - 4 \times 10^{-5}$
Ultraviolet	$7.5 \times 10^{14} - 3 \times 10^{18}$	$4 \times 10^{-5} - 10^{-8}$
X-ray	$3 \times 10^{16} - 3 \times 10^{20}$	$10^{-6} - 10^{-10}$
Gamma rays	$3 \times 10^{19} - 3 \times 10^{22}$	$10^{-9} - 10^{-12}$
Cosmic rays	3×10^{21} -	10^{-11} -

Table 1 The Electromagnetic Spectrum with approximate subdivisions.

* 1 Angstrom (A) = 10^{-8} cm

essentially the equations of electric circuit theory that are now in use. Maxwell and Lorenz, in developing the electromagnetic theory, accumulated in one set of equations the work of most of the scientists who preceded them. An understanding of the mathematical deductions from Maxwell's equations is of great importance if the theory of electromagnetic radiation is to be fully understood. A rigorous explanation and treatment of Maxwell's equations and electromagnetic theory is presented by Sarbacher and Edson (2), Brainerd and Koehler *et al.* (3).

The Electric Intensity E and Magnetic Intensity H

As mentioned previously an electromagnetic wave consists of components of electric and magnetic fields of force which are expressed quantitatively in terms of the electric and magnetic intensities E and H. Both quantities E and H are vectors, Fig. 1, which have at every point in the field both magnitude and direction.

It can be shown that the energy stored by the electric field per unit volume is:

$$\epsilon \frac{E^2}{2} \qquad \text{(a)}$$

This equation can be developed from the equation which represents the stored energy in a condenser namely:

$$W = \int_{t=0}^{t=t} V i \, dt = \int_{v=0}^{v=V} VC \frac{dv}{dt} = \left[\frac{CV^2}{2} \right]_0^V = \frac{CV^2}{2} \qquad \text{(b)}$$

Also:

$$W = \tfrac{1}{2} CV^2 = \tfrac{1}{2}\,\frac{EA}{d}\,V^2 \tag{c}$$

Where $C = \epsilon A$, since $V = Ed$ the potential difference between the two plates, the total energy stored is then:

$$W_e = \frac{E^2}{2} A d \tag{d}$$

Since the electric strain is equal in every part of the dielectric, the total energy may be divided by the volume Ad, thus the energy stored by a dielectric field per unit volume is:

$$W_e = \epsilon \frac{E^2}{2} \tag{e}$$

A similar development for the magnetic field gives for the energy stored per unit volume:

$$W_h = \mu \frac{H^2}{2} \tag{f}$$

Equations (e) and (f) permit one to evaluate the energy stored in an electromagnetic field by integration of these quantities. Magnetic energy is stored in all tangible materials, both ferromagnetic and paramagnetic, whereas electrical energy is stored in all dielectrics and in a vacuum but not in a conductor.

<u>Definition of Terms in Equations (e) and (f)</u>: W_e and W_h -- energy stored in a unit volume expressed in Joules per cubic centimeter for the electric (E) and magnetic (H) fields respectively.

ϵ is the dielectric constant and a dimensionless coefficient depending upon the material, and may be a complex number at high frequencies, of the form $\epsilon = \epsilon' + j\epsilon''$ and has a value depending upon the system of units used.

μ is the permeability. This may also be a complex number at high frequency, of the form $\mu = \mu' + j\mu''$ and has a value depending on the units used.

E -- electric field intensity = volts per meter.

ϵE -- electric flux density = electric induction in lines per square meter.

H -- magnetic field intensity = ampere turns per meter.

μH -- magnetic flux density = magnetic induction at a point in lines per square meter.

The relations $\epsilon E^2/2$ and $\mu H^2/2$ represent the energy per unit volume contained in the electric and magnetic fields respectively. Their sum, $\epsilon \frac{E^2}{2} + \mu \frac{H^2}{2}$, represents the total energy contained in a unit volume (V) of an electromagnetic field. Then the triple integral of volume V:

$$\iiint_V \left[\epsilon \frac{E^2}{2} + \mu \frac{H^2}{2} \right] dV \qquad \text{(g)}$$

represents the total energy of the electromagnetic field in the unit volume V. The time derivative represents the rate of change of this total energy, i.e.,

$$\frac{\partial}{\partial t}\left[\epsilon \frac{E^2}{2} + \mu \frac{H^2}{2}\right]$$

Sarbacher and Edson (2) and Silver (4) have used Maxwell's equations, data from Faraday, Ampere, and Gauss, and the equation (g) to write the general energy equation (h) of an electromagnetic field. This equation is presented below and is valid in a homogenous isotrophic medium. Air and free space meet these conditions rather exactly, while material including rubber, glass, and metals meet these requirements to an intermediate degree; whereas wood and earth are extremely inhomogenous and anisotrophic.

$$\iint_s S_n \, ds + \iiint_v i_c \, E \cos\theta \, dv = -\frac{\partial}{\partial t}\iiint\left[\epsilon \frac{E^2}{2} + \mu \frac{H^2}{2}\right] \quad \text{(h)}$$

ϵ and μ in equation (h) are functions of frequency and type of dielectric. Further discussion will be devoted to this under dielectric heating.

In words, equation (h) states that term A, the outward flux of vector S or rate at which energy is radiated through surface surrounding V, plus term B, the rate at which energy is expended in establishing current (generation of heat in V), is equal to term C, which is the rate of decrease of the electromagnetic field energy. This equation (h) is then a general statement of the conservation of energy of the electromagnetic field and will be used to develop an analytical approach to the possible effect of electromagnetic radio waves on insects.

<u>New Terms in This Equation Are</u>: S_n -- the poynting vector represents the flow of energy per second through unit surface area normal to the direction of S_n from Gauss' theorem. Mathematically: $S = EH \sin\theta$

Watts per square meter using the rationalized unit system.

i_c is the current density in volume V. The electromagnetic field must supply this current.

θ is the angle between the direction of E and H at any point in the region.

The Electromagnetic Spectrum above Radio Waves

There is in reality no sharp dividing line between the different forms of electromagnetic energy, i.e., radio waves, infrared, ultraviolet, etc. Jenkins (5) describes a theory presented by Maxwell's equations which definitely give the connection between light and electricity. These equations in the general energy form are essentially the same as equations (h) and (g) and are derived with the concept that light has the same electric and magnetic field components as shown in Fig. 1. Jenkins (5) *et al*. have presented a method of proof to show that the electric component of light waves plays the dominant part in the effect of light waves. It is the electric vector which affects the photographic plate and causes fluorescence, and also it is the electric vector which affects the retina of the eye. According to these deductions, the electric part of the electromagnetic light wave is the part which really constitutes light, and the magnetic component, though no less real, is of less importance.

Even though infrared, visible and ultraviolet energy may be described by the same Maxwell equations in free space, the process of generating these types of energy differ from that of generating radio waves. Part of the near infrared spectrum can be generated with electric circuits. Golay (6) has presented a discussion on bridges across the infrared radio gap. It is generally believed that all of the waves indicated on the electromagnetic spectrum through x-rays are generated by the action of electrons. Radio waves and the near infrared may be generated by the action of electrons in electronic tubes and resonant cavities. The energy necessary to obtain these wavelengths come from some electrical generator or battery.

Infrared, visible, and ultraviolet energy can be obtained from some heated body, from a gaseous discharge tube, or from arcs. The wavelengths emitted from a heated body as a function of temperature is presented in Fig. 3.

Infrared radiation involves the displacement of atoms in the molecule and is due to the rotations and vibrations of atoms. These displacements are caused by heat in a heated body and all solids give about the same distribution of radiation among the different wavelengths at a given temperature (5).

Radiation in the ultraviolet and visible spectrum is due to displacement of outer electrons in atoms or molecules and the return of these displaced electrons to their normal states (1). Fig. 4 shows how ultraviolet and visible light is produced in a gaseous discharge tube. X-rays are due to a similar cause except that the displacement of inner electrons close to the nucleus of the atom are involved. Gamma rays are emitted from excited nuclei of various materials (1). Gamma radiation will be discussed in more detail under the section on X- and gamma radiation. Radiation associated with cosmic rays, which reach the earth from interstellar space, will not be discussed here.

In order to explain fully the characteristics of the radiation of certain electromagnetic waves, (black body radiation, photoelectric effect and x-rays), the quantum concept (7) is required. This concept was studied by Planck and Einstein, who reasoned that radiation is not a smooth flow of energy, but a series of pulses of energy. The energy

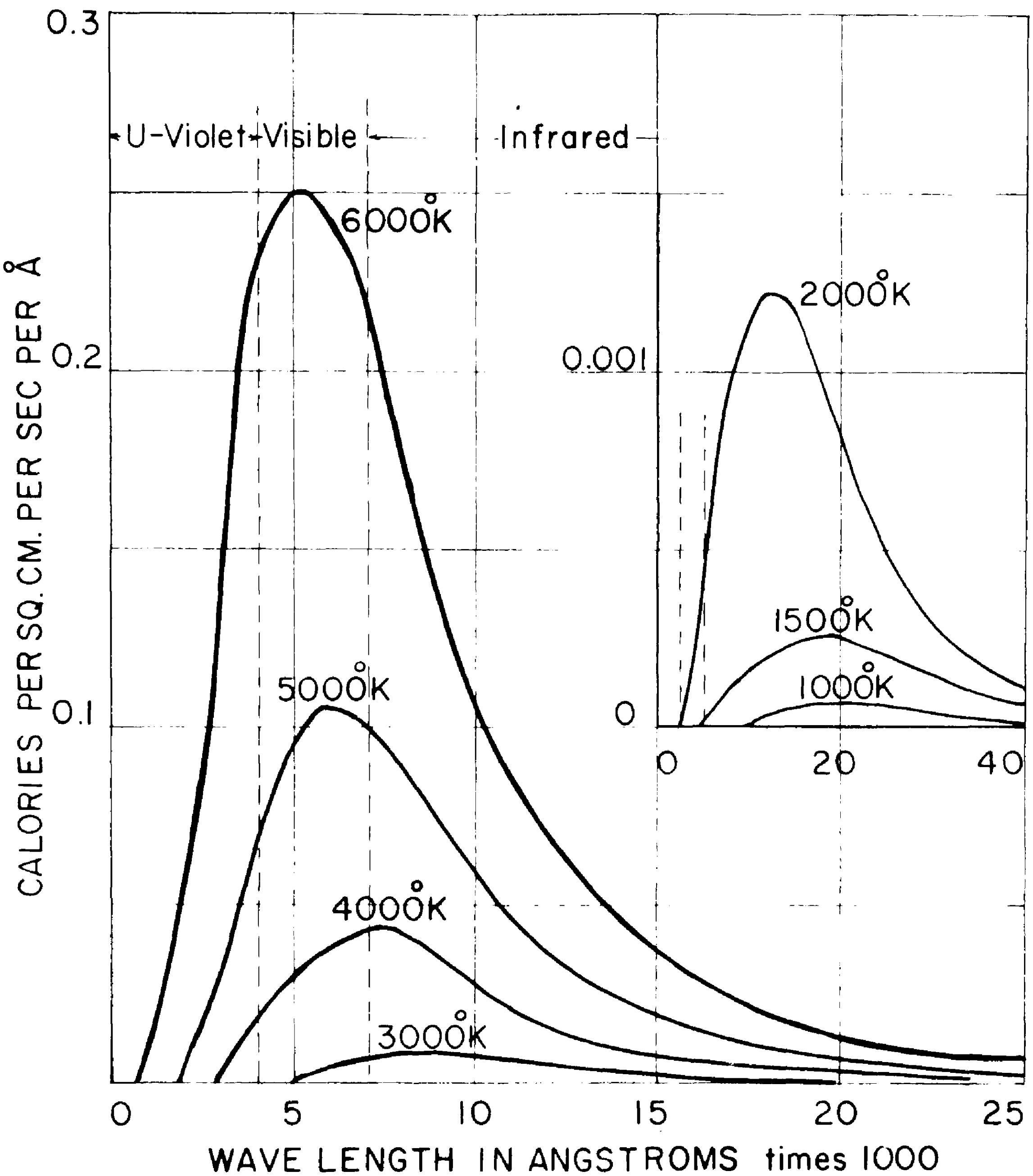

Fig 3. Black body radiation curves. For exact values see Smithsonian Physical Tables 8th ed. p134.

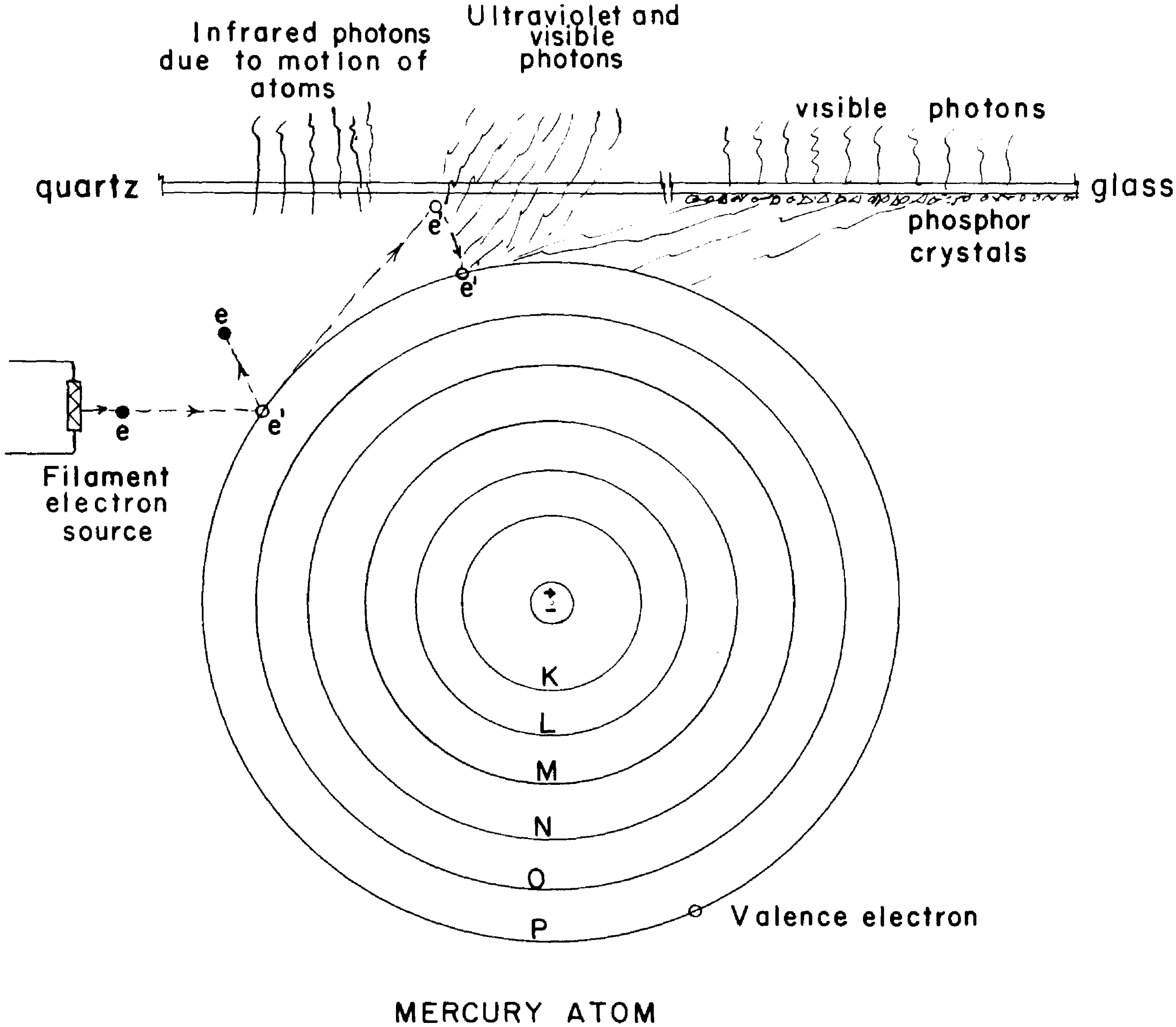

Fig 4. Generation of Ultraviolet, Visible, and Infrared energy in a gaseous discharge tube.

in each pulse increases with the frequency of the electromagnetic wave. The quantum concept is a theory that in the emission or absorption of energy by atoms or molecules the process is not continuous but takes place by steps, each step being the emission or absorption of an amount of energy called the quantum or photon. This energy may be represented by:

$$E = hV = \frac{hC}{X} \qquad (j)$$

E = the energy of the quantum in ergs

h = Planck's constant, a fundamental constant of nature = 6.62×10^{-27} erg sec. A method of determining h has been presented by Semat (8).

C = the velocity of light 3×10^{10} cm per sec.

V = the frequency of the radiation in cycles per sec.

X = the wavelength of the radiation in cm.

From the concepts of the quantum theory, black body radiation laws have been developed. A black body is defined (7) as a body which absorbs all of the radiation incident upon it, transmitting none and reflecting none. A black body will for equal area radiate more total power and more power at any given wavelength than any other source operating at the same temperature, unless that source radiates energy by some phenomenon other than temperature.

Planck's equation, Wien's radiation law, Wien's displacement law, have been presented (1, 5, 7) to give the radiation characteristics of black bodies, Fig. 3. The Stefan-Boltzmann law for black body radiation, obtained by integrating Planck's equation with the wavelength varying from zero to infinity, gives:

$$W = aT^4 \qquad (k)$$

W -- summation of power per unit area radiated by a black body at all wavelengths.

a -- 5.673×10^{-5} erg cm^{-2} sec^{-1} $^oK^{-4}$

T -- temperature of radiator (degrees Kelvin)

Equation (k) may be rewritten for bodies which are not true black bodies:

$$W = paT^4 \qquad (l)$$

where p = the emissivity factor.

Equations for the infrared source used in tests in this work will be presented under the section on infrared. Data will also be presented on the amount of energy at the various wavelengths of ultraviolet used under the section on ultraviolet.

Transmission and Propagation of Electromagnetic Energy

The so-called idea of ether waves as a transmitting medium for electromagnetic energy, as used by some scientists in past years, has been abandoned by modern physicists. It has been fairly well proven that the luminiferous ether, as referred to by Lapp and Andrews (1), does not exist. The present acceptable explanation of the transmission of energy by electromagnetic energy requires Einstein's theory of relativity and quantum mechanics. A discussion of these theories will be found in most modern physics texts.

Electromagnetic waves will travel through a vacuum, the atmosphere, and a number of solids containing relatively few free electrons, so-called non-conductors. The absorption of electromagnetic energy by matter will be discussed in another section of this thesis.

Polarization of Electromagnetic Waves

Polarized electromagnetic waves result from the nature of the source which produces them. The wave shown in Fig. 1 and the radiated waves of most commercial broadcasting stations are polarized with the electric field in the vertical plane and the magnetic field in the horizontal plane.

In light waves each atom or molecule acts individually in creating a light wave, resulting in radiation of a random nature, i.e., ordinary light, a form of electromagnetic energy, consisting of many separate components each polarized at some arbitrary angle. Thus the overall effect of such combinations shows none of the properties of a polarized wave, however, by the use of filters, the unpolarized components may be removed. The polarization of electromagnetic waves in the radio spectrum, however, depends on the type and orientation of antenna producing them.

Reflection, Refraction, and Diffraction of Electromagnetic Waves

When an object or an insect is placed in an electromagnetic field, polarized or unpolarized, some of the energy will be absorbed, some will be reflected, refracted, and diffracted. The extent to which these phenomena will take place will depend on the relative continuity and condition of surface of the object and the medium in which the wave is propagated.

Electromagnetic waves may be reflected from any sharply defined discontinuity of suitable characteristics and dimensions encountered in the medium in which they are traveling (9). In this case the angle of reflection is equal to the angle of incidence. The coefficient of reflection and refraction for electromagnetic waves are given by the formula which has been established empirically by Fresnel for light waves. Any insulator or conductor having a dielectric constant different from the medium in which the waves are traveling offers a discontinuity if its dimensions are at least comparable to the wave length. The reflection, refraction and diffraction properties of electromagnetic radio waves are similar to those of light (2).

An electromagnetic radio wave is bent when it moves obliquely into any medium having a refractive index different from that of the medium it leaves (in this study, from the air to the insect or from the air to the grain or bean to the insect). Since the velocity of propagation will probably be different in these media, that part of the wave that enters first travels faster if the insect or grain has a higher velocity of propagation. This tends to swing the wave around and "refract" it or direct the wave in a new direction.

The electromagnetic radio wave may be diffracted. When a wave strikes an edge of an object in passing it tends to be bent around that edge. This phenomenon called diffraction results in a diversion of part of the energy of those waves which normally follow a straight line.

Summary of Energy Equations for Electromagnetic Waves

A. Hertzian Radio Waves, up to and including part of the infrared spectrum.

1. Equation (h) -- conservation of energy equation for a Hertzian radio wave.

$$\iint_S S_n \, ds + \iiint_V \rho_c E \cos\theta \, dV = \frac{-\partial}{\partial t}\iiint_V \left[\epsilon \frac{E^2}{2} + \mu \frac{H^2}{2}\right]$$

2. Energy in Joules -- using MKS system of units per unit volume (V):

$$\frac{\epsilon E^2}{2} + \frac{\mu H^2}{2}$$

B. Radiation from heated bodies -- infrared, visible and ultraviolet

Equation (k) $W = aT^4$ calories per sq cm

C. Gaseous discharge tubes -- infrared, visible and ultraviolet. Some radiation from gaseous tubes follows Stefan-Boltzmann law equation (k) due to temperature of tube. Energy in the majority of radiation from a gaseous tube can be represented by Planck's equation (j). X- and gamma radiation can also be represented by:

$$E = hV = \frac{hC}{X} = \text{energy in quantum in ergs}$$

with system of units defined following equation (j).

Literature Cited

(1) Lapp, R. E. and Andrews, H. L., Nuclear Radiation Physics, Prentice-Hall Inc., New York, 1949, pp. 15-29.

(2) Sarbacher, R. I. and Edson, W. A., Hyper and Ultra High Frequency Engineering, John Wiley & Sons, New York, 1943, pp. 1-118.

(3) Brainerd, J. G., Koehler, G., et al., Ultra High Frequency Techniques, D. Van Nostrand, Inc., New York, 1943, pp. 369-434.

(4) Silver, S., Microwave Antenna Theory and Design, McGraw-Hill Book Co., New York, 1949, pp. 61-90.

(5) Jenkins, F. A. and White, H. E., Fundamentals of Optics, "The Electromagnetic Character of Light", McGraw-Hill Book Co., New York, 1950, pp. 406-442.

(6) Golay, M. J. E., "Bridges across the Infrared Radio Gap", Institute of Radio Engineers Proceedings 40: 1161-1165, October 1952.

(7) *Illuminating Engineering Society Handbook*, 1952, pp. 1-17.

(8) Semat, Henry, *Atomic Physics*, John Wiley & Sons, New York, N.Y., 1952, pp. 99-101.

(9) *The Radio Amateur's Handbook*, 1951, p. 80.

PART II

HEATING AND IONIZATION EFFECTS OF ELECTROMAGNETIC ENERGY

The physics involved in the application of electromagnetic energy and subatomic particles to biological materials is extremely complex. During and after World War II, with the accelerated program of atomic energy research, much has been learned about the effects of radiant energy on biological materials. Some of the most important findings of a number of scientists have been reported in a Symposium on Radio Biology (1) sponsored by the National Research Council and assisted by the Atomic Energy Commission and the Office of Naval Research. Other reports (2, 3, 4) contain a summary of the effect of electromagnetic energy and subatomic particles on biological materials.

Matter is considered by modern physics as made up of atoms and molecules. Every particle of matter is in constant vibration at a definite frequency unless the matter is at a temperature of absolute zero. In the final analysis, any kind of matter, an insect, a book or chair, is an assemblage of electrons and protons associated with a quantity of energy proportional to the mass of the object.

A sketch of the electromagnetic spectrum is presented in Figs. 2A and 2B. In examining Figs. 2A and 2B for possible effects of the different bands of energy on insects it will be found that there may be two main effects on living insects: (a) heating effect and (b) an ionization or chemical change or a combination of both effects. It is probable that these two effects will overlap.

Chemical Composition of Insects

If the chemical composition of a particular insect is known, the ionization frequency for the different elements can be calculated. The complex chemical composition of certain insects has been reported by Richards (5). A few pertinent points relative to Richards' work on the chemical composition of insects will be listed below.

1. Water

Most of the total weight of insects is water. Tests made with the adult *Tribolium* flour beetle show that the average moisture content (wet basis) is about 85 percent, i.e., 85 percent of the total weight is water.

2. Chitin (Polysaccharide)

Differs from cellulose in that it contains nitrogen. In purified chitin the molecular chains are, at least usually, associated together in a highly ordered manner, generally in chains. Chitin appears in the body wall of many insects and is prepared commercially from the shells of crustaceans.

3. Proteins (Amino acids)

When Odier discovered chitin in the elytra of May beetles in 1823, he recognized that this represented only about 30 percent of the weight of the cuticle and that the remainder of the material was mostly protein. Richards devotes one chapter in his book to the discussion of protein and amino acid content of various insects. The percentages of amino acids in various insect components are also presented. He also discusses the enzyme and mixed polymer content of insects.

4. Lipids

There is some evidence of the presence of sterols in insect cuticles, however most of the cuticular lipids on which information has been reported are waxes, i.e., esters in which the glycerol is replaced by some other alcohol. Paraffin may also be included as a lipid.

5. Inorganic constituents

The organic matter in insects may account for anywhere from less than one percent to greater than 99 percent, the remainder of the substance being referred to as lime or calcereous material and sometimes referred to as ash. Significant amounts of calcium, phosphorus, magnesium, aluminum, iron, silicon, and sulfur are found. Calcium is by far the most common and is generally found as calcium carbonate or as calcium phosphate.

It can be seen from the summary above that the chemical composition of insects is extremely complex. Most of the compounds listed above contain either carbon, hydrogen, oxygen, nitrogen, calcium and other elements in some arrangement. The ionization potentials for these and other elements have been determined (6). This information will enable one to calculate the wavelength of a quantum of energy necessary to knock an electron out of a given ring surrounding the nucleus and thus produce ionization.

Dividing Spectrum into Areas of Heating and Ionization

Lapp and Andrews (7) present a method of calculating the wavelength of the energy necessary to ionize a given element or compound. This equation is:

$$Ve = E = hV = \frac{hC}{X} \qquad \text{(a)}$$

Where:

V = volts

e = charge on electron = 4.8×10^{-10} esu

E = energy in ergs

h = Planck's constant = 6.6×10^{-27} erg sec.

V = frequency in cycles per sec.

C = velocity of light in space = 3×10^{10} cm per sec

X = wavelength

1 esu = 300 volts

From the equation (a): (b)

$$X = \frac{hC}{eV} = \frac{(6.62 \times 10^{-27})(3 \times 10^{10})}{(4.774 \times 10^{-10})(V/300)} = \frac{12,407}{V} \times 10^{-8} \text{ cm} = \frac{12,407}{V} \text{ A}$$

where A = Angstrom units.

Now from this equation the wavelength of ionization energy can be calculated.

The lowest ionization potential for the elements that are likely to be in an insect are listed in Table 2. The lowest ionization voltage in this table is 4.32 volts for potassium and the highest voltage is 390.1 volts for carbon.

From equation (b) $X = \frac{12,407}{V}$ A

The range of the wavelength of energy necessary to ionize potassium and carbon for the outer and inner ring respectively are:

potassium	$Xk_I = 2880$ A
carbon	$Xc_V = 31.9$ A

By referring to Fig. 2, it is seen that the X's for potassium and carbon lie in or above the ultraviolet spectrum. All other ionization X's for the elements and compounds listed in Table 2 would lie between 2880 A and 31.9 A, since the remaining ionization potentials lie between the values for potassium and carbon.

From this analysis it would seem logical to conclude that part of the spectrum with wavelengths less than 2880 A would contain more than enough energy in a quantum of photon of energy to ionize the elements listed in Table 2. This is true because the equation $E = hV$ developed by Einstein and Planck shows that as the frequency increases the energy in a quantum increases, where E is the energy of the quantum in ergs and h is Planck's constant.

It is on this basis that the line on Fig. 2 is drawn

Element	Atomic number	Ionization Potentials Volts I	II	III	IV	V	VI
Carbon	6	11.22	24.27	47.65	64.22	390.1	---
Ca	20	6.09	11.82	50.96	69.7	---	---
Cl	17	12.95	23.67	39.69	53.16	67.4	---
Fe	26	7.83	16.16	---	---	---	---
H	1	13.53	---	---	---	---	---
K	19	4.32	31.66	46.5	---	---	---
N	7	14.48	29.47	47.40	77.0	97.4	---
O	8	13.55	34.93	54.87	76.99	113.0	137.5

Compounds	I	Compounds	I
CO_2	14.4	NO_2	11.0
Cl_2	13.2	N_2O	12.9
H_2	15.6	O_2	12.5
H_2O	12.56	SO_2	13.1
N_2	15.51	S_2	10.7
NH_3	11.2	NO	9.5

Table 2 This table gives the ionization potentials in volts for the elements in the atomic state. The degree of ionization is indicated by the numerals I, II, etc. From Handbook of Physics and Chemistry - 1948 edition.

between heating effect and ionization effect. It should be pointed out here that when this analysis is applied to insects we must operate on the hypothesis that ionization of any of the compounds or elements listed in Table 2 would be lethal to the insect. If the ionization potentials necessary to break off certain bonds or ions from chitin, proteins, lipids, and atoms of other complex compounds in an insect were known, the ionization frequency could be calculated. Since this information apparently is not available, specific data on this subject must be obtained by further research.

The Absorption of Electromagnetic Energy by Biological Materials

The purpose of this section is to present the physical laws involved when electromagnetic energy is absorbed by biological material which may apply to insects. The previous section presented a dividing line in the electromagnetic spectrum between the heating and ionization effect on a living mechanism. It was pointed out that the heating and ionization areas overlap somewhat and that it is impossible to obtain ionization with a frequency below the far ultraviolet or near x-ray region. The effect of radio waves, infrared and most of the ultraviolet spectrum is essentially a dielectric heating or molecular excitation process.

Heating Effect

The discussion on heating effect will be divided into the following sections: radio waves from an antenna, dielectric heating between the plates of a condenser, in wave guides or in resonant cavities, infrared and near ultraviolet excitation. Even though the effect in all of these areas is essentially a heating process due to the vibration, rotation, and translation of molecules or atoms, Fig. 2A, it is believed that the division of the discussion into these categories will facilitate the discussion.

Radio waves from antenna: This discussion includes radio or Hertzian waves up to and including microwaves. The picture can best be presented here by a section of tissue as shown in Fig. 5. E is the energy intensity of the electromagnetic wave and X the depth of penetration. Data has been presented to show that in order to get any appreciable penetration into tissue, frequencies in the microwave spectrum must be used. The effect on the tissue is essentially a dielectric heating effect. This assumes that the tissue is receiving energy from a radiating source removed from the tissue. The process of dielectric heating between the plates of a condenser or in resonant cavities will be discussed in Part III of this thesis.

Part of the energy E in Fig. 5 will be reflected from the tissue (and part will be absorbed), the energy which is

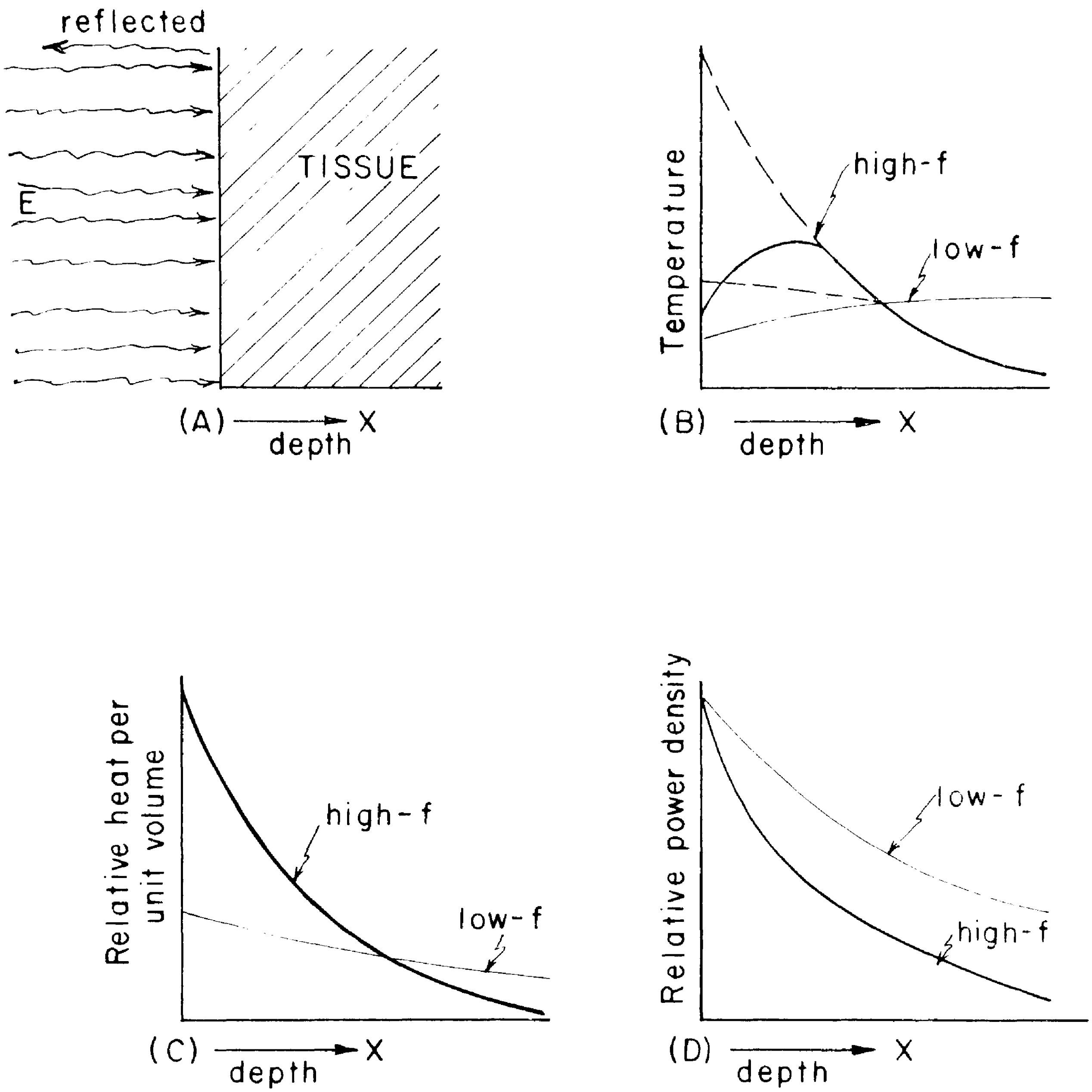

Fig 5. A, B, C, D Illustrating the relative effects of high frequency(f) energy(E) and low f energy on a section of tissue.

absorbed may follow Lambert's law of absorption which can be represented by the equation:

$$E = E' e^{-bx}$$

where E' is the energy density a distance X below the surface and b is the attenuation constant of tissue. Since b is the fraction of the energy removed from the wave a distance x in the tissue, the energy transferred to the tissue as heat is b times the density at any point X. From this the following equation may be written:

$$H(x) = b\,E(x) = b\,E'\,e^{-bx}$$

where H (x) is the number of watts per cc of heat energy transferred from the beam to the tissue.

This information may be used to present the possible effect on an ideal animal with homogenous tissue. These effects are represented essentially by Fig. 5 (B,C,D) (8).

The temperature at any point (x) below the surface of the exposed tissue where surface cooling is involved, may be represented by Fig. 5B. Without any surface cooling the temperature at any point T(x) will be proportional to the energy that has been absorbed by the tissue at point (x). A curve representing this fact may have the general shape of Fig. 5C. The relative power density requirements for a frequency at the high frequency end of the microwave spectrum (1-10 cm) and frequencies at the low end of the spectrum (75-100 cm) in order to obtain the temperature distributions shown in Fig. 5 (B,C) are presented in Fig. 5D.

It is well known that the loss factor and hence the attenuation constant of most materials increase with frequency. This is true with water which makes up the greatest part of tissue. Clark (9) points out that

> "the effect of microwaves on tissue is not a resonance phenomenon. The heated areas occur below the surface of the tissue because of the balance between energy absorption and energy cooling. It is not very critical; wave lengths between 6 cm and 12 cm are about equally effective in elevating body temperatures".

Very little work has been done on the exact depth of penetration of microwaves into tissue. Location of most intense heated areas will occur where the number of blood vessels are at a minimum. Clark (9) presented calculations to show that the longer the wavelength (50 cm, 8 cm, 4 cm) the deeper into tissue the maximum temperature occurred but the highest temperature accompanied the highest frequency. Further discussion will be devoted to this subject under the section on microwaves.

Inductive heating: This process is used in industry for heat treating, and melting various metals. Frequencies near 450,000 cycles per second are used. The metal to be heated is placed in a coil which is connected to a radio frequency generator. This method of heating is generally only satisfactory for metals or for materials with free electrons. Since most of the materials of interest in this study are non-conductors, this method of heating will not be discussed further here.

Dielectric heating between the plates of a condenser: The principle difference between this process of heating and that described for radiation from an antenna is that the product to be heated is placed between the plates of a condenser which are attached to a radio frequency generator. Theoretically any frequency in the radio spectrum could be used for this purpose, however, there are certain practical limitations which caused frequencies of 30 to 50 million cycles to be used in the past for dielectric heating. Recently developed equipment with wavelengths in the centimeter range may be used for this purpose. In this process the electromagnetic field penetrates the entire depth of the non-conductor product, whereas only a relatively shallow heat penetration is obtained when an electromagnetic radio wave from an antenna is absorbed by the product. See Fig. 5 (B,C,D). A considerable amount of research has been devoted to the study of radio frequency dielectric heating as a means of destroying insects in stored products. A review of the literature and a presentation of a theory of dielectric heating is presented in Part III of this thesis.

Heating with infrared energy: Infrared is that portion of the electromagnetic spectrum, 7600 A to about 3600 A, which bridges the gap between radio or microwaves and the visible light spectrum. The process of heating with infrared electromagnetic energy is well known and this principle is used widely in industrial and domestic heating applications. There is not sufficient energy in a quantum of infrared energy to ionize atoms or molecules, however, molecules may be vibrated or excited to a point that the thermal temperature of disassociation may be reached.

Infrared radiation penetrates thin materials such as paint films and glass; they have a limited penetration into solids such as grain, wood, and metals. Relatively high temperatures may be obtained on the surfaces of materials exposed to intense infrared energy. The rise in temperature below the heated surface is due entirely to heat conducted from the heated surface. Garber (10) has presented data to show the relationship between high temperature surface radiation to the overall heat pattern in slabs of material.

The penetration of infrared energy into human skin is listed in Table 3. The penetration of far infrared is superficial whereas near infrared penetrates relatively deeply into human tissue. This may be used as a criterion for determining the penetration of infrared energy into insect tissue.

Spectrum Region	Wavelength	Millimeter Penetration	Remarks
Far ultraviolet	1800-2900A	0.01-0.1	Superficial
Near ultraviolet	2900-3900A	0.1-1	Superficial
Visible	3900-7600A	1 - 10	Deep
Near infrared	7600-15000A	10 - 1	Deep
Far infrared	15000-150,000A	1 - 0.05	Superficial

Table 3 Penetration of infrared, visible, and ultraviolet energy into human skin (14).

Visible radiation: Table 3 shows that light visible to the human eye has relatively deep penetration into tissue. It is quite obvious that energy with intensities available from the sun and from ordinary artificial sources in this portion of the spectrum will have little practical value as a direct lethal agent on insects. The visible portion of the spectrum does have great importance when considering the indirect method of killing insects by attracting them to "light" or insect traps. Since the electromagnetic energy in this case does not have direct lethal effect on the insect, this subject will not be pursued further in this study. A considerable amount of research on this subject has been done by the Division of Farm Electrification, Agricultural Research Administration, Beltsville, Maryland.

Ultraviolet heating and ionization effect: The ultraviolet area of the spectrum (about 10 to 4000 A) is in the region of overlapping of the heating and ionization effect. Ultraviolet bridges the gap between the longest wavelength of x-rays and the shortest wavelengths of light visible to the human eye. The ultraviolet spectrum is divided into far, middle, and near wavelength areas: 4000-3000 A near, 3000-2000 A middle, and 2000-40 A far ultraviolet. That portion of the spectrum between 2000 and 40 A is strongly absorbed by air. This area includes the photochemical, erythemal, and germicidal effects. Physicists and other scientists do not all agree on the effects that ultraviolet energy has on living tissue, plants, and chemical reactions. Much study has been devoted to the ultraviolet spectrum and volumes have been written on this subject (11, 12, 13, 14).

Some investigators refer to the ultraviolet spectrum as the region of molecular specificity or that portion of the ultraviolet region that is marked by strong selective absorption in specific atomic and molecular structures. In previous discussion the electromagnetic spectrum was divided into heating and ionization areas. It was pointed out that there was not sufficient energy in a quantum or photon of ultraviolet with a wavelength greater than about 2880 Angstroms to cause ionization for the elements listed in Table 2. According to this a photon of ultraviolet energy with a wavelength greater than about 2880 A would not contain enough energy to ionize the elements in an insect listed in Table 2.

The germicidal effect or lethal wavelength of ultraviolet energy on bacteria peaks at about 2600 A (13). According to the above discussion the germicidal area would appear to be in the ionizing portion of the spectrum and the erythemal effect which peaks at about 2970 A (13, 14), Fig. 6A, would appear to be in the heating or molecular excitation portion of the ultraviolet spectrum. Thus, if an insect is exposed to a source of far, near, and

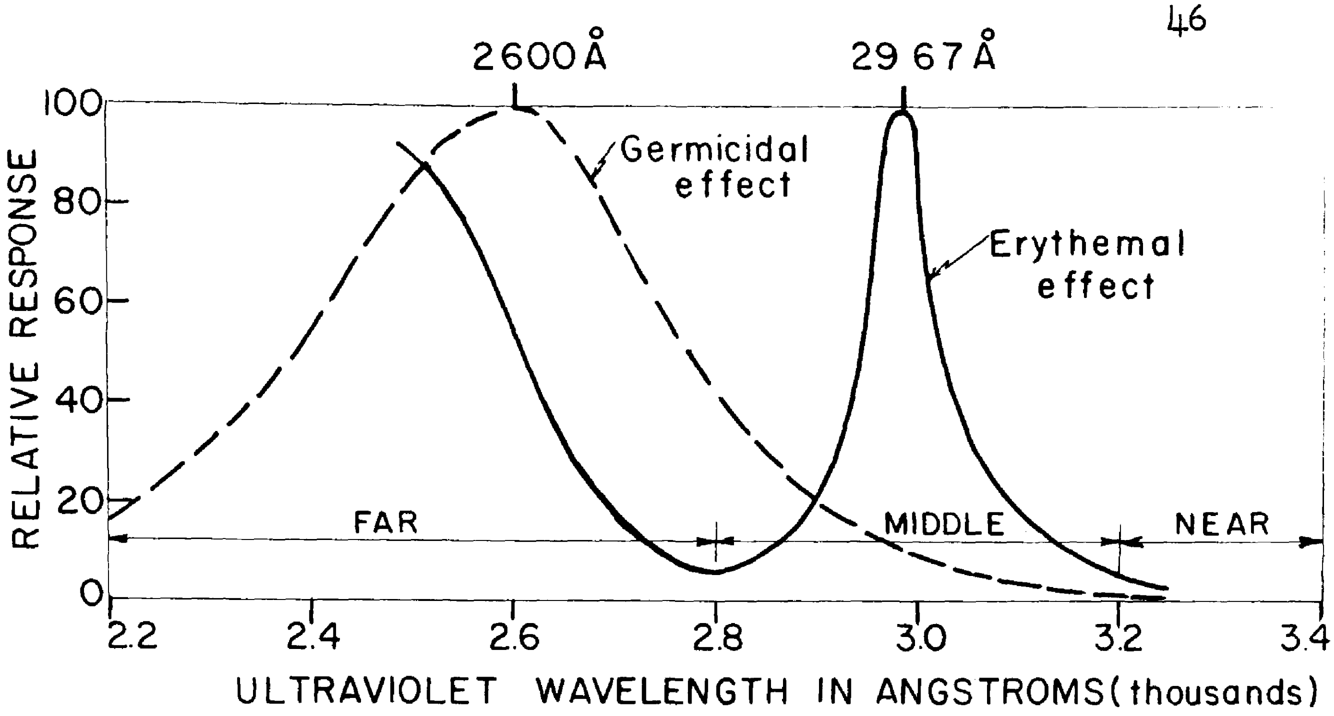

Fig 6A. Germicidal and Erythemal effects(13).

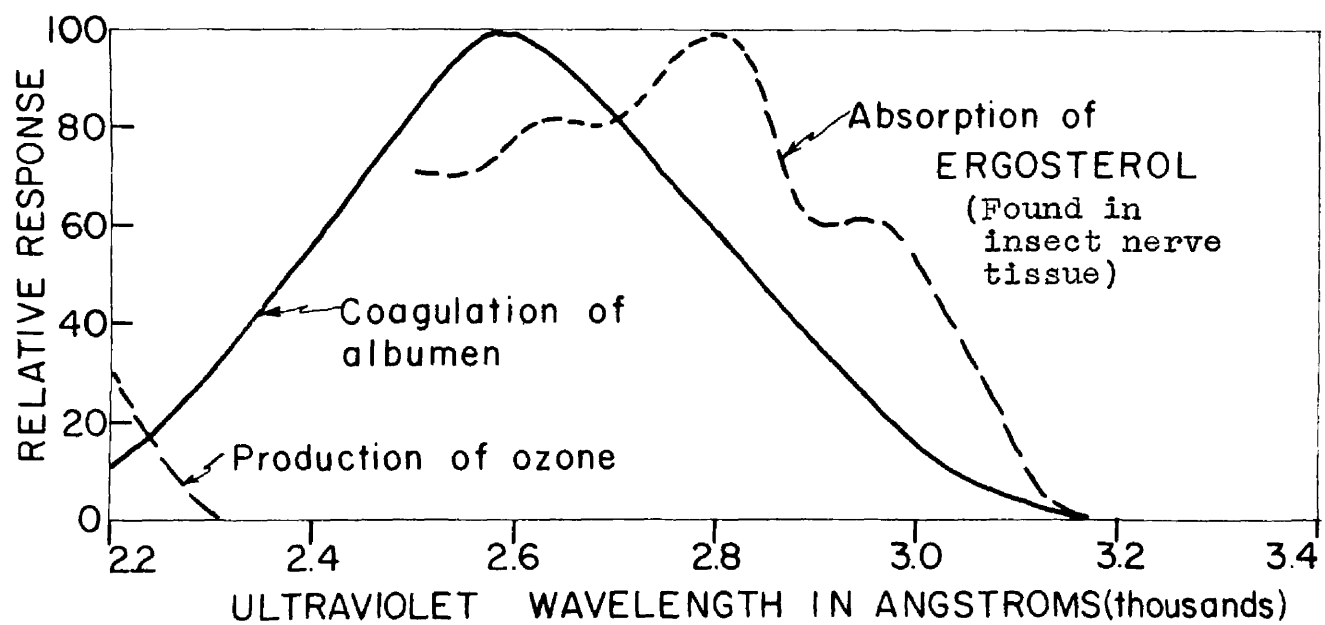

Fig 6B. The coagulation of albumen and the absorption of ergosterol by ultravolet energy (14).

middle ultraviolet wavelengths, there would be a possibility of heating and ionization effects or the coagulation of albumen or proteins, Fig. 6B. Either of these effects would affect only the surface of the materials of interest in this study, i.e., flour, wheat, beans, tissue, etc., because ultraviolet does not penetrate these materials to any appreciable depth. Table 3 shows that the maximum penetration of ultraviolet energy into human skin is about one millimeter. The penetration into insect cutin and tissue would probably be less than this.

Photochemical effect: Relatively little is known about the effect of ultraviolet and visible light in producing chemical changes in animal tissue. It has been known for some time that visible and ultraviolet energy enters into the photosynthesis process in plants, however even this process has not been fully explained. Einstein postulated a theory which states that the energy in ergs absorbed when each molecule of a gram-molecular weight absorbs one quantum of radiation is equal to Nhv where N is Avogadro's number 6.06×10^{23}, the number of molecules per gram molecule, and hv is the energy in a quantum. Some investigators believe that the primary effect of light absorbed to be a loosening of the valence electrons, thus rendering the molecule chemically active. Ellis and Wells (11) point out that there is no fundamental distinction between the reactions due to visible or ultraviolet light and it is not feasible to discuss their effect separately.

<u>Effects of high temperatures on living cells</u>: Most of this section is a summary of a report by Rahn (15). Heat energy at some definite temperature can have lethal effects on every type of cell of plants or animals. The rate of the lethal effect depends on the temperature and time of exposure. Practically all living cells are controlled by a narrow range of temperature of about 75° F above the freezing point of water. Life on earth is not permanently possible outside this range of temperature.

The laws of thermodynamics can be applied to the living organism with one exception. This exception is that no mathematical or physical laws have been able to predict the effects on "extra-sensory perception" in the living organism. Some biologists have developed empirical equations in an effort to tie in this effect with physical laws.

Generally, temperature affects almost all chemical reactions. The rate of reaction of ions of many chemicals have been measured by the chemist. This reaction rate changes with a change in temperature and practically all reactions which take place at a definite speed show an increase in rate with an increase in temperature. The final result may be the same. However, the end result is reached much faster at higher temperatures.

The proteins that are necessary for life in the protoplasm of living cells are coagulated by heat. The coagulation of the protoplasm in heat killed cells is plainly visible under a microscope. If a vital protein whose function is necessary for cell life coagulates completely, the cell dies. Not all of the many proteins in any one cell have the same coagulation temperature. The overall effect is a matter of rate of coagulation. If the coagulation takes place slowly, the living cell can produce new enzymes and oxidase and repair the damage. So long as the rate of repair keeps up with the rate of inactivation, the cell will continue to live and be normal. When the rate of repair is equal to the rate of destruction, this is called the optimal temperature, or the temperature of greatest life activity. When the cell temperature increases above this point, a lethal temperature will be reached, the destruction rate is increased considerably at this temperature and the repair rate is practically negligible. When the cell temperature is increased above the optimal temperature, cell catalysts will be destroyed and the cell will die.

The death rate of single cell animals due to lethal temperature generally follows the so-called "logarithmic order of death". This does not apply to multicellular animals but may be applied to individual cells of multicellular animals including insects. Individual insects normally show no body temperature of their own because they give off surplus energy of respiration; however in large masses their body heat accumulates.

From this discussion it would seem logical to conclude that insects can be killed by raising their temperature above the lethal point. Previous analysis in another section of this report leads one to believe that the lethal effect of radio frequency dielectric heating, microwave, infrared, and most of ultraviolet radiation, is merely a temperature effect, i.e., a lethal temperature is induced which causes death to the insect.

Ionization Radiation

Subatomic Particles

The terms electron beam, cathode rays, and beta particles are used interchangeably to designate the flow of electrons. The term beta particle is reserved for an electron emitted from an excited nucleus. The biological and ionization effects of an electron beam and x-rays on matter are the same and no radioactivity is induced except at voltages greater than 21 million volts (16). Electrons accelerated by potentials of several million volts are capable of penetrating a number of substances. This penetration is inversely proportional to the density of the irradiated substance. Penetrating electrons ionize living tissue so that the chemical composition of the tissue is changed. These penetrating electrons may be thought of as a special kind of bullet. As these bullets impinge on or collide with atoms of living tissue, ions are produced which are fatal to the organism. The efficiency of electron beam production is relatively high. From 50 to 75 percent of the energy in an electron beam can be utilized.

Alpha particles are positively charged helium nuclei emitted from radioactive substances. Alpha particles have superficial penetration into matter. Alpha particles can be stopped by a sheet of paper (7, 17). Therefore alpha particles would not seem to be practical for deinfestation of grain, flour, and other stored products.

Neutrons and protons are subatomic particles. The proton is the positively charged nucleus of the hydrogen atom. The neutron has no electric charge. The mass number of an element A represents the total number of particles in the nucleus. The atomic number Z is the number of protons in the nucleus and A minus Z is the number of neutrons in the nucleus. The isotopes of any one element differ only in the number of neutrons in the various nuclei.

Neutrons are not found as free particles in nature. Lapp and Andrews (7) describe three processes by which neutrons are produced, namely, by the absorption of gamma rays in nuclei, emitted from nuclei of light and intermediate mass elements under proton bombardment; and neutrons are produced by a beam of deuterons impinging on a target of heavy ice. The neutron has been postulated to be radio-active, decaying by beta particle emission to form a proton.

Neutrons then create induced radioactivity in the material they strike.

Neutrons have relatively deep penetration into matter and their sterilizing effect is caused by the production of positive ions or charged nuclei. The charged nuclei ionize and cause destruction of bacteria (17). The production of neutrons is relatively inefficient (18). For every 100,000 deuterons hitting a target, the yield is only one neutron. Since neutrons induce radioactivity and at the present stage of atomic devëlopment, the generation of neutrons is not efficient, neutron radiation does not appear to be feasible for the deinfestation of stored products.

Thus it would appear from this discussion that accelerated electrons would be the only subatomic particles which would seem to have merit for deinfesting stored products, since accelerated electrons meet the requirements of efficiency, practicality, and safety. It is for these reasons that accelerated electrons are the only subatomic particles used in tests in this report.

X-rays and Gamma Rays

X-rays and gamma rays are electromagnetic waves which penetrate relatively deep into matter and have essentially the same effect on living tissue as accelerated electrons (19). X-rays are produced by electron bombardment of target materials. The quantity of x-rays produced depends on the electron energy, beam intensity, and the atomic characteristic of the target. The conversion of electron energy into x-rays is a very inefficient process. At 50 kilovolts, the power conversion efficiency is about 0.1 percent for heavy target materials.

Gamma rays are produced by the disintegration of atomic nuclei. They come from many nuclear reactions and are among the radiation emitted by natural radioactive elements. Gamma rays, like x-rays, are regarded as "bundles" or quanta of energy, and they have the same effect on living tissue as high frequency or hard x-rays. Gamma rays propagate in a spherical pattern from a radioactive source. Since the spherical pattern is not the most desirable pattern for irradiating foods, radio active rods, with a diameter section of about 2 cm in order to prevent excessive self absorption, has been found satisfactory (19). A gamma-ray source suitable for irradiating food or insects is available in the form of radioactive cobalt-60, obtained by bombarding ordinary cobalt in a nuclear-reacting-pile. This subject will be discussed further in Part VII.

Absorption of Ionization Radiation by Biological Tissue

Every quantum of ionizing electromagnetic energy absorbed by biological tissue can affect at most only one primary absorbing atom (16). The secondary product from an absorbed quantum, usually a dislodged electron, will then be set free to strike other atoms and thus form ions. Then most of the effect on living tissue of ionization radiation, whether it be an electromagnetic quantum or an initial subatomic particle, are due to ionizing particles. The three mechanisms by which electromagnetic energy is absorbed are shown in Fig. 7. These processes are the photoelectric effect, Compton effect, and pair production effect. These processes are valid for that portion of the spectrum which produces ionization, far ultraviolet, x-ray, and gamma radiation. It was pointed out, under the section of subatomic particles, that these same processes occur when subatomic particles are used for ionization of biological material.

The photoelectric effect obeys Einstein's equation:

$$hv = \phi + \frac{1}{2} mv^2$$

where hv represents the total energy of the incident photon; ϕ the energy required to remove the electron from its atom and $\frac{1}{2} mv^2$ represents the kinetic energy of the ejected electron. These ejected electrons have enough energy to cause ionization to occur in nearby atoms.

The Compton effect is shown in Fig. 7B. This process is important for photons of relatively high energy, 2 Mev (see appendix for definition of Mev), or greater (7) or with wavelengths less than 0.01 A. The photons which play an important role in this type of process have greater associated masses than the electron mass. Fig. 7B illustrates that when a photon of energy in the x-ray or gamma region strikes an electron in an atom, part of the energy in the ejected photon causes the compton recoil electron to be ejected at angle (b) and the remaining energy in the incident photon is scattered at angle (a) with a change in wavelength. Lapp and Andrews (7) have applied the laws of conservation of energy and momentum to the Compton collision process thus permitting an accurate calculation of the change in wavelength of the scattered photon. The wavelength of the scattered photon must be longer than the wavelength of the incident photon. If the scattered photon has enough energy to eject another recoil electron, the compton recoil effect will be repeated.

The phenomena of pair production is shown in Fig. 7C. In the process of pair production all the energy of the photon goes into the formation of the electron pair (electron e^- and positron e^+) and to imparting energy to the pair formed. This may be represented by

$$h\nu \longrightarrow e^+ + e^- + \text{kinetic energy}$$

Using Einstein's equation $E = mc^2$, the electron mass is equivalent to 0.51 Mev. Thus in the pair production process both the electron and positron removes 0.51 Mev or a total of 1.02 Mev from the photon. Then 1.02 Mev is the minimum energy required for pair production.

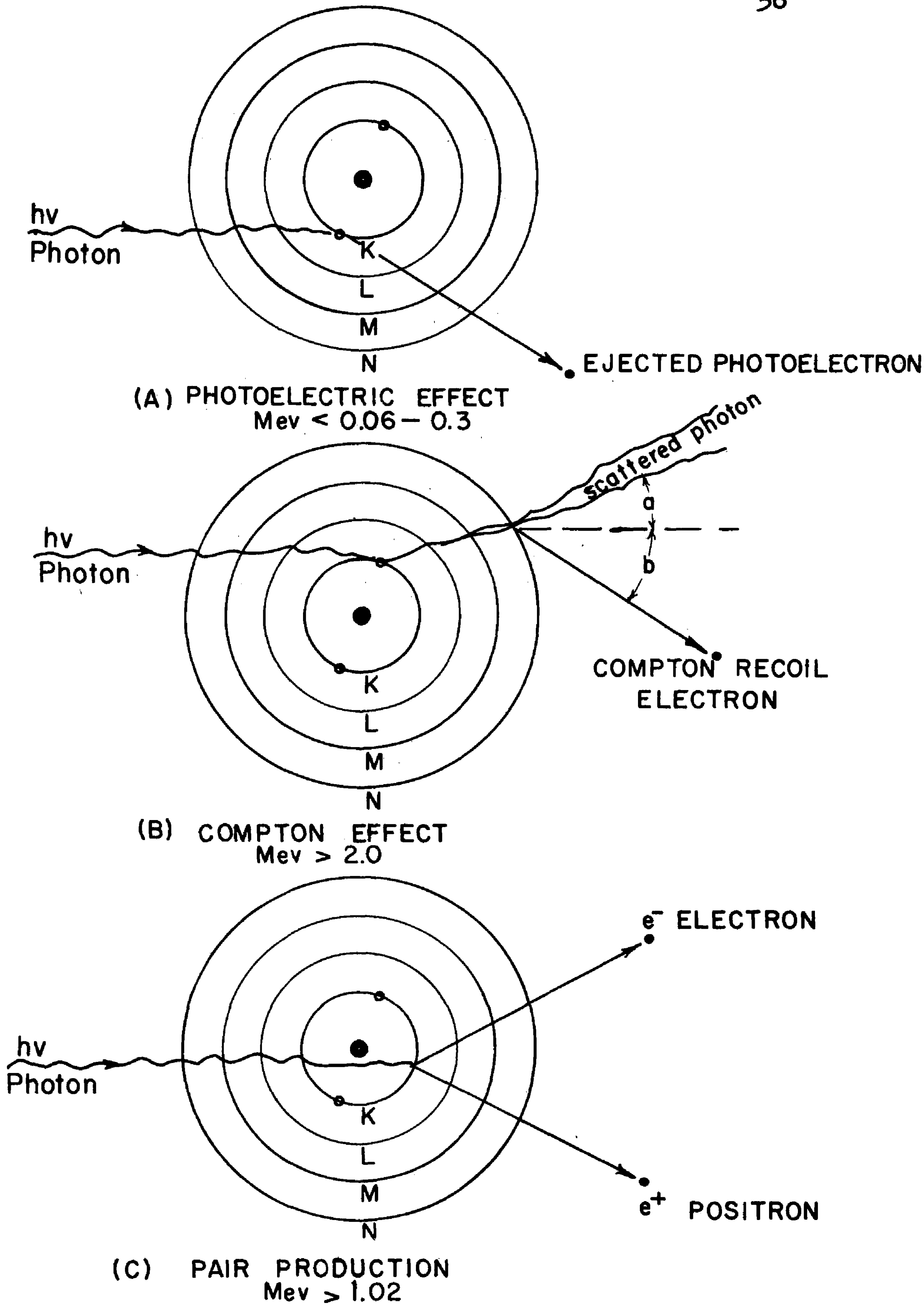

Fig 7. – A, B, C – Mechanism by which far-ultraviolet, x-rays, and gamma rays are absorbed by matter — illustrating processes occurring when photons strike an atom.

Lapp and Andrews state:

> "For energies below about 0.06 Mev the photoelectric effect predominates. This effect decreases with an increase in the energy in a photon and becomes negligible at 0.3 Mev. At this point most of the energy lost to Compton recoil electrons. Above 1 Mev, pair production occurs and becomes increasingly important at still higher energies. The end result of the absorption of ionizing electromagnetic radiation is the production of ionizing particles and tissue damage is caused by these particles."

X- and gamma radiation will penetrate deep into matter. Because of the low probability that a photon will interact with surface tissue, all quanta are not absorbed near the surface of the tissue. The ions produced by photon-electron interactions move only short distances from the point at which they were formed, but they will be formed fairly uniform throughout a mass the size of the human body and all tissue in the body will be exposed to injury.

Effects of Ionization on Living Cells

The living cell can be killed as a result of ionization of protoplasm or chromosome damage when the cell is bombarded with quanta of ionizing electromagnetic energy or accelerated electrons. The protoplasm in a cell is divided into an inner compact nucleus and a surrounding fluid layer. The nucleus is the principal part of the cell. It contains the nucleo-protein which in the process of cell division forms thread-like structures known as chromosomes, Fig. 8. These chromosomes in the germ cells provide the mechanism of heredity. The chromosomes are made up of building blocks

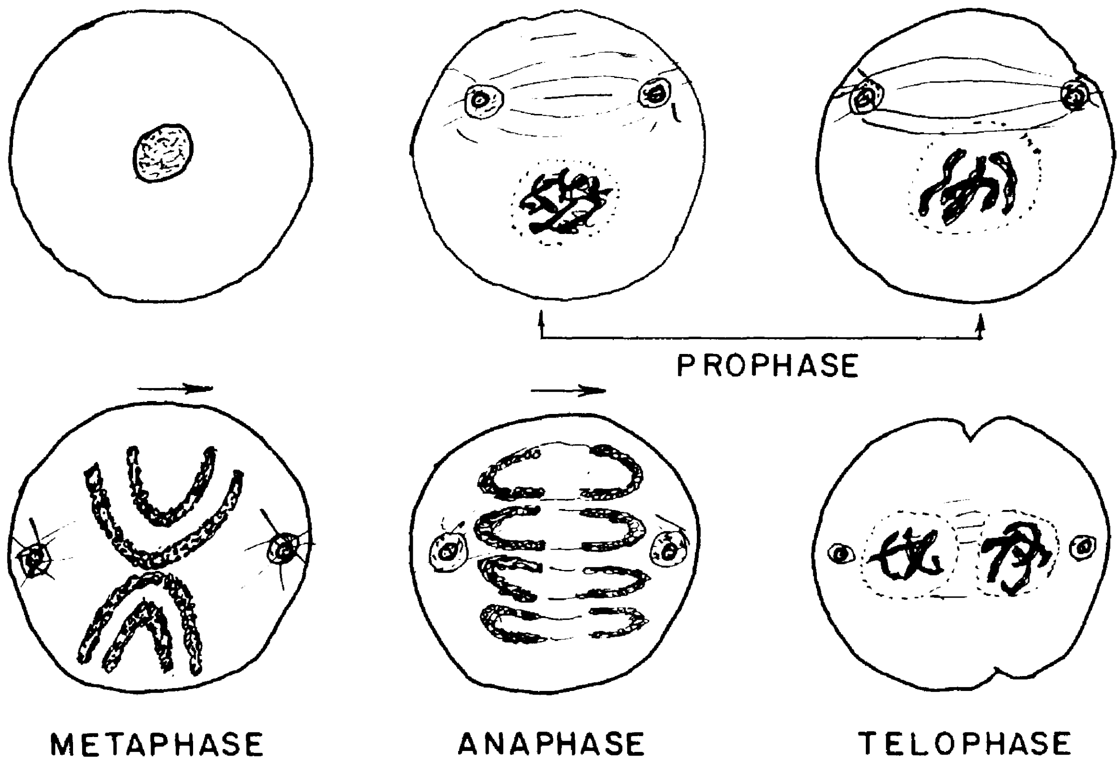

Fig 8. sketch illustrating cell division.

called genes, which contain the factors that determine the specific qualities of the parent cell and any cells produced by cell division.

All organisms reproduce from a single cell, the ovum. In the union of male and female germ cells, one-half of the chromosomes are contributed by the sperm and one-half come from the ovum. Following fertilization, a rapid division takes place. The division follows a definite plan throughout the life of the organism. A complete description of the cell division process may be found in most texts on biology.

The process of cell division is shown in Fig. 8. During cell division, the nuclear material condenses to form long threads, the nuclear membrane disappears, then these threads form the chromosomes (20) as shown in the prophase section of Fig. 8. At metaphase the chromosomes become oriented in the cell and they split longitudinally. Then at anaphase the two halves of the chromosomes separate and move to opposite poles of the cell. The nuclear membrane reforms, the chromosomes become indistinct and the cell divides. The two daughter cells have the same number of chromosomes as the parent.

In the process of life, there is a continuous destruction and replacement of cellular tissue within the body of a living organism. The different layers of tissue in an organism contain similar nuclei, but the surrounding cytoplasm is different for each different type of tissue layer. After the organism reaches maturity, cell division levels off, and a balance of cellular death and replacement takes place.

A great deal of information is available concerning the effects of radiation-induced chromosomal breaks and rearrangements. This subject as well as the genetic aspects of radiation has been the topic of many volumes. The main concern here is the mechanism by which short-term lethal effects are obtained by ionization radiation.

When a great number of cells in an organism are destroyed or damaged as a result of ionization radiation, the repair processes within the cell are stimulated and cell division proceeds at an increasing rate. Damage to the reproductive apparatus of the living cell produces changes in the ability of the daughter cell to survive and multiply.

Sparrow and Rubin (21) point out that the immediate consequences of chromosome breakage are mitotic inhibition and cell death, and that death is more likely to occur when chromatin material is lost. Cells that do survive with chromosome changes and breakages will cause genetic changes. In addition to the actual genetic changes that may be associated with chromosome breakage, sterility or partial sterility or death, may occur in offspring from damaged cells.

Martin (20) states that:

> "One or two ionizations within a chromosome break the rod and destroy or eject a gene at the point of rupture. With restitution of the break, cell division will continue, and the successive daughter cells may be normal or abnormal depending on the importance of the gene removed by the process. In the apparently normal daughter cells, the absence of the gene may be manifested much later after numerous divisions. If restitution does not occur, or if multiple breaks occur and the fragments interchange during restitution, the effect will be more serious and death of the cell probably will occur at or following cellular divisions. . . . There are intermediate effects between these two extremes depending on geometrical configurations assumed by the injured chromosomes."

The photomicrographs presented in Fig. 9 show the effects of 500 roentgens of X-radiation on the chromosomes in a pollen cell from the Tradescantia reflexa plant. The effects of radiation on a cell of this plant is relatively easy to show in a photomicrograph, because the nucleus in each cell contains only six chromosomes. In this thesis it would be almost impossible to obtain a clear picture of chromosome damage in the nucleus of wheat irradiated because wheat has 42 chromosomes in each nucleus, however the principles involved are the same for both plants.

The photomicrographs in Fig. 9 were taken by Dr. G. B. Wilson of the Botany Department of Michigan State College. Fragments of chromosomes are visible in each of the photomicrographs. Chromosome fragments are clearly visible in the late anaphase stage of Fig. 9-3. As the cell progresses to the early telophase stage and then to complete division,

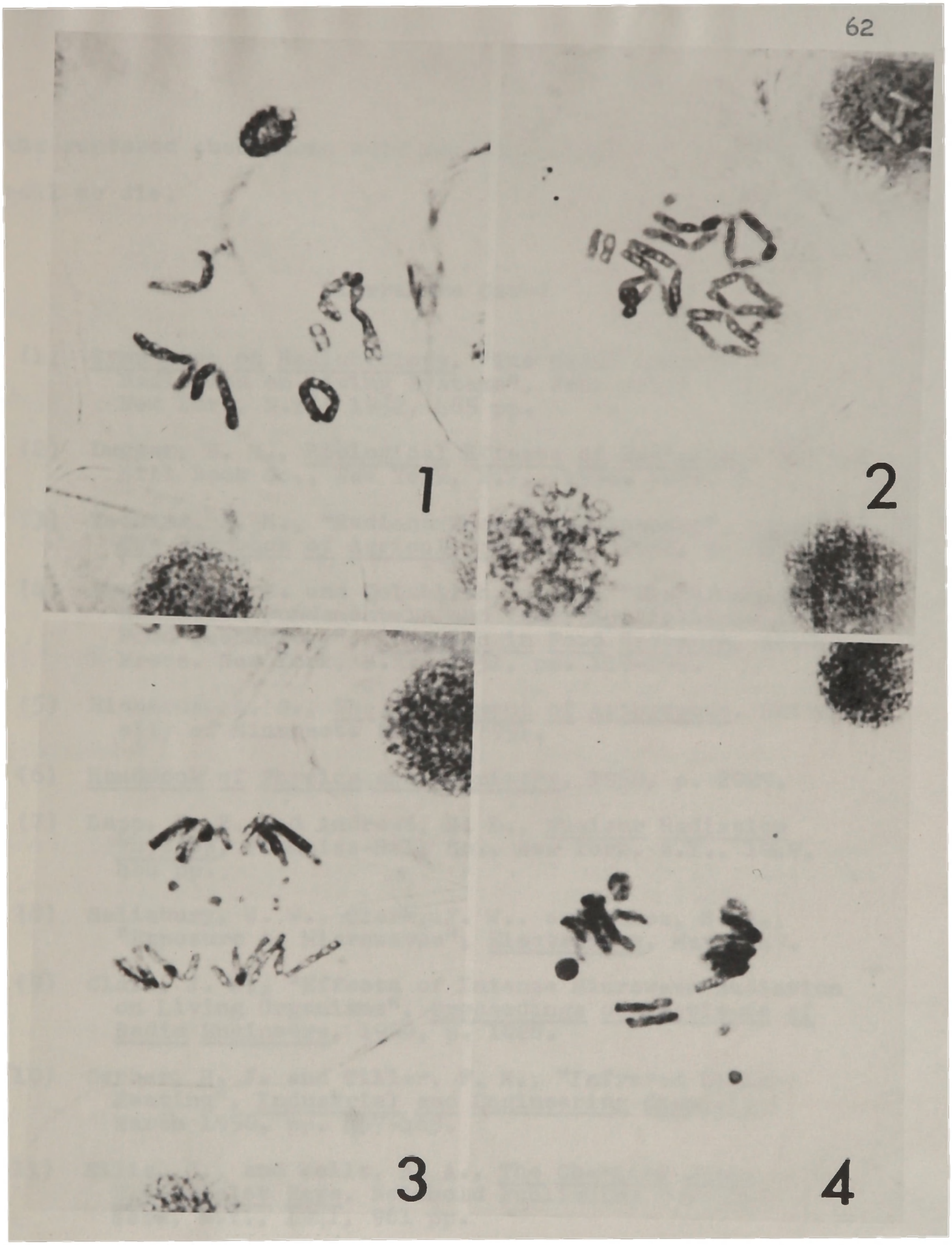

Fig. 9. Photomicrographs of various stages of cell division of a pollen cell from the Tradescantia reflexa (Wandering Jew) plant -- illustrating the effects of 500r of X-radiation on chromosomes, (1) metaphase, (2) early anaphase, (3) late anaphase, (4) early telophase.

the ruptured cheomosome will probably cause the offspring cell to die.

Literature Cited

(1) Symposium on Radiobiology, "The Basic Aspects of Radiation on Living Systems", John Wiley & Sons, New York, N.Y., 1952, 465 pp.

(2) Duggar, B. M., Biological Effects of Radiation, McGraw-Hill Book Co., New York, N.Y., 1936. Vols. I, II.

(3) Yeomans, A. H., "Radiant Energy and Insects", Insects: The Yearbook of Agriculture, USDA, 1952, pp. 411-421.

(4) Proctor, B. E. and Goldblith, S. A., "Electromagnetic Radiation Fundamentals and Their Applications in Food Technology", Advances in Food Research, Academic Press, New York, N.Y., 1951, pp. 119-196.

(5) Richards, A. G., The Integument of Arthropods, University of Minnesota Press, 1951.

(6) Handbook of Physics and Chemistry, 1950, p. 2029.

(7) Lapp, R. E. and Andrews, H. L., Nuclear Radiation Physics, Prentiss-Hall Co., New York, N.Y., 1949, 484 pp.

(8) Salisbury, W. W., Clark, J. W., and Hines, H. M., "Exposure to Microwaves", Electronics, May 1949.

(9) Clark, J. W., "Effects of Intense Microwave Radiation on Living Organisms", Proceedings of Institute of Radio Engineers, 1950, p. 1028.

(10) Garber, H. J. and Tiller, F. M., "Infrared Radiant Heating", Industrial and Engineering Chemistry, March 1950, pp. 457-463.

(11) Ellis, C., and Wells, A. A., The Chemical Action of Ultraviolet Rays, Reinhold Publishing Co., New York, N.Y., 1941, 961 pp.

(12) Radley, J. A. and Grant, J., Fluorescence Analysis of Ultraviolet Light, D. Van Nostrand Co., Inc., New York, N.Y., 1949, 424 pp. 3rd ed.

(13) Koller, L. R., Ultraviolet Radiation, John Wiley & Sons, New York, N.Y., 1952, 270 pp.

(14) Luckiesh, M., Applications of Germicidal, Erythemal, and Infrared Energy, D. Van Nostrand Co. Inc., New York, N.Y., 1946, 461 pp.

(15) Rahn, Otto, "Temperature and Life", Temperature: Its Measurement in Science and Industry, Reinhold Publishing Co., New York, N.Y., 1947, pp. 409-418.

(16) Morrison, P., "Radiation in Living Matter", Symposium on Radiobiology, John Wiley & Sons, New York, N.Y., 1952, pp. 1-12.

(17) Proctor, B. E. and Goldblith, S. A., "Food Processing with Ionizing Radiations", Food Technology, V(9): 376-380, 1951.

(18) Pollard, E. and Davidson, W. L., Applied Nuclear Physics, John Wiley & Sons, New York, N.Y., 1942.

(19) "X-rays, Radioactivity, and Electrons", Technical Bulletin D-2, High Voltage Engineering Corporation, Cambridge, Mass., 1952.

(20) Martin, J. R., "Radiation, Its Biological Effects and Problems", Mechanical Engineering, Nov. 1949, pp. 893-898.

(21) Sparrow, A. H. and Rubin, B. A., "Effects of Radiation on Biological Systems", U.S. Atomic Energy Commission Bulletin BNL-97, Technical Information Services, Oak Ridge, Tenn., 1952.

PART III

RADIO FREQUENCY DIELECTRIC HEATING

Theory of Dielectric Heating

Electrostatic capacity exists wherever an insulator (i.e., material with few free electrons) separates two conductors between which a difference in potential can exist (1). If a voltage V is applied to the plates of a condenser, Fig. 10, an electric charge will flow into them from the battery or DC generator, with the resulting production within the dielectric between the plates of an electrostatic stress. This electrostatic stress represents stored energy in the electrostatic field and depends upon the voltage applied to the plates and the capacity of the condenser.

If a DC voltage is applied to the plates of the condenser, the field between the plates will be static, i.e., the direction of the lines of force will not change as long as the charge on the condenser remains positive and negative. If an AC voltage be applied to the plates of the condenser, the electric field between the plates will become dynamic, i.e., the electric field will change directions each time the voltage changes and the field between the plates will no longer be electrostatic but will be electromagnetic. The AC voltage between the plates will cause an electromagnetic field to be set up between the

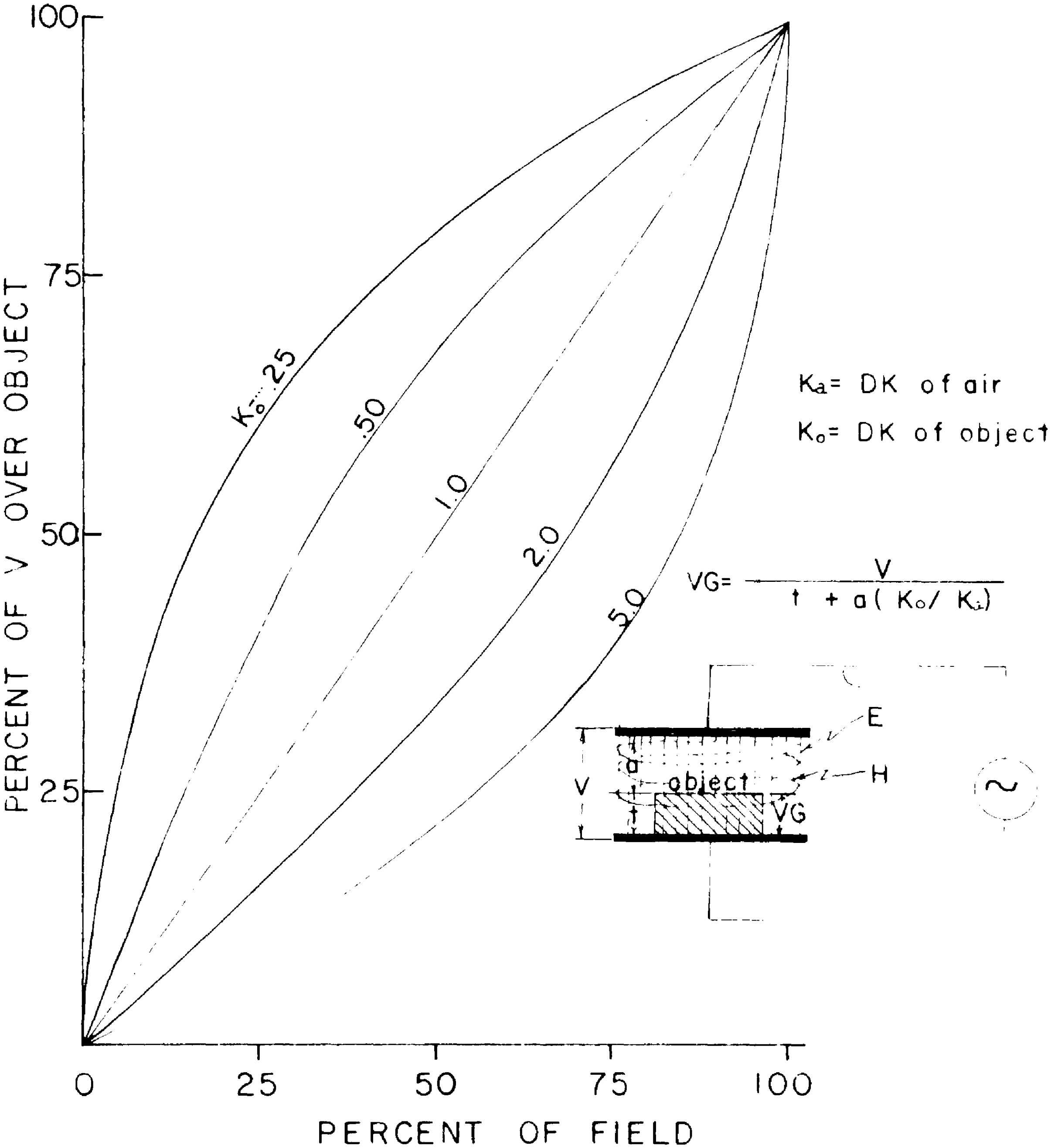

Fig 10. Theoretical voltage gradients across objects of various dielectric constants with sketch of object between condenser plates — with formula for voltage gradient across object.

plates. The electric field component will cause a displacement current to flow in the dielectric material between the plates of the condenser, which in turn will cause a magnetic field to be established.

Displacement Current

With an AC voltage applied to the plates of the condenser in Fig. 10, the classical formula for representing the current density in the dielectric is:

$$i = \epsilon \frac{\partial E}{\partial t} = \frac{\partial D}{\partial t} \qquad \text{(a)}$$

Maxwell (2) suggested that the quantity $\frac{\partial D}{\partial t}$ be called a displacement current. This displacement current flows in the condenser whenever i_c (conduction current) flows in the wire. The total current is then continuous. If the conduction current i_c and the displacement current $\frac{\partial D}{\partial t}$ flow in the same material, they may be added to obtain the total current, i.e.:

$$I = i_c + \frac{\partial D}{\partial t} \qquad \text{(b)}$$

The majority of the current in the wire leading to the condenser is conduction current. In the space between the condenser plates the conduction current density is small in comparison with the displacement current density. Any conduction current flowing through the condenser is called leakage current. It has been proven experimentally that the displacement current produces a magnetic field just as a conduction current does (2).

The ratio of the displacement current, for a given electric field strength and frequency between the condenser plates, for a given dielectric, to the conduction current between the plates with free space as the dielectric, is defined as the dielectric constant.

Power Loss in a Dielectric Material

The center of the negative charge in a molecule of a dielectric material may not necessarily be at the center of the positive charge. If this is true, a molecular dipole or couple is produced. When molecules of a dielectric material are exposed to a high frequency electric field, the molecular dipoles within the dielectric material tend to line up with the new field. (3) When the field reverses, the molecular dipoles tend to reverse their direction. In any dielectric there is a time lag in the alignment of the dipole with the new field direction. If the frequency of the field changes so that the alignment of the molecular dipole is 180 degrees out of phase with the electric field, then maximum energy will be absorbed by the dielectric. This concept holds true for a material between the plates of a condenser or for a material receiving energy from an antenna.

Since the change in the molecular configuration in the dielectric, due to the impressed voltage, imparts kinetic energy to the molecules of the dielectric which is dissipated as heat in the dielectric, an equivalent displacement current must flow into the dielectric in phase with the voltage impressed on the dielectric.

Whiteman (4) and Brown (5) developed an equation to show the power dissipated in the dielectric. If the power loss in watts for each cubic inch of the dielectric is P and the electric field intensity in volts per inch is E, then by definition the ratio of the power P to E^2 is the effective conductivity σ. The numerical value of σ is generally a very involved function of the frequency and is not a constant.

For materials that have a very small conductivity, the algebraic relation for σ is:

$$\sigma = 2\pi f \epsilon \theta \tag{c}$$

In this equation ϵ is the dielectric constant at the operating frequency f and θ the power factor of the dielectric material and is defined as the angle in radians by which the current flowing into the condenser fails to be 90 degrees out of phase with the voltage.

By equating equation (a) to the ratio of P to E and solving for the power dissipated in a unit cube we have:

$$P = 2 \cdot \pi \cdot f \cdot \epsilon \cdot E^2 \cdot \theta \tag{d}$$

This equation is a simple linear equation showing the relationship between the various parameters, and it clearly indicates that the power dissipated in the dielectric material depends on the frequency, dielectric constant , the electric field intensity and the power factor of the dielectric material.

Whiteman points out that it is possible to make the frequency f as well as the dielectric constant ϵ independent of the electrode shape. It is however impossible to make the electric field intensity through the dielectric material independent of the electrode shape. In order to have a uniform distribution of power density, it is necessary to have a uniform electric field intensity, which can be achieved in practice by properly arranging the electrodes.

Theoretical Voltage Gradient Across Objects Between Plates of a Condenser

In order to determine the field intensity across an object between the plates of a condenser, it is necessary to determine the voltage gradient across the object (6). The object could represent a box of cereal or it could represent a single insect or an insect egg in a given sample of grain, cereal, etc. The theoretical voltage gradients across objects of various dielectric constants are shown in Fig. 10. The object is placed in an RF field which includes an air gap as a function of the percent of field vertically occupied by the object, i.e., (t/a + t)100. The equation for the voltage gradient across the object is:

$$VG = \frac{V}{t + a\,(DK_o/DK_a)} \qquad \text{(e)}$$

where: VG = voltage gradient in volts per centimeter across the object

V = voltage between plates

t = thickness of treated object

a = thickness of air gap

DKo = dielectric constant of treated object

DKa = dielectric constant of air = 1

The above equation and the data given in Fig. 10 may be used to determine the actual field intensity for a specimen placed between the plates of a condenser.

Properties of a Dielectric Material -- Dielectric Constant, Relaxation Time and Resonance Phenomena

Non-metallic solid materials have few free electrons and the effect of the electric field on the molecules of the dielectric material becomes a very important factor. In accordance with this theory the electric field causes a definite displacement of the electrons in the atoms of the dielectric material as well as a displacement of the molecules in the material. Whiteman (4) reports that these displacements have translational as well as rotational components which are very important in radio frequency dielectric heating. As the electric field components of the molecules are lined up with the electric field component between the condenser plates, a displacement of charge within the dielectric material takes place. As a result of this displacement charge in the dielectric material, the displacement current is greater due to the presence of the dielectric than that occurring due to free space. The ratio of the former to the latter displacement current for a given electric field intensity, is defined as the dielectric constant of the material.

When considering the possible effects of an electromagnetic field on the insect, equation (d) shows that the dielectric constant and the dielectric power factor can be affected by the insect. This equation shows how these two factors affect the amount of energy dissipated over a given time. By knowing the power factor of the insect, the dielectric constant, and the lethal exposure time, the lethal energy can be calculated. However, with this equation, no possible physiological effect on the nervous system or body metabolism can be predicted.

The dielectric constant and dielectric power factor for different insects have not been determined. These factors would be extremely variable with different living insects, because their chemical and moisture content and shape would vary. The dielectric power factor and dielectric constant of a dielectric vary considerably with the moisture content, and temperature. This would also be true if an insect is considered as a dielectric.

In order to evaluate the possible effects of high frequency electric fields on dielectric materials containing permanent dipoles, such as insects when exposed to a high frequency field, it may be worthwhile to discuss in more detail the dielectric constant.

Debye (7) and Frohlich (3) suggested that the dielectric constant of a material can be represented by the equations on the following page.

A graphical representation of the real and imaginary dielectric constant is shown in Fig. 11. Slater (8) points out that if the dielectric material does not contain permanent molecular dipoles the imaginary part of the dielectric constant becomes zero in Fig. 11. If this is true for a given dielectric then the ratio $\frac{\epsilon''}{\epsilon'}$, referred to by Von Hippel (9) as the loss tangent of the dielectric, would be zero. Slater (8) also reported that the curve presented in Fig. 12 shows the dielectric constant and absorption as a function of frequency.

> "The range of frequency over which the dielectric constant is falling from its low frequency to its high frequency value is quite large (several powers of ten) and absorption is strong in this range. <u>The transition is not determined by any natural frequency of the system, for there is no characteristic resonant frequency, but it is related to what is called the relaxation time</u>. . . .

$$\epsilon = \epsilon' - j\epsilon'' \quad \text{(f)}$$

$$\epsilon' = \epsilon_s + \frac{(\epsilon_\infty - \epsilon_s)(WT)^2}{1 + (WT)^2} \quad \text{(g)}$$

$$\epsilon'' = \frac{(\epsilon_\infty - \epsilon_s)(WT)}{1 + (WT)^2} \quad \text{(h)}$$

Where:

ϵ = total dielectric constant

ϵ' = as defined by equation (g), real part

ϵ'' = as defined by equation (h), imaginary part

ϵ_s = static dielectric constant

ϵ_∞ = dielectric constant at optical or infinite frequency

T = relaxation time

$W = 2\pi f$

f = frequency in cycles per second

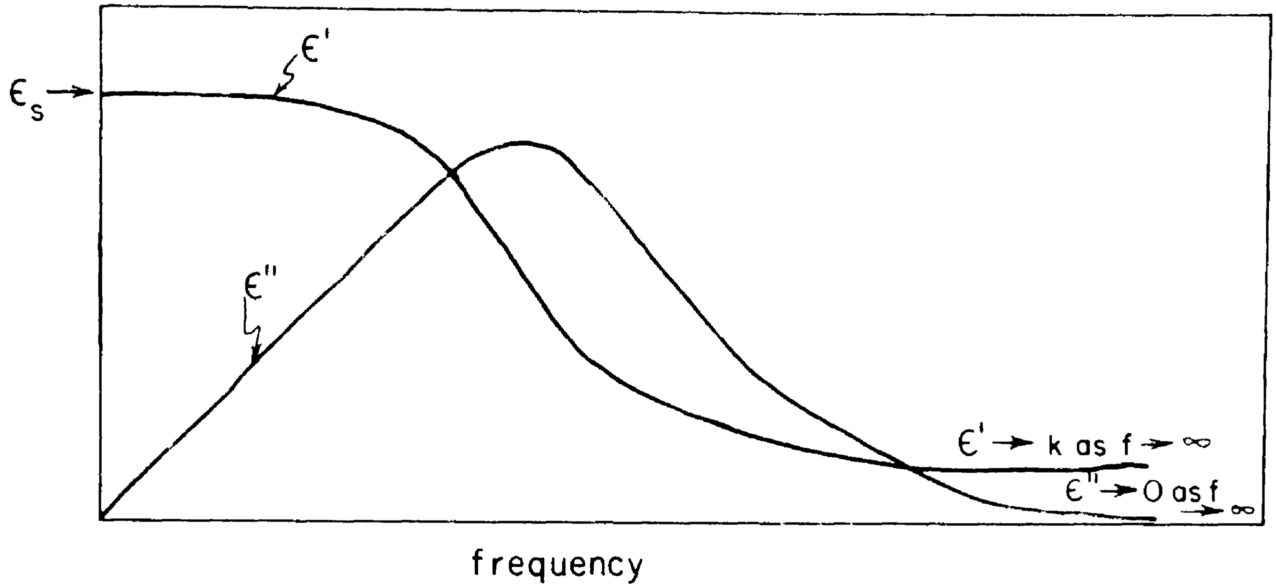

Fig 11. Variation of the real and imaginary dielectric constants with frequency.

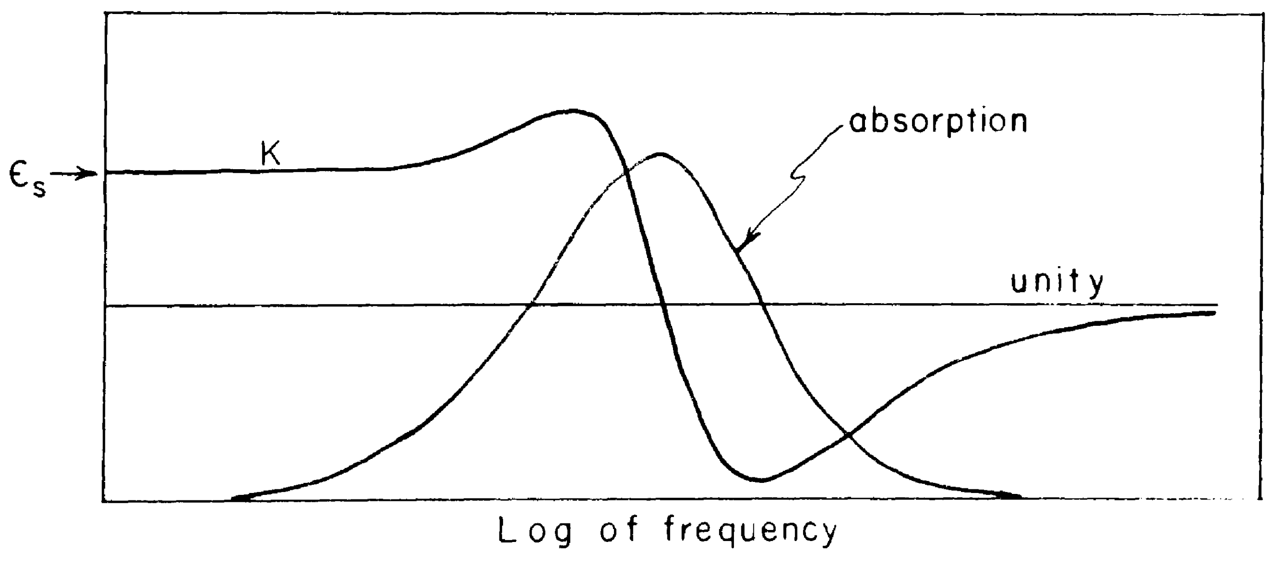

Fig 12. Dielectric constant and absorption as a function of frequency for a dielectric containing permanent dipoles subject to temperature agitation (9).

> The relaxation time proves to be proportional to the viscosity of the medium in which the dipoles are immersed."

The relaxation time as defined by Smyth (10) is the lag in response of a system to change in the forces it is subjected and the relaxation rate is the rate at which a system comes into equilibrium with its surroundings when such a change occurs. In terms of theory developed by Debye (7), dielectric relaxation is the lag in dipole orientation behind an alternating electric field.

The natural resonant frequencies associated with electronic polarizations are found by the quantum theory to be just within the visible part of the spectrum. The part of the dielectric constant associated with electronic polarization goes through a condition (steep portion of dielectric curve in Fig. 12) called anomalous dispersion coupled with absorption. In this part of the spectrum (above and including x-rays) the dielectric constant remains less than unity. According to the theory presented by Debye (7) electronic polarization is practically independent of frequency up to a frequency of about 1000 megacycles. Some work has been done in the microwave spectrum to study the dielectric constant at wavelengths of 1, 3, 5, 6, and 10 centimeters (9). Coolie (11) found that the maximum absorption for water was at a wavelength of 1.8 cm.

A summary of possible significance of the information given in this section will be presented after a review of the literature on the experimental use of dielectric heat for controlling insects is presented.

Review of Literature on the Effects of Dielectric Heating on Certain Insects

In a number of the papers reviewed there is a general misuse of terms. The use of the terms electromagnetic waves, electrostatic field, radio frequency waves (RF), dielectric heating, have been used interchangeably. These terms are related and it is generally believed that a changing electric field between the plates of the condenser will produce a changing magnetic field and the two fields cannot be separated as long as the electric field is changing. Therefore the term electromagnetic energy will be used in this discussion to refer to the changing energy between the plates of a condenser for dielectric heating purposes.

Effects of Electromagnetic Field

No attempt here will be made to review the literature on the medical or diathermic effects or the physical or engineering aspects of electromagnetic energy. The literature is voluminous on these two aspects. Only the effects on insects will be considered here with a brief mention of the results of early medical and scientific experiments.

d'Arsonval (12), the French scientist, in 1893, was probably the first investigator to observe the effects of high frequency electric fields on bacteria and animals. He observed a marked increase in the temperature of animals when exposed to high frequency fields. He also observed in 1896 changes in bacteria in cultures that were exposed to radio waves. Schereschewsky (13), Schliephake (14), Christie and Loomis (15) were among the first investigators to investigate the diathermic effects of radiant electric energy.

Schereschewsky observed some degree of specificity between frequency and tissue temperature of mice subjected to an electrostatic field between the plates of a condenser. Schliephake concluded that high frequency fields induce lethal changes in bacteria apparently as a result of dielectric hysteresis. Christie and Loomis investigated the effects of high frequency fields on tissue.

The most extensive studies on the lethal effects of electromagnetic energy on insects were made by Headlee (16, 17, 18, 19, 20, 21, 22) and his co-workers Burdette and Jobbing, Hadjinicolaou (23), and Pyenson (24). Studies were made by these investigators on the lethal effect of an electromagnetic field of different frequencies on insects during the various stages of development of the insect and on the effects on the different families of insects. Headlee and his co-workers also investigated the effects of high frequency electromagnetic energy on plant tissue. A summary of Headlee's *et al.* work may be listed as follows:

1. The important factors in killing insects in an electromagnetic field between the plates of a condenser are: frequency, time, and field strength.

2. The more highly centralized the nervous system of the insect the more rapidly it was killed. Adults of holometabelous insects were killed more rapidly than their larvae. Variation between families and variation between development stages from the egg to the adult appeared to support this thesis.

3. The lethal effect was apparently attributed to the induction of temperatures reaching the thermal death point of the insect.

4. They concluded that it was possible that cholesterol in the nervous tissue of insects caused this part of the insect to heat rapidly.

5. The higher frequencies 9 to 18 megacycles per second (mc) heated plant and animal tissue similarly. The lower frequencies 1 to 3 mc per second were effective against insects but did not appreciably heat the plant material. They thought that this differential at lower frequencies might be used to kill insects on plants without injuring the plants, however, no tests were made. The investigators did not list the field strength for all frequencies used. This would have an important bearing on any comparison made with the different frequencies used.

Other tests were conducted by McKinley and co-workers (25, 26, 27). They were not interested in insect control, but with the insects studied essentially the same results were obtained as reported by Headlee. McKinley concluded that there exists an effect other than heat which accounts for the death of a parasitic wasp when exposed to a high frequency electromagnetic energy between the plates of a condenser, but he did not list a hypothesis or give reasons for his conclusions.

Duggar (28), and Ark and Parry (29) have summarized the previous work on the applications of high frequency electrostatic (he means electromagnetic) energy in agriculture. Ark and Parry summarized the findings of a group of Russian investigators, Vishniakova (30), Feshott (31), Evreinov (32), Andreiev and Balkashin (33), who were interested in the control of weevils and mites in stored grain. These investigators reported that energy in an electric field between the plates of a condenser had practical value in insect control, and also increased the germination of treated seed.

Fringes (34) has summarized the work of Davis (35), Mouromtseff (36), Graham and Fabian (37), Kocia (38), and the Japanese investigator Yagi (39).

Davis and Mouromtseff reported excellent control from tests of equipment for the control of insects in grain. Davis conducted tests in cooperation with the Baltimore and

Ohio Railroad using the dielectric process of treating wheat, beans, corn, tobacco, spices, cereals, etc. between the plates of a condenser using a 20 kw oscillator with plate voltages up to 9100 DC at a frequency of 42 mc. The most favorable lethal temperature was 125° F.

Mouromtseff, in reporting on the work of Davis, mentioned that safe energy for lethal effects was 443 watt-seconds per cubic inch or 970,000 watt-seconds per bushel or 0.27 kw-hr was needed to treat a bushel of wheat using equipment with a frequency of 40-50 mc. The DC input to the 20 kw machine was 0.67 kw-hr per bushel of wheat treated.

Results of tests were explained by the selective heating produced by high frequency fields used in animal and plant tissue. Temperatures up to 180° F did not seem to affect the wheat. Marked carbonization of the internal tissues of the weevil was noted in all tests. Eggs of the insects treated were also sterilized.

Kocia studied the effect of radio waves on pupa and larvae. He concluded that the increase in metabolism and development rate were probably due to the increased internal temperatures. Yogi, in his paper describing his test with the silkworm between the plates of a condenser, pointed out a number of items that the previous investigators did not mention.

1. He pointed out that in the previous work the death point was not clearly described and that immobility and

death are not the same.

2. Yogi also noted the importance of the orientation of the insect between the plates of the condenser. Silkworms with the long axis of the body perpendicular to the condenser plates were killed rapidly at a relatively low voltage gradient, whereas, if the insects were placed parallel with the condenser plates at the same voltage, they were killed slowly or possibly not at all.

Development of Equipment During and After World War II

During and since World War II, new and improved high frequency electromagnetic equipment was developed. The literature is quite extensive on these developments. Sherman (40), Whiteman (4), Brown *et al*. (41), Cathart (42), Tillson (43), Bartholomew (44), Morse and Revercomb (45), Baker (46), and Mittelman (47) are among a few of the references applicable to new equipment since World War II. No attempt will be made here to review this literature. However, they contain excellent information which will help one to become acquainted with some of the high frequency equipment that has become available since World War II.

In 1946, after World War II, Weber *et al*. (48) conducted tests with a dielectric heating unit in an effort to control various insects in packaged products such as cereal and whole wheat flour. The plates of this unit had dimensions of 25.4 cm in width, 35.5 cm in length and the distance between them could be varied from 0 to 9.85 cm. The field intensity was apparently not given but was probably 27 megacycles. The field strength was varied between 1200 to 1700 volts per cm. The insects exposed were *Ephestia kuhniella* and *Tribolium confusum*. Some of Weber's results may be summarized as follows:

1. The lethal temperature of externally applied heat (when *Tribolium confusum* was in the test tube in a water bath) was 65° C (149° F) for larvae, pupae, and adult. This temperature was compared with the work of Belehradek (49). Weber measured temperatures with a mercury thermometer.

2. One hundred percent mortality was obtained when *Tribolium confusum* adult, larvae, and pupae were exposed to field strengths of 1350, 1550, and 1775 volts per cm for a period of 30 seconds or longer.

Brown (41) reported that the application of radio frequency heating to dry food products such as cereals and flour which are infested with weevils and their eggs is a straightforward and simple process. He pointed out that the insects usually contain more moisture than the bulk material which they infest and that selective heating often takes place and the mean temperature of the package need not reach excessive values. Tests conducted with one-pound packages of cereal revealed that a temperature of 140° F was sufficient to inactivate weevils and eggs.

Fringes (34) reported on the effects of electromagnetic energy on insects between 15 cm diameter plates of a condenser. The maximum power was 1 kw. Frequencies varied between 2.6 and 25 mc. Field strengths up to 3000 volts per cm were used. Temperatures of the specimen were measured with a thermocouple placed in the specimen. Fourteen specimens were exposed. The work of Fringes was designed to test the possibility of using high frequency electromagnetic energy to kill insects inside fruits and vegetables without damaging the plant material -- specifically this work centered about the possibility that eggs and larvae of the oriental fruit fly, *Dacus dorsalis*, could be destroyed in papayas and other fruits without heating the fruits appreciably. Fringes also discusses the voltage gradient factor, the vertical fraction factor, the frequency factor, the physiological factors, and the morphological factors. Fringes' general results may be listed as follows:

1. Fruits and vegetables are heated and insects are killed when placed in the electromagnetic field between the plates of a condenser when the frequency is varied between 3-27 mc. The main cause of death is heating of the insect.

2. The rate of heating of a treated object depends on the frequency, voltage gradient, the vertical fraction of the field occupied by the object treated, chemical composition, physical state, and shape of the object (in insects age, sex or physiological condition).

3. No critical differential in heating at various frequencies between plant and animal tissue was found.

4. It is probably impossible to heat an insect inside a fruit or vegetable without also heating the plant material.

5. Fringes pointed out that if experiments of this type are to be duplicated, the following information must be given about the treated material: age, sex, size and shape, physiological state of treated insects and exact death point or lethal temperature. Also the following treatment conditions must be listed: time of treatment, voltage gradient and frequency of field, and the vertical fraction of field occupied by objects.

Dennis and Soderholm (50, 51) reported on the use of dielectric heat to control the rice weevil (Sitophilus oryza) in wheat. Tests were conducted at the Nebraska Agricultural Experiment Station in cooperation with the United States Department of Agriculture. The equipment used was operated on a frequency of 27 megacycles per second and at a maximum power of 25 kilowatts, which was capable of penetrating a depth of one foot of wheat. Small samples of wheat of 12, 14, 16, and 18 percent moisture were treated in one-pint plastic containers, 2 3/8 inches high by 3¼ inches in diameter with time of exposure from 2 to 12 seconds in a field strength of 1800 volts per inch.

The results of the work by Dennis and Soderholm show that an exposure of the wheat samples for 9 seconds gave 100 percent mortality for the adult rice weevil, and an exposure of 11 second was required for 100 percent mortality of immature stages of the rice weevil. During the 9-seconds exposure time the temperature of the samples rose from 75 to 130° F, whereas, the temperature in the 11-seconds exposed samples rose to 148° F.

Soderholm (51) reported further that a 100 percent kill of adult rice weevil in 12 percent moisture wheat may be obtained 12 days after treatment by the application of 40 mc radio frequency field for periods of approximately one second duration. Temperatures as high as 160° F did not seem to produce any appreciable change in germination, or baking and milling qualities. A 100 percent kill of pink bollworm larvae in 10 percent moisture cottonseed may be obtained by the application of a 40 mc radio frequency field for periods of 14 to 29 seconds when the mass temperature approaches a temperature of 170° F.

General Summary of Previous Work between Plates of a Condenser

1. Electromagnetic energy between the plates of a condenser with frequencies of 1 to 50 mc per second can kill insects. The lethal effect is mainly a result of internal heating of the insect.

2. Factors which influence the amount of internal heating are: voltage gradient, time of exposure, frequency, orientation of insect in field, age, sex, and type of insect.

3. The degree of lethal effect has been theoretically

associated with the specialization of the nervous system, i.e., the more specialized adult insects (bees) are killed more rapidly than the less specialized insects (cockroaches).

4. At higher frequencies (5 to 50 mc per sec) plant and animal tissues heat rapidly and similarly, whereas at lower temperatures (1 to 3 mc per sec), plant tissues do not heat while animal tissues heat very rapidly. (This statement needs more qualification than was given in the original paper).

5. It is probably impossible to heat an insect inside a fruit or vegetable, without also heating the fruit or vegetable.

6. In the papers reviewed, the study of possible practical utilization of electromagnetic energy for insect control remains chiefly experimental.

Discussion of Dielectric Heating as a Method of Controlling Insects

Equation (d) shows that the power dissipated in a dielectric is directly proportional to the frequency of the applied electric field. Most of the dielectric machinery used in the experimental literature review operated on a frequency below 50 megacycles. Dielectric heating equipment has been designed to operate on frequencies as high as 1050 megacycles (52). With this higher frequency it is necessary to heat the material in resonant cavities or waveguides. With this high frequency widely varying temperatures are likely to occur in the treated product if the dimensions of the product are comparable to the wavelength.

Calculations have been presented under this section on ionization to show that none of the frequencies used for dielectric heating cause ionization, unless a temperature is reached which would cause heat of dissociation.

Since it has been demonstrated that a temperature of 170° F is lethal to insects which infest wheat, a simple calculation will show the energy required to raise 100 pounds of wheat from a temperature of 70 to 170° F, assuming 50 percent efficiency is $BTU = wt(t_1 - t_2)(sh)$ for 100 pounds per minute or 6000 pounds per hour.

$$6{,}000\ (170-70)(.40) = 240{,}000\ \text{BTU}$$

$$KW = \frac{6{,}000\ (170-70)(.40)}{3413\ (.5)} = 140$$

If electricity costs 2 cents per kwh, then the cost for energy per hour would be $2.80 for 3 tons or 93 cents per ton at a rate of 100 pounds per minute.

A conservative estimate for the cost of steam is $0.001 per 1000 BTU. Using the data above, the cost of energy for raising the temperature of wheat from 70 to 170° F, using steam coils for a wheat flow rate of 100 pounds per minute, for a period of 1 hour, assuming a heat transfer efficiency of 60 percent, will be:

$$\frac{240{,}000\ (.001)}{1000\ (.85)} = 28¢ \text{ for 3 tons or } 9.3¢ \text{ per ton}$$

Proctor and Goldblith (53) have reviewed the economics of radio frequency heating. They reviewed the work of Smith, Kinn, and Sherman. Smith (54) discussed the prevention of insect contamination in packaged foods and he reported that deinfestation of insects in food products can be obtained at a cost of .01 cent per package. Kinn (55) presented a number of charts and tables for determining the economic feasibility of dielectric heating. Sherman (42) states that the total of all the elements of operating costs rarely exceeds 10 cents per kilowatt of output.

The following conclusions merit consideration:

1. Dielectric heating can be used to kill various stages of insect life in wheat, flour, and beans, etc. This process may be used for processing large quantities of foods at rapid rates of production, because the dielectric heating process has the ability to penetrate almost instantaneously into products such as wheat, flour, and certain packaged products.

2. It has been postulated by some investigators that selective heating occurs when high moisture content insects infesting low moisture content products such as wheat and flour are heated. This theory does not seem to have merit because in all cases reviewed, it was necessary to raise the temperature of the mass of material to the lethal temperature of the insect before 100 percent mortality was obtained.

3. It has been demonstrated in another section of this thesis that the only effect that can be obtained, with the frequencies normally used in the dielectric process, is a heating effect. There is no resonant molecular frequency or other apparent effect other than heat which can be depended upon to cause lethal effects.

4. Since a pure heating process is necessary to kill insects in a dielectric spectrum, the use of steam coils for raising the temperature of thin layers of wheat or some direct method of utilizing energy from coal such as in an oven, etc. would appear to be more economical when large masses of wheat are to be treated. This process is illustrated in Fig. 13. An illustrative problem was solved to show that the cost of energy for the dielectric treatment for 100 pounds per minute for wheat was 88 cents per ton and 9.3 cents per ton with steam coils. The steam coil operation should also show a considerable savings in overhead and maintenance costs.

Literature Cited

(1) Terman, F. E., Radio Engineering, McGraw-Hill Book Company, New York, N.Y., 1937, p. 23.

(2) Sarbacher, R. I., Hyper and Ultra High Frequency Engineering, John Wiley & Sons, New York, N.Y., 1943, p. 43.

(3) Frohlich, H., Theory of Dielectric, Oxford University Press, Ames Hourse, London EC4, 1949.

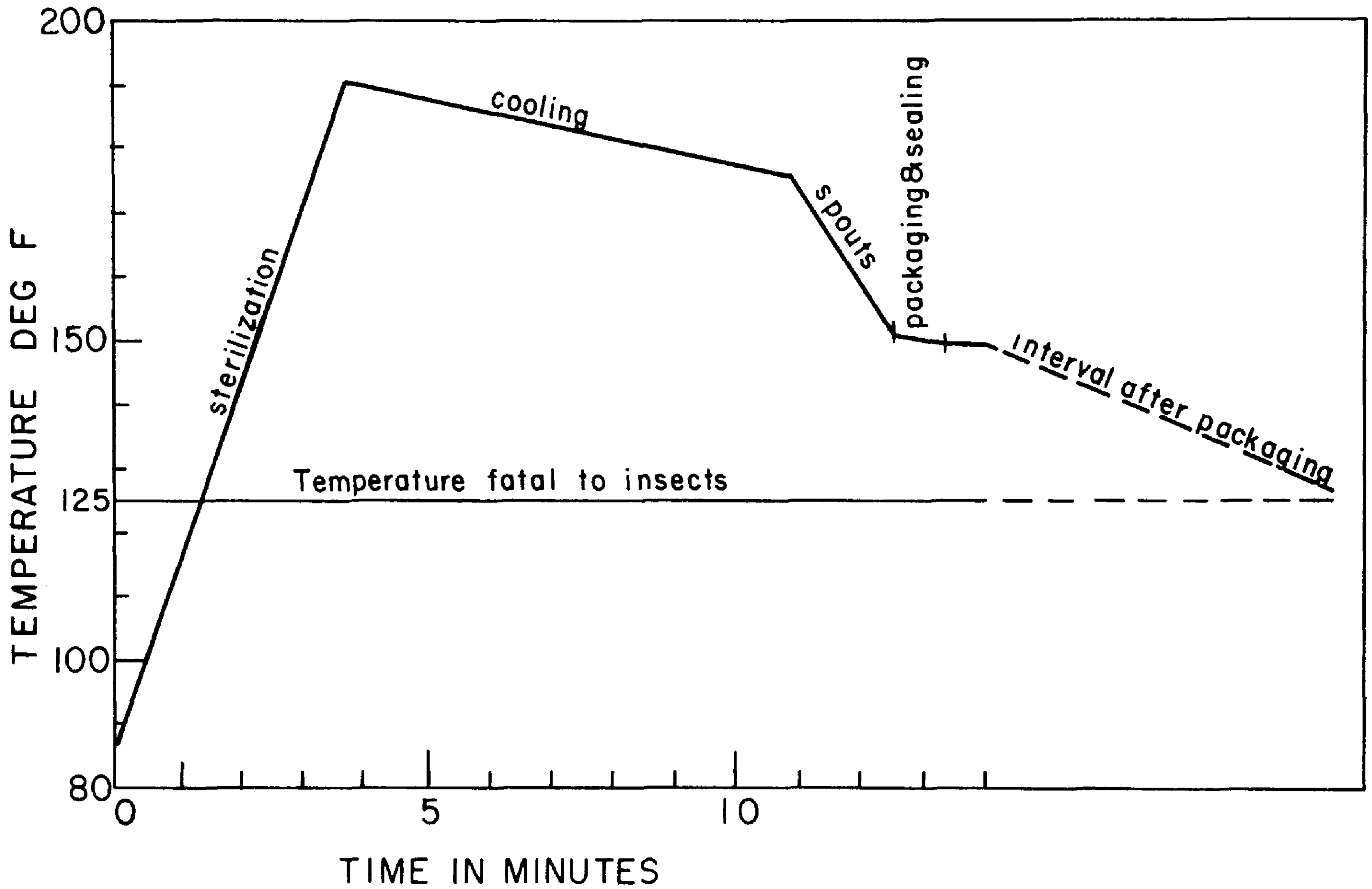

Fig 13. Temperature of cereals during process of sterilization and packaging, from Chapman (56) and Cotton (57), which has been used satisfactory for insect control.

(4) Whiteman, R. A., "Electrodes for High Frequency Heating", Radio and TV News, August 1950, p. 3A.

(5) Brown, G. H. and Hoylen, C. N., Theory and Application of Radio Frequency Heating, Van Nostrand, New York, N.Y., 1947, p. 208.

(6) Lanton, L. L., Radio Heating Equipment, Pittman Publishing Co., New York, N.Y., 1949.

(7) Debye, P., Polar Molecules, Chemical Catalog Co. Inc., New York, N.Y., 1929, pp. 95-100.

(8) Slater, J. C., "Structure and Polarization of Molecules", Electrical Engineering, October 1950.

(9) Von Hippel, A., "Dielectrics in Electrical Engineering", Electrical Engineering, September 1952, p. 3.

(10) Smyth, C. P., "Dielectric Relaxation in Liquids and Solids", Electrical Engineering, November 1950.

(11) Coolie, C. H., Hosted, J. B., and Ritson, D. M., "The Dielectric Properties of Water and Heavy Water", Proceedings of the Physical Society of London, 1948, p. 145.

(12) d'Arsonval, A., "Influence de la frequence sur les effets physiologiques des courants alternatifs", Compt. Rend. Acad. Sci (Paris) 116:630-632, 1893.

(13) Schereschewsky, J. W., "The Physiological Effects of Currents of Very High Frequency", Public Health Reports 41:1939-1963, 1926.

*(14) Schliephake, E., "Die biologische Wärmewirkung im elektrischen Hochfrequenzfeld", Gesellschaft für innere Med. 40:307-310, 1928.

(15) Christie, R. V. and Loomis, A. L., "The Relation of Frequency to the Physiological Effects of Ultrahigh Frequency Currents", Jour. Exp. Med. 49:303-321, 1929.

(16) Headlee, T. J. and Burdette, R. C., "Some Facts Relative to the Effect of High Frequency Radio Waves on Insect Activity", Jour. N.Y. Ent. Soc. 37:59-64, 1929.

(17) Headlee, T. J., "The Differential between the Effect of Radio Waves on Insects and on Plants", _Jour. Econ. Ent._ 24:427-437, 1931.

(18) Headlee, T. J., "Further Studies on the Effects of Electromagnetic Waves on Insects", _Jour. Econ. Ent._ 25:276-288, 1932.

(19) Headlee, T. J., "The Effect of Radio Waves on Internal Temperature of Certain Insects", _Jour. Econ. Ent._ 26:313-319, 1933.

(20) Headlee, T. J., "Some Observations on the Effect of Radio Waves on Insects and Plant Hosts", _New Jersey Agr. Exp. Sta. Bull._, 1934, pp. 568-583.

(21) Headlee, T. J. and Jobbin, D. M., "Further Studies of the Use of Radio Waves in Insect Control", _Jour. Econ. Ent._ 29(1):182-187, 1936.

(22) Headlee, T. J. and Jobbins, C. M., "Progress to Date on Studies of Radio Waves and Related Forms of Energy for Insect Control", _Jour. Econ. Ent._ 31:559-563, 1938.

(23) Hadjinicolaou, J., "Effect of Certain Radio Waves on Insects Affecting Certain Stored Products", _Jour. N.Y. Ent. Soc._ 39:145-150, 1931.

(24) Pyenson, L., "The Shielding Effects of Various Materials when Insects are Exposed to the Lines of Force in a High-frequency Electrostatic Field", _Jour. N.Y. Ent. Soc._ 41:241-252, 1933.

(25) McKinley, G. M. and Charles, D. R., "Certain Biological Effects of High Frequency Fields", _Science_ 71:490, 1930.

(26) McKinley, G. M., "Some Biological Effects of High Frequency Electrostatic Fields", _Proc. Pa. Acad. Sci._ 4:43-46, 1930.

(27) McKinley, G. M. and McKinley, J. G., Jr., "The Vacuum Tube Oscillator in Biology", _Quart. Rev. Biol._ 6:322-328, 1931.

(28) Duggar, B. M., _Biological Effects of Radiation_, McGraw-Hill Book Co., New York, N.Y., 1936. Vol 1: 541.

(29) Ark, P. A. and Parry, W., "Application of High-frequency Electrostatic Fields in Agriculture", Quart. Rev. Biol. 15:172-191, 1940.

*(30) Vishniakova, M. W., "Issledovanie letalnogo deistviia ultrakorotkikh voln na dolgonosikov i vliianiia ikh na khoziaistviennuiu godnost pshienitsi", Mekh. i Elektr. Sotsial. sel'sk Kohz., 1934, pp. 26-33.

*(31) Feshott, L., "O deistvii radiovoli i ultrafioletovikh luchiei na nasekomikh", Zaschita rastenii, 1935, pp. 147-158.

*(32) Evreinov, M. G., "Deistvie UHV na nasekomikh i semena", Makhan. i Elektr. Sotsial, sel'sk Khoz., 1935, pp. 20-29.

*(33) Andreiev, S. and Balkashin, B., "Toki visokoi chastoty v borbie s muchnimy kleschanii", Zaschita rastenii, 1935, pp. 121-123.

(34) Fringes, Hubert, "Factors Determining the Effects of Radio-frequency Electromagnetic Fields on Insects and Materials they Infest", Jour. Econ. Ent. 45: 396-407, 1932.

(35) Davis, J. H., "Radio Waves Kill Insect Pests", Scientific Amer. 148:272-273, 1933.

(36) Mouromtseff, I. E., "Oscillator Kills Grain Weevils In Few Seconds", Electr. World 102:667, 1933.

(37) Graham, H. T. and Fabian, F. W., "A Note on the Influence of High Frequency Alternating Current On Animals", 48th Ann. Rept. Mich. State Coll. Agr. Expt. Sta., 1935, pp. 197-201.

*(38) Kocia, V., "Über den Einfluss des Elektrizitatsstrome mit einer hohen Frequenz und Spannung auf die Metamorphose und Sauerstoffverbrauch der Insektempuppen und larven", Zool. Jahrb., Abt. Allg. Zool. u. Physiol. 56:1-6, 1936.

*(39) Yogi, S., "Effect of High Frequency Electric Oscillation on Insect, Especially on Its Life and Conduct" (In Japanese), Shokubutu oyobi Dobutu 6:285-298, 1938.

(40) Sherman, V. W., "Electronic Heat in the Food Industries", Food Industries 18:506-509, 628, 630; 1946.

(41) Brown, G. H., Hoyler, C. N., and Bierwith, R. A., Theory and Application of Radio-frequency Heating, Van Nostrand, New York, N.Y., 1947, pp. 328-350.

(42) Cathcart, W. H., "High Frequency Heating Produces Mold-free Bread", Food Industries 18:864-865, 1946.

(43) Tillson, E. D., "Electronic Sterilization", American Miller 73(4):43, 1945.

(44) Bartholomew, J. W. et al., "Electronic Preservation of Boston Brown Bread", Food Technology 2:91-94, 1948.

(45) Morse, P. W. and Revercomb, H. E., "UHF Heating of Frozen Foods", Electronics 20(10):85-89, 1947.

(46) Baker, R. M. and Madsen, C. J., "High Frequency Heating of Conductors and Non-conductors", Proceedings of the National Electronics Conference 1:360-380, 1945.

(47) Mittelmann, E., "New Methods and Techniques in High Frequency Heating", Proceedings of the National Electronics Conference 1:392-406, 1945.

(48) Weber, H. H., Wagner, R. P. and Pearson, A. G., "High-frequency Electric Fields as Lethal Agents for Insects", Jour. Econ. Ent. 39:487-498, 1946.

*(49) Belehradek, J., Temperature and Living Matter, Gebruder Borntraeger, 1935.

(50) Dennis, N. M. and Soderholm, L. H., "Killing the Rice Weevil with High Frequency Radio Waves", Unpublished preliminary report, Bur. Ent., USDA, 1952.

(51) Soderholm, L. H., "The Effect of Dielectric Heating on the Pink Bollworm", Paper presented at the Winter Meeting of ASAE at Chicago, Ill., Dec. 15, 1952.

(52) Nelson, R. B., "A Magnetron Oscillator for Dielectric Heating", Jour. Applied Physics, April 1947.

(53) Proctor, B. E. and Goldblith, S. A., "Economics of Radio Frequency Heating", Advances in Food Research, Academic Press, New York, N.Y., 1951. Vol. 3, pp. 144-145.

(54) Smith, C., "How to Prevent Insect Contamination", Intern. Confect. 54(9):30, 48, 52; 1948.

(55) Kinn, B. T. P., "The Practical Economics of Radio Frequency Heating", Iron Age 161(24):72-77, 1948.

(56) Chapman, R. N., "Insects Infesting Stored Food Products", Univ. Minn. Agr. Expt. Sta. Bull. 187, 76 pp., 1921.

(57) Cotton, R. T., Insect Pests of Stored Grain and Grain Products, Burgess Publishing Co., Minneapolis, Minn., 1952, p. 235.

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*Work by authors so marked not readily available for review. Work by these authors was summarized by other authors as referred to in the text, namely Ark and Parry (29).

PART IV

SOME EFFECTS OF MICROWAVE ENERGY ON CERTAIN INSECTS

Some aspects of the use of microwave energy were discussed in Part II of this thesis. The factors previously discussed relative to microwave energy are absorption by tissue and heating effect. The factors involved in developing an equation for the conservation of energy in an electromagnetic wave was also discussed in Part II.

As justified in the previous discussion, there is not enough energy in a quantum of a microwave frequency with wavelength of about 0.25 cm to 15 cm to produce ionization in tissue. When microwave energy is absorbed in tissue or any dielectric loss material, the electromagnetic energy is changed into heat.

Review of Literature

It has been demonstrated by Clark (1) and Herrick (2) that the principle effect obtained by exposing various parts of animals, including eyes, internal body cavities, testicles, and muscular tissue to modest amounts of microwave energy, was a heating effect. Clark stated that:

> "I should like to emphasize again that this damage is entirely due to the heat generated as a result of the absorption of microwave energy by the body tissue and is not due to any mysterious property of microwave radiation as such."

Most damage was to areas where proteins exist, such as in eye lens. Heat from microwaves seems to coagulate areas in the eye to form cataracts and the damage is not apparent immediately after exposure.

The work reported by Hines and Randall (3), Richardson *et al*. (4), and Salisbury *et al*. (5) point out some interesting effects of microwave energy on tissue. It was found that from studies (3) made with 1600, 75, 12, 8, and 3-cm radiations that the shorter electromagnetic waves were relatively more effective for increasing the temperature in superficial tissue than in deeper tissue and that longer wavelengths were more effective for heating of deep tissue than for superficial tissue. Tests were made to determine the effects of 12-cm microwaves on the testes of adult rats. It was found that a single 10-minute exposure to microwaves caused testicular degeneration at a temperature of only 35° C measured in the central area of the gland.

Salisbury *et al*. (5) found that microwaves produce heat in the body where an abundant amount of blood is not supplied and that blood is an effective coolant and acts to distribute heat developed evenly. It was pointed out that certain parts of the body are not effectively cooled by the blood; examples include, lens in the eyes, gall bladder, parts of the intestines, and the testicles. When such organs are subjected to microwave irradiation, very high local temperatures may result. Richardson *et al*. (4)

found that when the flow of blood was sufficiently increased by continuous irradiation, the temperature ceased to rise and eventually was diminished when the rate of flow was great enough, so that the peak temperature often preceded the termination of irradiation.

Microwaves from an Antenna

It may be worthwhile to list the factors involved in trying to arrive at an equation so that the electromagnetic energy required to heat an insect in free space can be calculated. If equation (h) in Part I (the section on electromagnetic radiation) be examined in a practical way for possible effects on insects it would seem that the rate of decrease of the electromagnetic energy in a given insect with an approximate volume is given by the right side of the equation (h), and this is equal to the rate at which heat is expended in V plus the rate at which the vector S flows through the surface surrounding V. The relationship between frequency of an electromagnetic wave and its energy content is shown indirectly in equation (h) since ϵ is a function of frequency. This relationship could be very important in predicting the lethal effect of high frequency waves on insects.

Insects in an electromagnetic field in free space may meet the conditions in equation (h) to an intermediate degree, since it is probable that most insects will be inhomogeneous and anisotropic. In order for an insect to meet fully the requirements of a homogenous medium, and thus satisfy the medium in which equation (h) would be completely valid, the parameters , , and should be constant in the insect in question. If these parameters have the same properties in all directions in the insect, the insect would be isotropic.

Schwan (6) proposed that the electromagnetic theory and information presented in the two papers by Schwan and Li (7) and Schaefer and Schwan (8) be combined into an equation which would give the field strength required to develop enough heat in insects in free space in order to have lethal effects. At the time of this writing a complete equation had not been fully developed using Schwan's suggestions, however, the equation presented in the next paragraph gives the relationship between the various factors involved.

The power necessary to raise the temperature of a given object in space, a distance r from an antenna in a given time, may be represented by the following formula:

$$WC\ (T_2 - T_1) = 4.2P(t)(e)(G)\frac{A}{r^2}$$

Solving for P:

$$P = \frac{WC\ (T_2 - T_1)r^2}{4.2(t)(e)(G)A}$$

where: W = weight of object in grams

C = specific heat of object

$T_2 - T_1$ = temperature rise in degrees Centrigrade

4.2 calories = 1 Joule

P = power in watts

t = time in seconds

e = overall efficiency

G = gain of antenna = K/λ^2, where K is some constant depending on type of antenna

λ = wavelength

r = distance from object to antenna

It can be seen in the above equation that the power necessary to raise the temperature of an object in space with a given antenna is directly proportional to the square of the distance r and inversely proportional to the time t.

A specific problem is solved below using the following assumptions: An insect with a weight of 0.1 g, a specific heat of 1, an exposed cross sectional area of 0.1 sq cm is to be given a temperature rise of 55° C in one second at a distance of one meter from the antenna. Assume also that the gain of the antenna is 10, and that the overall efficiency is 37 percent, The overall efficiency of 37 percent is obtained by multiplying .50 x .75 = .37. This assumes that the radio or microwave equipment is 50 percent efficient and that the efficiency of absorption is 75 percent, i.e., 75 percent of the incident energy is abosrbed by the insect and 25 percent is reflected.

The solution is:

$$P = \frac{.1\ (1)\ (55)\ (100)^2}{4.2\ (1)\ (.37)(10)(.1)} = 35{,}000 \text{ watts}$$

If the distance (r) be increased to 5 meters, then the power required would be 880,000 watts.

If the antenna gain be unity, which may be the case for certain vertical antennas, the power required in the above two cases would be 350,000 watts and 8,800,000 watts respectively.

Other values for t and G may be substituted in the equation and power requirements determined if desirable.

No experiments have yet been performed in order to evaluate the relative dangers or effects on insects or animal tissue of pulsed power as compared to continuous power. However, rough calculations by Salisbury et al. (5) of the thermal time constants of typical physiological structures indicate that these are long as compared to the interval of a pulse of typical radar set. Accordingly, they pointed out that it would seem reasonable to evaluate the danger from apparatus of this type in terms of average power rather than peak power.

Salisbury et al. (5) also reported that the field strength known to be dangerous to human beings is 3 watts per sq cm, and is not likely to occur except in the immediate vicinity of a powerful transmitter. The area of a cross section of a typical 10-cm wave guide is about 28 sq cm. A power of about 90 watts is required to reach the danger level in this wave guide. In free space, the energy level is much less concentrated so a much larger total power would be required to reach the danger point.

Apparently no information is available on the effect of microwave electromagnetic energy on insects. Although it has been fairly well predicted that any lethal effect of microwaves on insects would be due to a pure heating effect, it was decided to conduct tests using microwave energy in order to determine possible lethal effects on insects.

Equipment and Procedure

The data for the three tests conducted is recorded in Tables 4, 5, and 6. Flour beetle adults, eggs and larvae were irradiated in The Radarange, Model 1132A, manufactured by the Raytheon Mfg. Co., Waltham, Mass. A picture of a Radarange is shown in Fig. 14. This equipment operated on a frequency of 2,450,000,000 cycles per second employing the magnetron oscillator. The resonant cavity oven calibrated laboratory model used for the tests was set at a power output (measured in a standard 1-liter water load) of 940 watts. An absorption of the energy equivalent of this output would be considered maximum power transfer.

Microwave Test 1

Tribolium confusum (flour beetle) adults and eggs

Sample No.	Exposure Time Seconds	Temp. Degree F	Dead 1 day after test	Additional dead 2 days after test	Additional dead 3 days after test	Additional dead after 1 week	Total dead	Eggs Hatched
1	3	90	2	0	0	0	2	121
2	3	90	0	0	1	0	1	115
3	3	90	1	1	0	2	4	143
4	6	108	17	0	2	0	19	139
5	6	108	20	0	1	2	23	149
6	6	108	29	2	0	2	33	119
7	9	129	50	-	-	-	50	98
8	9	129	48	1	0	0	49	83
9	9	129	50	-	-	-	50	75
10	12	154	48	0	0	0	48	60
11	12	154	50	-	-	-	50	72
12	12	154	50	-	-	-	50	42
13	15	165*	50	-	-	-	50	10
14	15	165	50	-	-	-	50	15
15	15	165	50	-	-	-	50	29
16	18	171	50	-	-	-	50	9
17	18	171	50	-	-	-	50	11
18	18	171	50	-	-	-	50	5
19	21	178	50	-	-	-	50	3
20	21	178	50	-	-	-	50	3
21	Check	-	1	0	0	0	1	142
22	Check	-	0	0	0	0	0	110
23	Check	-	1	0	0	0	1	137
24	Check	-	0	0	0	1	1	151

* Estimated Temperature

Table 4 Microwave test 1 using the RADARANGE operating on a frequency of 2,450,000,000 cycles per second. Test conducted at the Raytheon Mfg. Co. Research Laboratory, Waltham, Mass. April 28-29, 1953. Fifty (50) adult flour beetles were irradiated in one-half pint glass jars containing 75 grams of whole wheat flour.

Microwave Test 2

Sitophilus granarius (Granary Weevil) adults and eggs

Sample No.	Exposure Time Seconds	Temp. Deg. F	Additional dead 1 day after test	Additional dead 2 days after test	Additional dead 3 days after test	Additional dead 1 week after test	Total dead after one week	Number of eggs hatched
1	3	90	1	0	0	21	22	160
2	3	88	1	0	0	25	26	120
3	3	88	1	0	0	11	12	145
4	6	108	8	1	2	14	25	137
5	6	108	13	0	1	10	24	89
6	6	108	11	2	0	21	34	63
7	9	135	33	1	1	14	49	72
8	9	135	34	1	0	14	49	19
9	9	135	47	0	0	3	50	31
10	12	162	46	0	0	4	50	6
11	12	162	48	0	0	2	50	2
12	12	162	50	-	-	-	50	4
13	15	172	49	0	0	1	50	0
14	15	172	49	0	0	1	50	0
15	15	172	49	0	0	1	50	0
16	18	190	50	-	-	-	50	0
17	18	190	48	0	0	2	50	0
18	18	190	50	-	-	-	50	0
19	21	197	50	-	-	-	50	0
20	21	192	50	-	-	-	50	0
21	check	-	0	0	0	0	0	128
22	check	-	0	0	0	2	2	173
23	check	-	0	0	1	0	1	161
24	check	-	1	1	0	0	2	146

Table 5-Microwave test 2 using the RADARANGE operating on a frequency of 2,450,000,000 cycles per second. Test conducted at the Raytheon Mfg. Co. Research Laboratory, Waltham, Mass. April 28-29, 1953. Fifty (50) adult granary weevils were irradiated in one-half pint jars, containing 75 grams of Cornell variety wheat.

Microwave Test 3

Tribolium confusum (flour beetle) larvae

Sample Number	Exposure Time Seconds	Temp. Degree F	Total dead larvae 35 days after test	Alive adults appeared 35 days after test
1	3	90	0	57
2	3	90	0	65
3	3	90	0	63
4	6	120	2	40
5	6	120	0	72
6	6	120	5	50
7	9	129	52	10
8	9	129	40	3
9	9	129	45	7
10	12	138	37	2
11	12	138	42	4
12	12	138	55	1
13	15	180	64	0
14	15	180	38	0
15	15	180	47	1
16	18	187	57	0
17	18	187	72	0
18	18	187	45	0
19	21	182	35	0
20	21	182	56	0
21	Check	–	0	60
22	Check	–	1	63
23	Check	–	0	75
24	Check	–	0	39

Table 6 Microwave test 2 using the RADARANGE operating on a frequency of 2,450,000,000 cycles per second. Test conducted at the Raytheon Mfg. Co. Research Laboratory, Waltham, Mass., April 28–29, 1953. Flour beetle larvae were irradiated in one-half pint jars containing 75 grams of whole wheat flour.

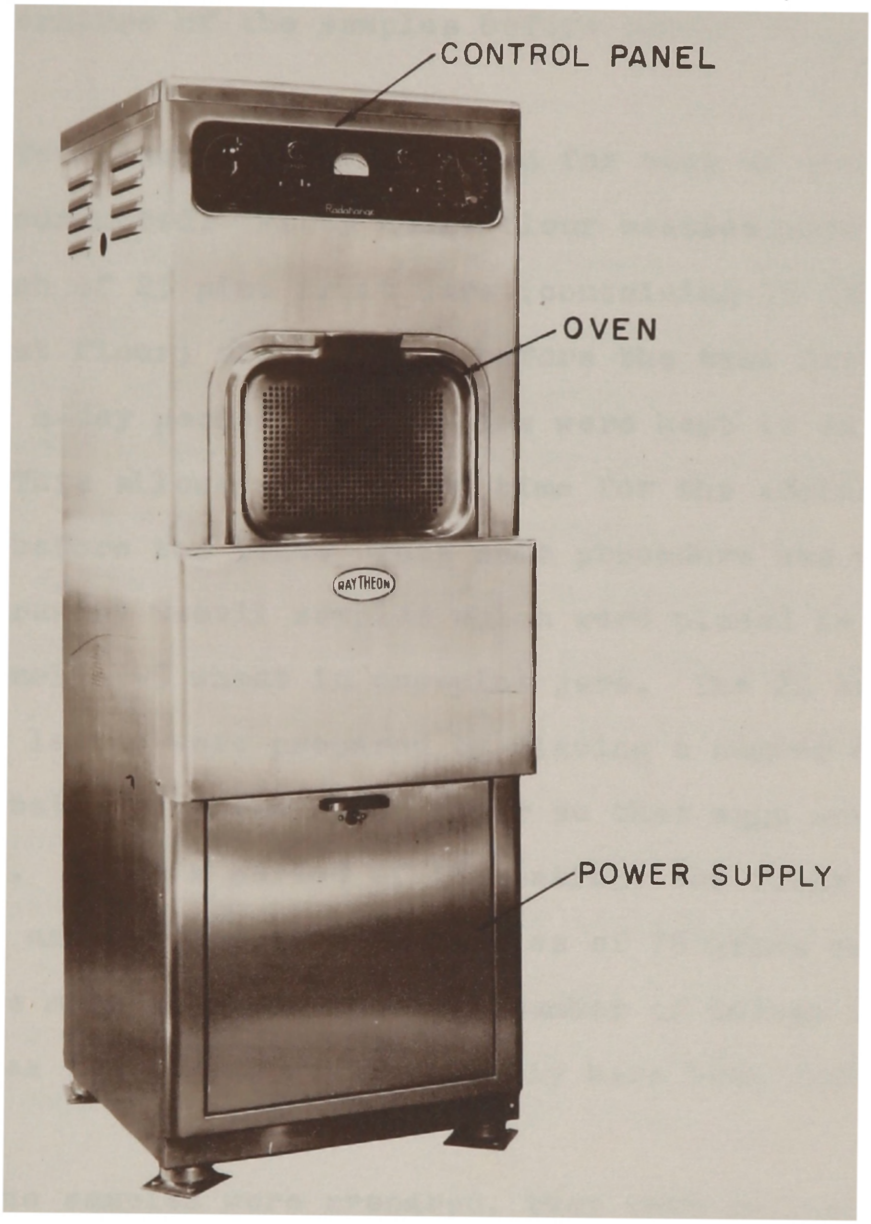


Fig 14 The RADARANGE showing control panel and oven——— operating on an approved frequency of 2,450,000,000 cycles per sec. or a wave-length of 12.25 centimeters.

Temperatures were taken on the samples, indicated in the tables, by a mercury thermometer, after exposure. Initial temperature of the samples before treatment was about 73° F.

Twenty-four samples were prepared for each of the three tests conducted. Fifty adult flour beetles were placed in each of 25 pint fruit jars (containing 75 grams of whole wheat flour) about 4 days before the test date. During this 4-day period, the samples were kept in an incubator. This allowed sufficient time for the adults to oviposit before the test. This same procedure was used for the 24 granary weevil samples which were placed in 75 grams of Cornell 595 wheat in one-pint jars. The 24 samples of *Tribolium* larvae were prepared by placing a number of adults in a batch of whole wheat flour so that eggs would be deposited. After a period of incubation, the flour was mixed gently and divided into 24 samples of 75 grams each. No effort was made to place an equal number of larvae in each sample as the larvae would possibly have been injured if handled.

After the samples were prepared, they were shipped via air express to the Raytheon Research Laboratory, Waltham, Mass. The air express company was requested to see that the temperature of the samples did not fall below 60° F. The samples were irradiated soon after they arrived at the Raytheon Laboratory. The samples arrived back in Lansing four days from the date of shipment from Lansing and were placed in an incubator. Then observations were made for lethal effects.

Results and Discussion

The data in Tables 4, 5, and 6 indicate that a maximum temperature of 165° F with an exposure time of 21 seconds in the Radarange was lethal to 100 percent of adult flour beetles one week after treatment. Under these conditions 23 percent of the eggs hatched. Two percent of eggs hatched when exposed for 21 seconds at a temperature of 178° F. A temperature of 187° F at an exposure time of 18 seconds was lethal to 100 percent of the flour beetle larvae.

An exposure time of 15 seconds at a temperature of 172° F was lethal to 100 percent of the adult granary weevils one week after treatment. No flour beetle eggs hatched with this treatment. Only 2.5 percent of the eggs hatched when exposed at a temperature of 162° F for 12 seconds.

According to Dr. David Copson of the Raytheon Research Laboratory, the heat occurring in irradiated flour and grain is of high enough order to put these materials in the category of good absorbers of microwave energy. As such, the validity of a selective action between the material and insects at various stages is questionable. The statement seems to have merit because in each test temperatures approximating the lethal temperature found by other investigators was necessary before a 100 percent kill was obtained.

Cost to Operate Magnetron

Calculations in order to show the cost to raise the temperature of 1000 pounds of wheat per hour or flour from 70 to 140° F are presented below (9):

70° (0.4 Sp. Heat)(0.00029 KWH/BTU)1000 lbs/hr = 8.18 KW of radio frequency (RF) output required.

For an industrial application we may assume that magnetron oscillators for microwave generation would be available at a cost which would amount to $125 per 1000 KWH of RF output. Therefore the above flow rate for one hour would cost:

$$\frac{8.18\ (\$125)}{1000} = \$\ 1.02 \text{ per hour for RF}$$

The electric power may be used for conversion to RF on a basis of about 60 percent efficiency. Thus,

$$\frac{8.18}{0.6} = 13.62 \text{ KW}$$

Estimating the cost per KWH at 2.0 ¢, this would mean 27.2 ¢ per hour and added to the cost for magnetron generators, it would be $1.29 per hour total. The further requirement would be for the machine or basic equipment and the cost of comparable output equipment from other suppliers to be a reasonable estimate. A rough estimate of $5000 for the equipment to do this calculated load may be made. The cost would then be on the order of 13¢ per 100 pounds of grain or flour irradiated.

Literature Cited

(1) Clark, J. W., "Effects of Intense Microwave Radiation on Living Organisms", Proceedings of I.R.E., 1950, p. 1028.

(2) Herrick, J. F., "Application of Microwaves in Physical Medicine", Paper read at the National Meeting of I.R.E., New York, N.Y., March 1952.

(3) Hines, H. M. and Randall, J. E., "Possible Industrial Hazards in the Use of Microwave Radiation", Electrical Engineering, October 1952.

(4) Richardson, A. W., et al., "The Relationship between Deep Tissue Temperature and Blood Flow during Electromagnetic Irradiation", Archives of Physical Medicine, January 1950, pp. 19-25.

(5) Salisbury, W. W., et al., "Exposure to Microwaves", Electronics, May 1949.

(6) Correspondence from Dr. H. P. Schwan, Physicist at Univ. of Pennsylvania, Philadelphia, April 21, 1953.

(7) Schwan, H. P. and Li, K., "Capacity and Conductivity of Body Tissues at Ultra-high Frequencies", Mimeograph Report, Univ. of Pennsylvania, 1953, 13 pp.

(8) Schaefer, H. and Schwan, H., "Zur Frage der Selektiven Erhitzung Kleiner Teilchen im Ultrakurzwellen-Kondensatorfeld Annalen der Physik", 5 Fole. Bd. 43 Heft 1, 2. 1943.

(9) Correspondence from Dr. David Copson, Raytheon Mfg. Co. Research Laboratory, Waltham, Mass., June 3, 1953.

PART V

SOME EFFECTS OF INFRARED ENERGY ON CERTAIN INSECTS

Introduction and Review of Literature

It has been pointed out in another section of this thesis that infrared energy produces molecular vibration and excitation which cause a pure heating effect in tissue. It was also mentioned that living cells will die, due to coagulation of protoplasm, if exposed to excessively high temperatures. Also, the penetration of infrared into tissue, and the method of generation of infrared energy were discussed, see Parts I and II.

Infrared energy has been used in industry and agriculture for many years to heat thin films or layers of material as in baking paints and drying surfaces and for brooding chickens, etc. Infrared energy is used widely in the medical profession for heating certain areas of the body. Hall (1), Koller (2), and Canada (3) are among those investigators who have written treatises on infrared energy. According to Koller (2) "infrared" refers to electromagnetic radiation of longer wavelength than 7800 Angstroms.

There are a number of sources of infrared radiation. The simplest are incandescent solids. The most convenient form is the infrared lamp. A number of investigators have used the infrared lamp for dying seed and heating various objects. Nicholos (4) reported on preliminary studies using infrared lamps to dry thin layers of grain. Garber and Tiller (5) presented a paper on the "skin heating effect" of infrared on materials of low conductivity. They pointed out that infrared could be used to raise the surface temperature of material such as wood and that relatively high surface temperatures could be obtained with infrared energy. Any increase in temperature below the surface would be by conduction from the surface to the depths of the material.

A number of investigators have conducted experiments on the effects of infrared energy on various insects apparently without reviewing the physics involved in the process. Duane and Tyler (6) presented a hypothesis that certain moths communicate with each other on a frequency in the infrared spectrum, but they did not collect enough data to prove their hypothesis. MacLeod (7) studied the effects of infrared on the cockroach. Headlee (8) also studied the effects of infrared on the cockroach and the transmission of infrared through various layers of wheat products. Headlee's infrared source penetrated 0.03 inch of various wheat products. Other investigators suggested that a battery of infrared lamps be used for treating rice to control insects. Cotton (9) states that a temperature of 140° F for 10 minutes is fatal to all grain insects and that a temperature of about 180° F is considered the safe temperature for drying wheat without injury to milling and baking qualities.

Frost *et al.* (10) concluded that death of *Tribolium confusum* and other insects exposed to infrared radiation was due to increased internal body temperature. In all tests conducted the internal temperature at the end of the test approached the average fatal temperature which according to Uvarov (11) is 122° F. Hall (1) reported that infrared energy has been used successfully in the rapid extermination of various insects. Fleas on dogs may be killed with exposure to infrared without any apparent discomfort to the animal. Hall also mentioned that radiant heat has been found useful in delousing clothes. Kleis (12) and Cheklich (13) made studies on treating loose smut in wheat with infrared energy.

Realizing that more information would be desirable before infrared energy could be recommended for the extermination of insects in grain and flour, a series of tests were conducted in order to study the effects of infrared on the flour beetle and granary weevil.

Equipment and Procedure

A series of six tests using the type R-40 250-watt infrared lamp as a source of energy was conducted. The major equipment used in the tests is shown in Figs. 15, 16, and 17. The lamp height for all tests was measured from the bottom of the petri dish to the bottom of the lamp bulb.

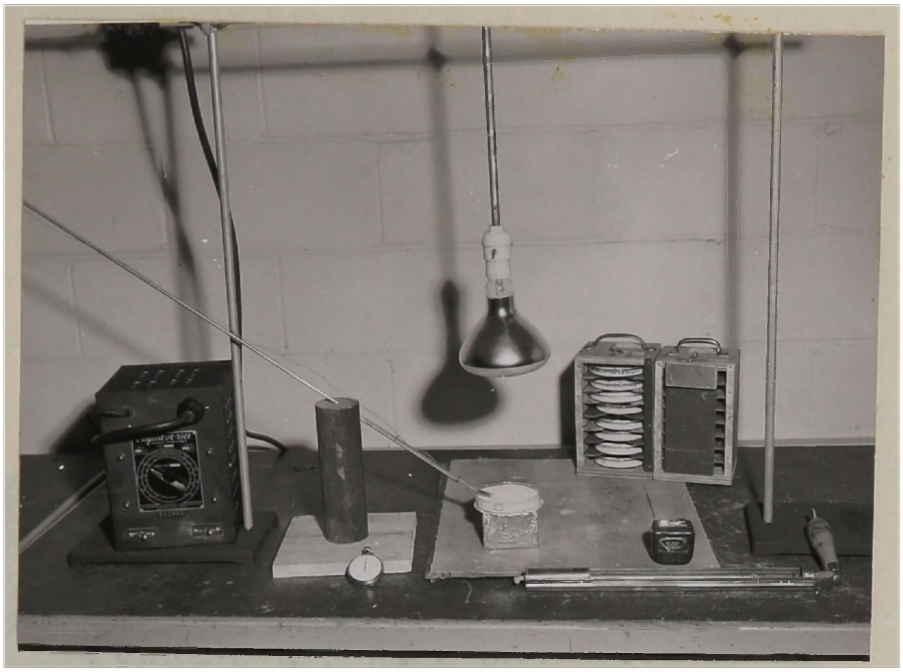


Fig. 15. Showing voltage regulator, radiation meter, psychrometer, stop watch, thermocouple in sample of flour, and infrared lamp. The temperature was recorded with potentiometer shown below.

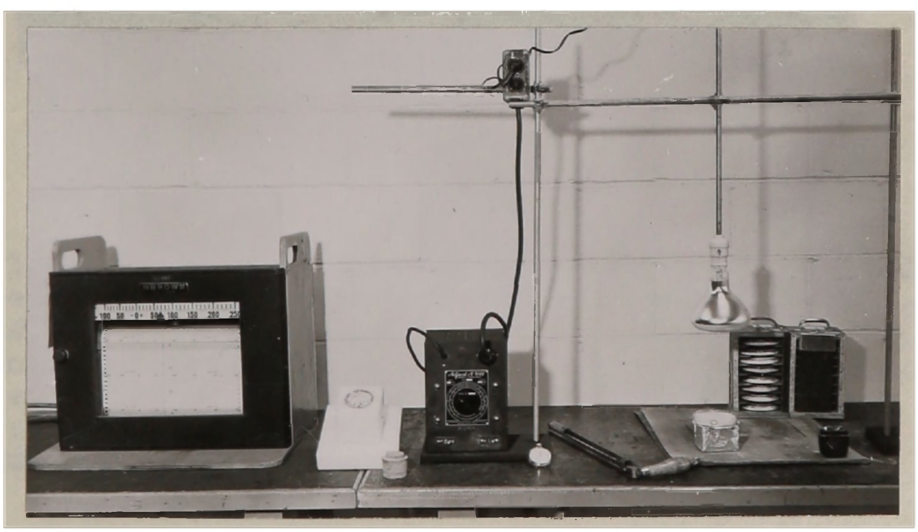


Fig. 16. Same as above except that sample of wheat was treated under the lamp and immediately emptied into the insulated container to the left of the recorder.

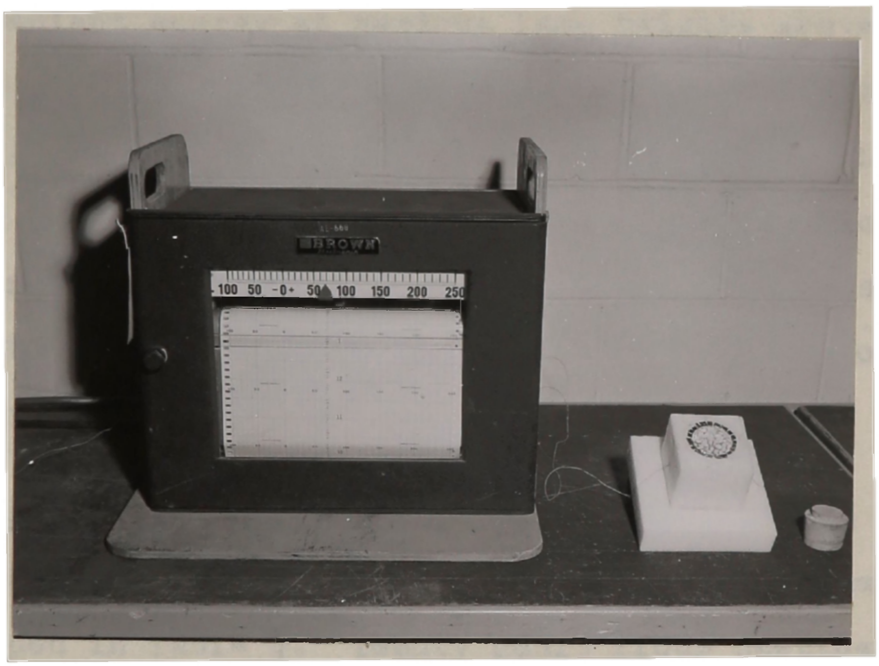


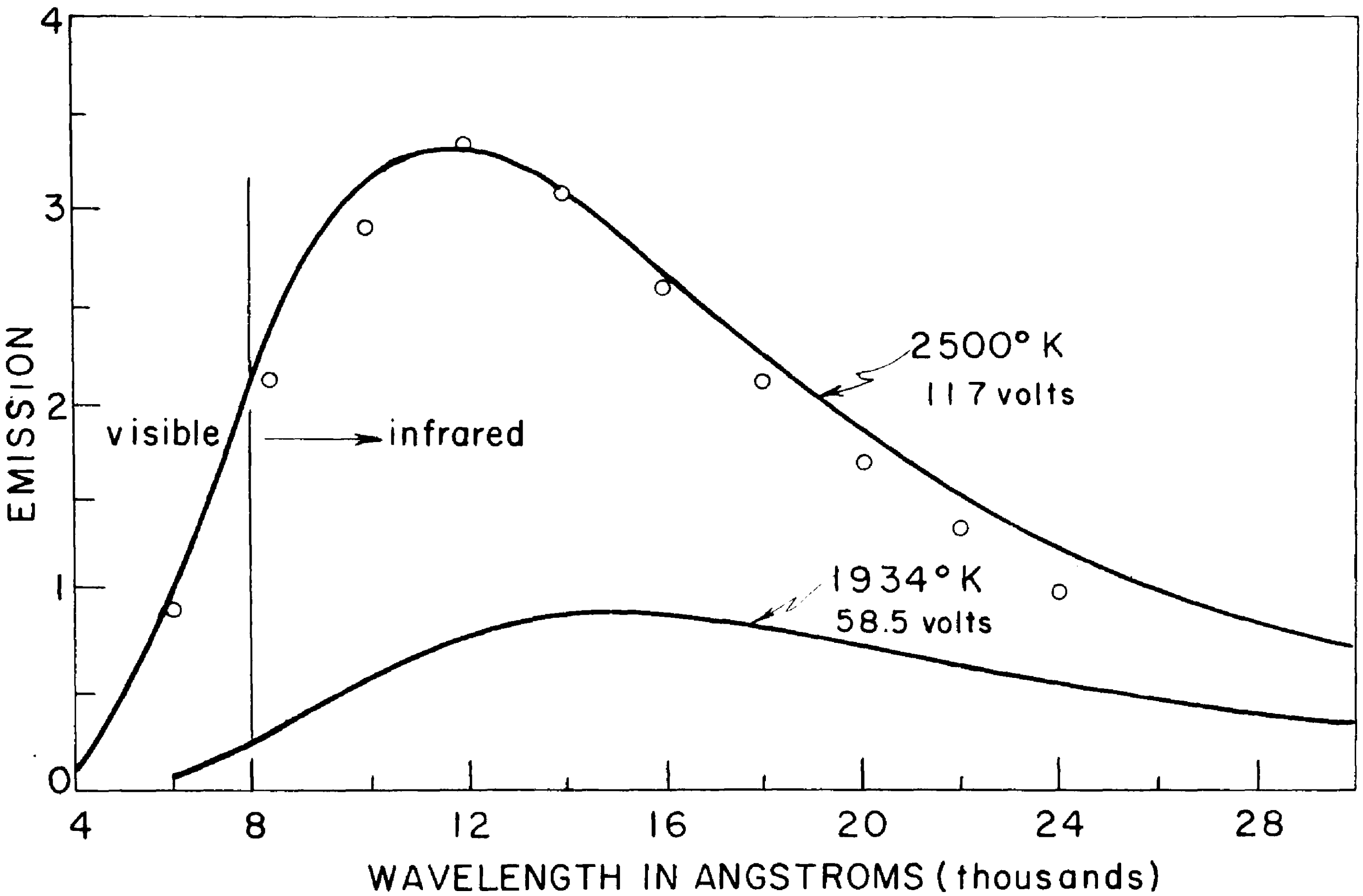
Fig. 17. Close-up of insulated compartment in which samples were placed soon after exposure. The compartment is made of Styrofoam, manufactured by Dow Chemical Company, and is lined with aluminum foil. A thermocouple, located in the compartment, indicated the temperature of the mass, and this temperature was recorded with the Brown Potentiometer.

Unless otherwise indicated the lamp voltage was maintained at 117 volts. The radiation spectrum for the filament of the type R-40 lamp as compared to a black body is shown in Fig. 18. The relative energy output and the percent transmittance for infrared in two thicknesses of water for the type R-40 lamp radiation (Fig. 19A) is shown in Fig. 19B. The radiant energy at various lamp heights above the measuring instrument is shown in Fig. 30. In all the tables that follow, the percent adults killed or eggs hatched for check samples for each test were averaged and used as a 100 percent check. Since the procedure for each test differed slightly, a description of the equipment and procedure for each test will be presented.

Infrared Test 1

Test 1 was of a preliminary nature. The data is recorded in Table 7. Twenty adult flour beetles placed in each of 20 9-cm plain petri dishes were exposed to various levels of infrared energy as shown in Table 7. The radiant energy was measured with a type DW-60 radiation meter and was changed by varying the voltage to the lamp with a variable transformer, Fig. 15. The data collected for the second part of test 1 is listed in the lower part of Table 7.

Results: The results of test 1 are shown in Table 7. Only one insect was dead 48 hours after the test. Thirteen out of a total of 25 adults were dead 48 hours after exposure with a lamp height of 10 inches.



——— ACTUAL RADIATION FROM FILAMENT AT 2500°K

○ CALCULATED BLACK BODY RADIATION AT 2500°K

Stefan-Boltzmann equation for black body radiation

$$E = 5.673 \times 10^{-12} \cdot T^4 \text{ watts/sq cm}$$

Fig 18 Radiation from Type R-40 infrared lamp as compared with radiation from a black body.

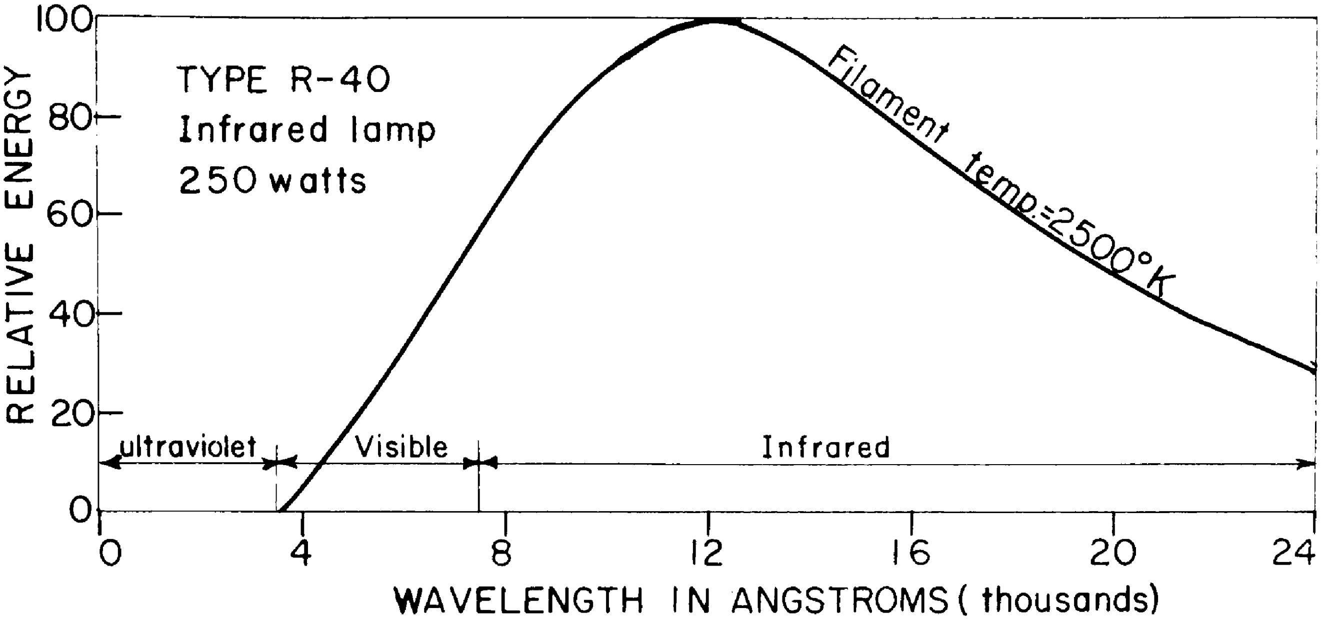


Fig19A-Radiation spectrum for type R-40 250 watt Infrared lamp_ from GE Lamp Bulletin 1946 p 36.

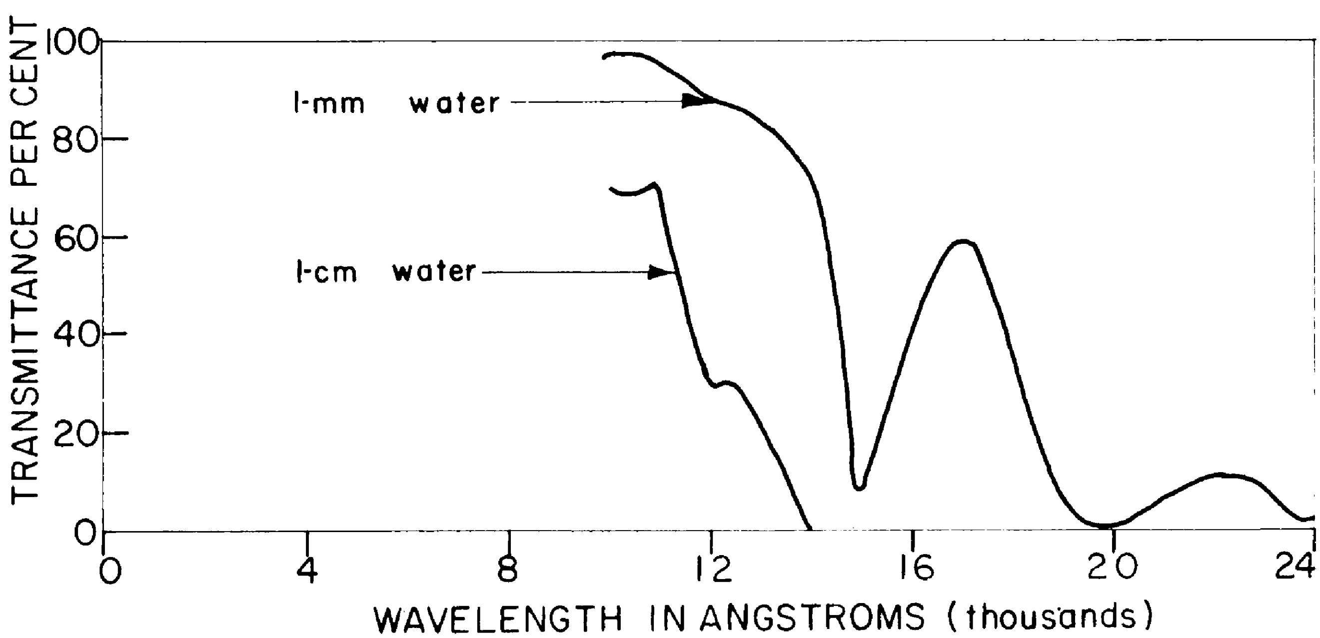


Fig19B-Relative absorption of Infrared energy for two thicknesses of water - from International Critical Tables Vol. V p 268.

INFRARED TEST 1

Tribolium confusum (Flour Beetle)

Sample Number	Time In Seconds	Volts	Gram Calories Per Square Centimeter Per Minute	Number Dead 48 Hours After
1	5	48	.5	0
2	10	48	.5	0
3	15	48	.5	0
4	20	48	.5	0
5	25	48	.5	0
6	5	67	1.0	1
7	10	67	1.0	0
8	15	67	1.0	0
9	20	67	1.0	0
10	25	67	1.0	0
11	5	86	1.5	0
12	10	86	1.5	0
13	15	86	1.5	0
14	20	86	1.5	0
15	25	86	1.5	0
16	5	101	2.0	0
17	10	101	2.0	0
18	15	101	2.0	0
19	20	101	2.0	0
20	25	101	2.0	0

Sample Number	Time In Minutes	Volts	Lamp Height	Dead After 48 Hours
1	1	117	10	0
2	2	117	10	7
3	3	117	10	13
4	.5	117	8	0
5	1	117	8	8

TABLE 7 Infrared Test with 25 Tribolium adults in 9 cm petri dishes.

Infrared Test 2

The data tabulated for test 2 is shown in Table 8. Twenty adult flour beetles were placed in each of 26 petri dishes. One petri dish containing 20 adult insects was used as a check. Refer to Table 8 for time of exposure, lamp height, and energy level. The apparatus for this test is shown in Fig. 15. The petri dish containing the insects was set on an insulated block. The energy radiating on the petri dish was measured with the DW-60 radiation meter. This information is plotted in Fig. 30. The bottom of the petri dish was in a horizontal plane with the element of the DW-60 radiation meter. The lamp height was measured from the bottom of the petri dish to the bottom of the 250-watt type R-40 infrared bulb.

Results: The data in Table 8 and Fig. 20A and 20B indicate that the minimum energy necessary to kill 100 percent of adult flour beetles 48 hours after the test was 3.25 gram calories per sq cm per minute with a lamp height of 6 inches and with an exposure time of 60 seconds. An energy level of 2.60 gram calories per sq cm per minute, with a lamp height of 8 inches and an exposure time of 75 seconds was lethal to 100 percent of the adults one week after exposure.

INFRARED TEST 2

Tribolium confusum (Flour Beetle) Adults

Sample Number	Time In Seconds	Lamp Height In Inches	Gram Calories Per Square Centimeter Per Minute	Number Dead 48 Hours After	Additional Dead After 72 Hours	Additional Dead After 1 Week	Total	Per Cent Dead
1	15	12	1.83	0	0	1	1	5
2	30	12	1.83	0	0	0	0	0
3	45	12	1.83	0	1	0	1	5
4	60	12	1.83	0	1	0	1	5
5	75	12	1.83	0	2	0	2	10
6	15	10	2.20	0	0	0	0	0
7	30	10	2.20	0	0	0	0	0
8	45	10	2.20	0	0	0	0	0
9	60	10	2.20	4	6	0	10	50
10	75	10	2.20	16	1	1	18	90
11	15	8	2.60	0	4	0	4	20
12	30	8	2.60	2	5	0	7	35
13	45	8	2.60	4	6	3	13	65
14	60	8	2.60	12	3	0	15	75
15	75	8	2.60	18	1	1	20	100
16	15	6	3.25	12	7	0	19	95
17	30	6	3.25	10	3	1	14	70
18	45	6	3.25	19	0	0	19	95
19	60	6	3.25	20	0	0	20	100
20	75	6	3.25	20	0	0	20	100
21	15	4	4.00	9	4	0	13	65
22	30	4	4.00	17	3	0	20	100
23	45	4	4.00	20	0	0	20	100
24	60	4	4.00	20	0	0	20	100
25	75	4	4.00	20	0	0	20	100
26	Check	—	—	0	0	0	0	—

TABLE 8 Infrared Test 2 with 20 adult Tribolium confusum placed in 9 cm petri dishes with no flour.

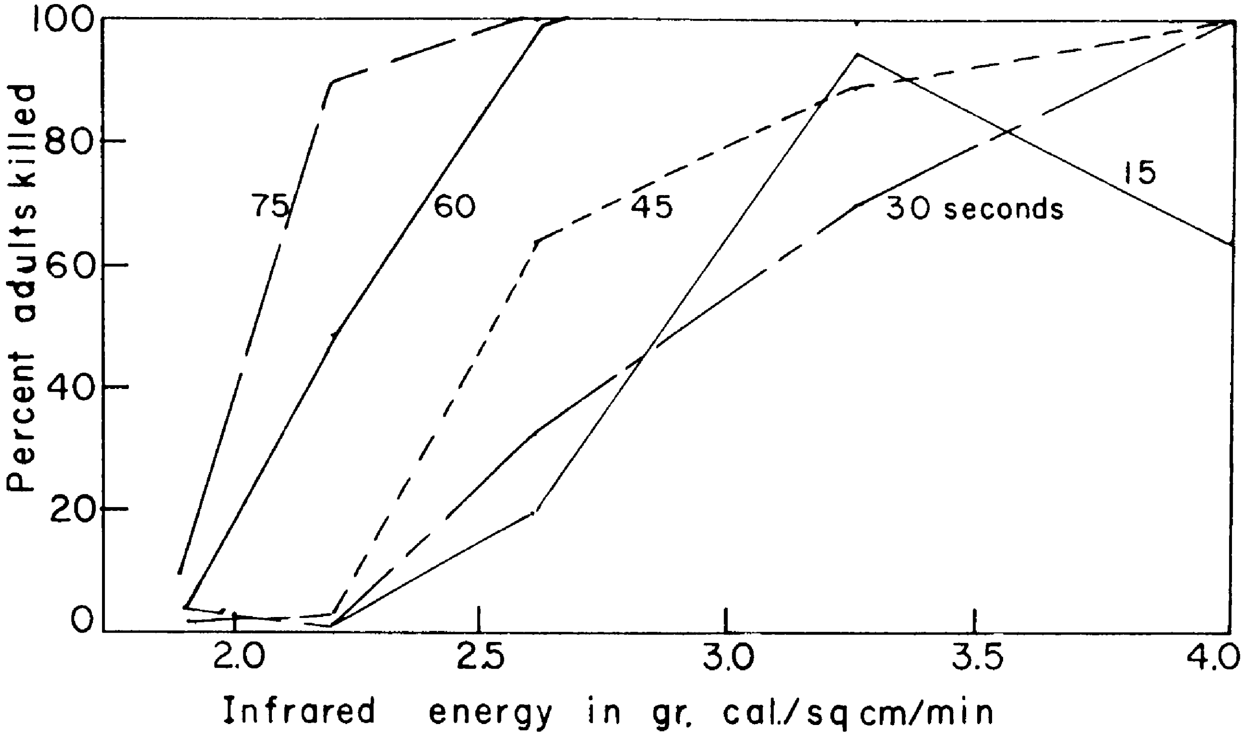


FIG20 A

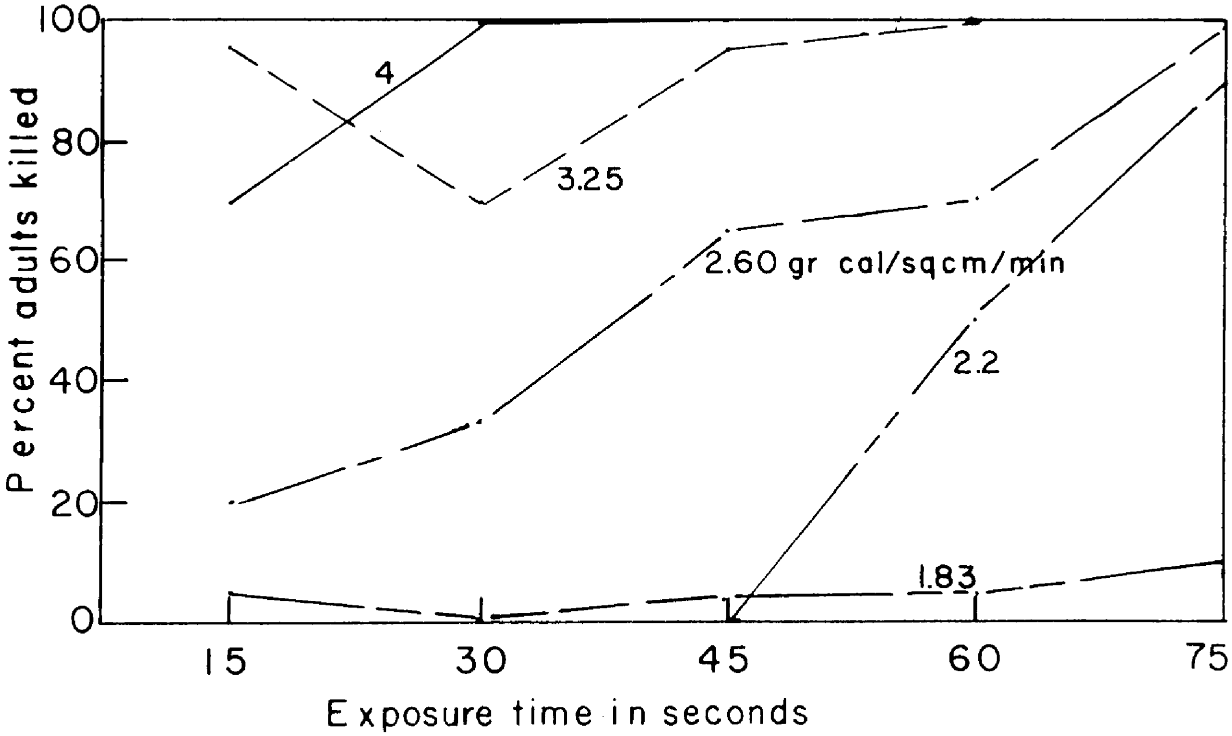


FIG 20B

FIG20 A-B Percent Tribolium adults killed for infrared test 2 with 20 adults in plain petri dishes.

Infrared Test 3

Infrared test 3 was designed to determine the effects of infrared energy on flour beetle eggs. The results and data for this test are shown in Table 9 and Figs. 21A and 21B.

Fifty adult flour beetles were placed in each of 30 petri dishes containing 20 grams of 13 percent moisture (wb) whole wheat flour. The flour was sifted through a 24-mesh wire screen before use. The adults remained in the samples for 76 hours for ovipositing. During this 76-hour period all 30 samples were kept in an incubator at 80° F and 75 percent relative humidity. After the incubation period, the adults were removed from the flour and the eggs and flour in each of the 25 samples were treated with various amounts of infrared energy as shown in Table 9. Just before each test the flour in each dish was leveled evenly so that the depth of flour in each petri dish was about $\frac{1}{4}$ inch.

At the end of each exposure time, the lamp was turned off and the thermocouple attached to the inclined rod, Fig. 15, was inserted into the flour so that the thermocouple junction touched the bottom of the petri dish. The readings of Leeds and Northrup potentiometer (shown in Fig. 26) from the thermocouple were recorded in millivolts. After the test the samples were kept in the incubator for a period of 36 days. The number of eggs hatched after three successive counts is shown in Table 9.

INFRARED TEST 3

Tribolium confusum (Flour Beetle) Eggs

Sample Number	Time In Seconds	Lamp Height In Inches	Milli-Volts	Degrees F.	Hatched Nov. 10	Additional Hatched Nov. 11	Additional Hatched Nov. 12	Total	Per Cent of Check
1	Check	—	—	—	100	87	1	188	100
2	15	12	1.23	88	75	48	0	123	73
3	30	12	1.24	88	110	61	0	171	101
4	45	12	1.26	89	91	61	0	152	90
5	60	12	1.33	92	74	110	6	190	112
6	75	12	1.35	93	115	52	0	167	99
7	Check	—	—	—	101	60	0	161	100
8	15	10	1.23	88	79	54	0	133	79
9	30	10	1.33	92	93	31	4	128	76
10	45	10	1.39	94	60	71	10	141	84
11	60	10	1.45	97	85	39	1	125	74
12	75	10	1.58	103	147	75	0	222	130
13	Check	—	—	—	150	64	0	214	100
14	15	8	1.30	90	73	33	0	108	64
15	30	8	1.32	92	90	145	10	245	140
16	45	8	1.38	94	100	146	0	246	140
17	60	8	1.67	106	75	86	2	163	97
18	75	8	1.72	109	83	27	0	210	124
19	Check	—	—	—	71	52	0	123	100
20	15	6	1.32	92	65	67	1	133	79
21	30	6	1.48	98	103	89	1	193	114
22	45	6	1.57	102	98	52	1	151	89
23	60	6	1.60	104	105	72	0	177	105
24	75	6	1.92	117	90	31	0	127	75
25	Check	—	—	—	99	69	0	168	100
26	15	4	1.33	92	110	65	0	175	74
27	30	4	1.57	102	118	60	0	178	105
28	45	4	1.56	102	87	75	0	164	92
29	60	4	1.74	110	97	27	0	124	74
30	75	4	1.87	115	92	29	0	121	72

TABLE 9 Fifty adult Tribolium were left in 20 grams of whole wheat flour for 76 hours. Then the adults were removed and flour was treated in petri dishes under 250 watt infrared lamp, voltage 117 v. Depth of flour in petri dishes about ¼ inch. Treated October 4, 1952.

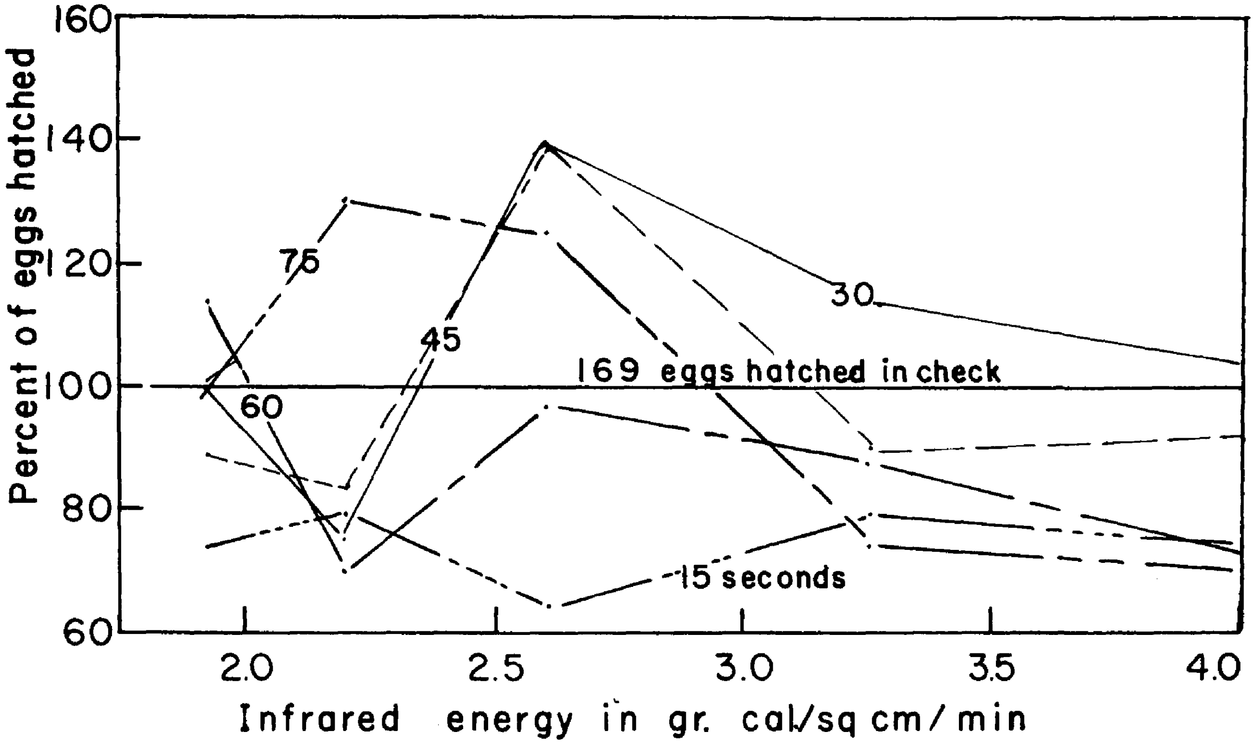
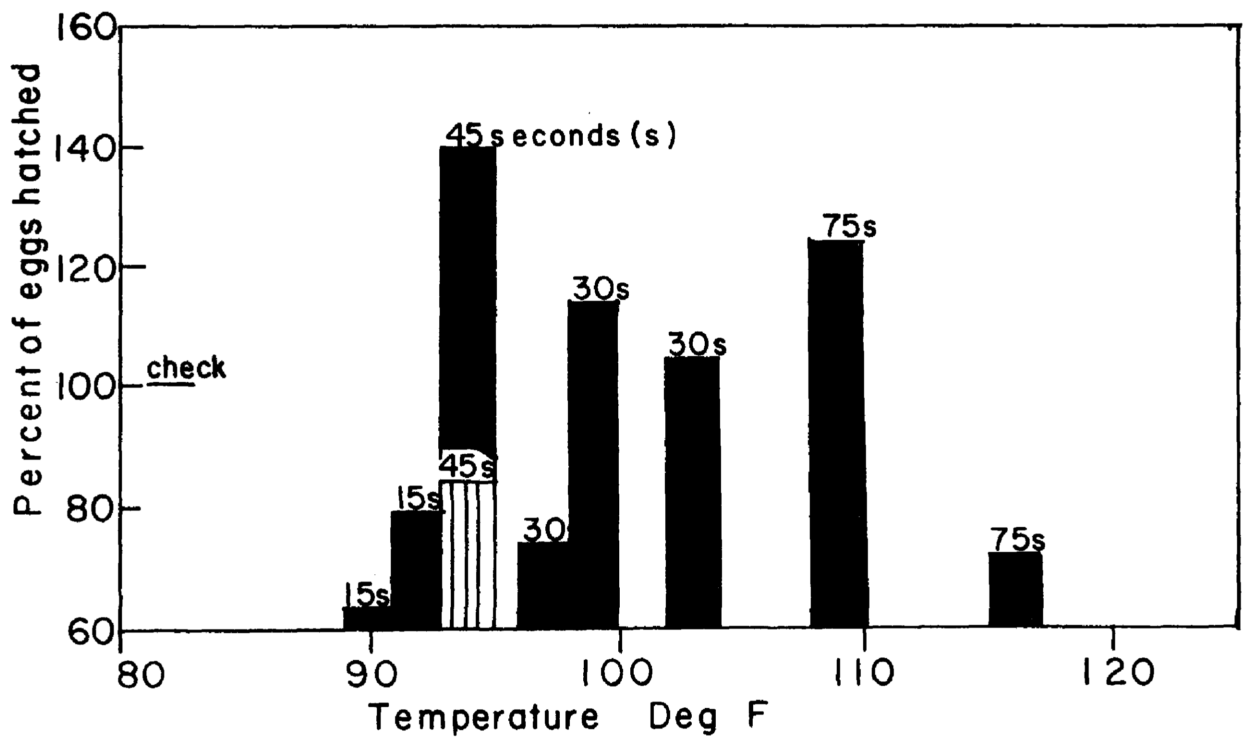


FIG21 A Percent Tribolium eggs hatched for infrared test 3.



FIG·21 B Percent Tribolium eggs hatched bar chart for infrared test 3.

<u>Results:</u> The charts, Figs. 21A and 21B, show that no treatment used sterilized 100 percent of the eggs. An average of 169 eggs hatched in each of the 5 check samples. The data in Fig. 21A indicates that some exposures actually increased the percentage of eggs hatched.

Infrared Test 4

Infrared test 4 was designed to determine the effects of various amounts of infrared energy on adult flour beetles covered with flour. The results and data for this test are shown in Table 10 and Figs. 22A and 22B.

Twenty adult flour beetles were placed in each of 30 petri dishes (9 cm diameter) containing 20 grams of 13 percent moisture whole wheat flour. The flour was sifted through a 24-mesh screen before use. Immediately before each sample was exposed to infrared energy all insects were covered with flour. The total depth of flour was about $\frac{1}{4}$ inch. The time of exposure, maximum temperature, and other observations made are tabulated in Table 10. Temperatures were recorded by the Brown potentiometer, Fig. 15. The thermocouple on the incline rod, Fig. 15, was inserted in the flour immediately after each exposure so that the thermocouple element touched the bottom of the petri dish. After the samples were treated, the treated samples plus the untreated samples were placed in an incubator and observed at intervals as shown in Table 10.

INFRARED TEST 4

Tribolium confusum (Flour Beetle) Adults Only

Sample Number	Time In Seconds	Lamp Height In Inches	Degrees F.	Number Dead 24 Hours After	2 Days After	4 Days After	1 Week After	Total	Per Cent Kill	Insects Came to Top During Test
1	Check	—	—	0	0	0	0	0	0	—
2	45	10	95	1	0	0	0	1	5	7
3	60	10	105	0	0	0	0	0	0	2
4	75	10	108	1	0	0	0	1	5	11
5	90	10	112	2	0	0	0	2	10	3
6	105	10	113	1	0	0	0	1	5	1
7	—	—	—	0	0	0	0	0	0	—
8	45	8	115	2	0	0	0	2	10	2
9	60	8	121	1	0	0	0	1	5	6
10	75	8	122	6	1	0	0	7	35	1
11	90	8	131	7	2	0	0	9	45	0
12	105	8	127	4	0	0	0	4	20	1
13	—	—	—	0	0	0	0	0	0	—
14	45	6	132	4	0	0	0	4	20	5
15	60	6	137	3	0	1	0	4	20	3
16	75	6	141	5	3	0	0	8	40	6
17	90	6	146	3	0	0	0	3	35	4
18	105	6	149	5	1	0	0	6	30	7
19	—	—	—	0	0	0	0	0	0	—
20	45	4	127	5	0	1	0	6	30	5
21	60	4	138	1	0	0	0	1	5	1
22	75	4	156	4	0	0	0	4	20	2
23	90	4	159	3	0	0	0	3	15	0
24	105	4	175	4	0	1	0	5	25	0
25	—	—	—	0	0	0	1	1	5	—
26	45	2	164	7	3	0	0	10	50	0
27	60	2	169	11	1	0	0	12	60	2
28	75	2	174	8	2	0	0	10	50	0
29	90	2	187	12	3	0	0	15	75	1
30	105	2	213	17	3	0	0	20	100	0

TABLE 10 Infrared Test 4. Twenty adult tribolium flour beetles were placed in 20 grams of whole wheat flour. The flour was sifted through 20 mesh screen. Depth of flour in dish about ¼ inch. When test was started, all insects were covered; however, during test some insects came to top of flour.

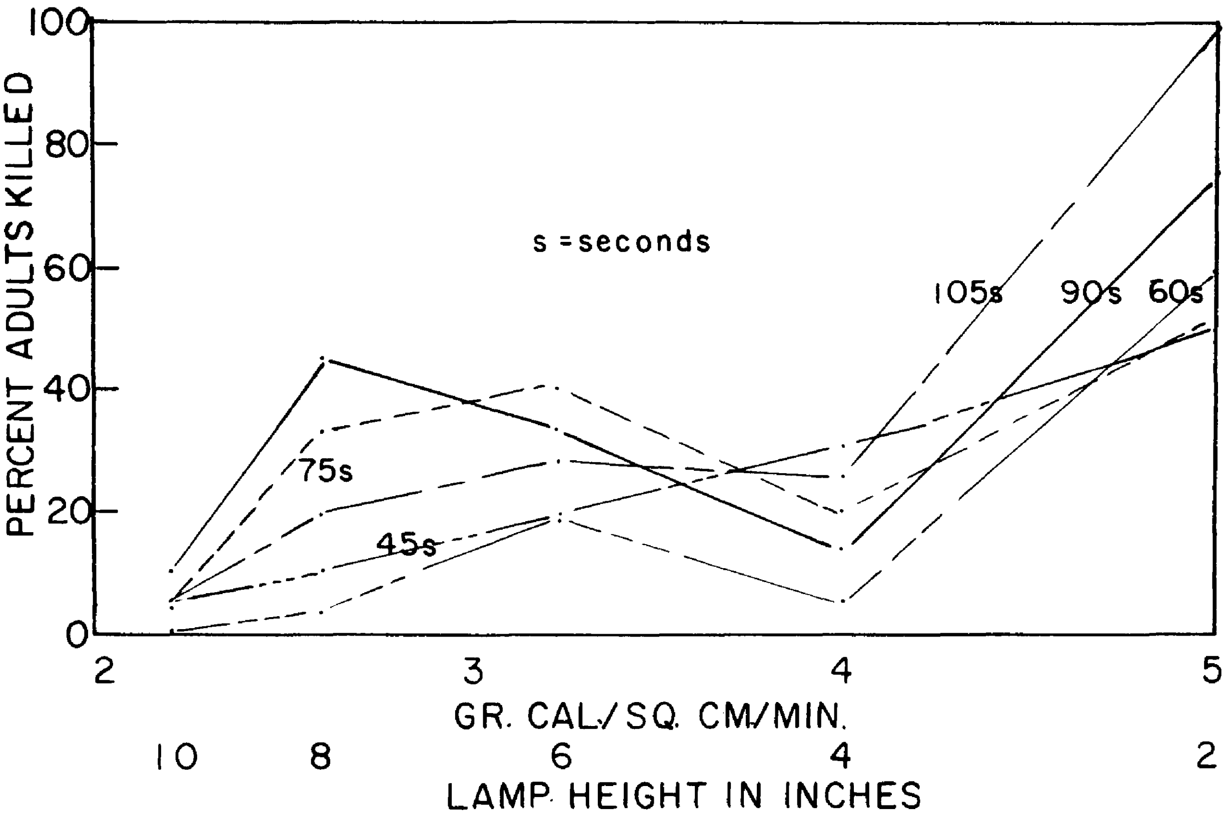


Fig 22 A Percent adult Tribolium killed for infrared test 4

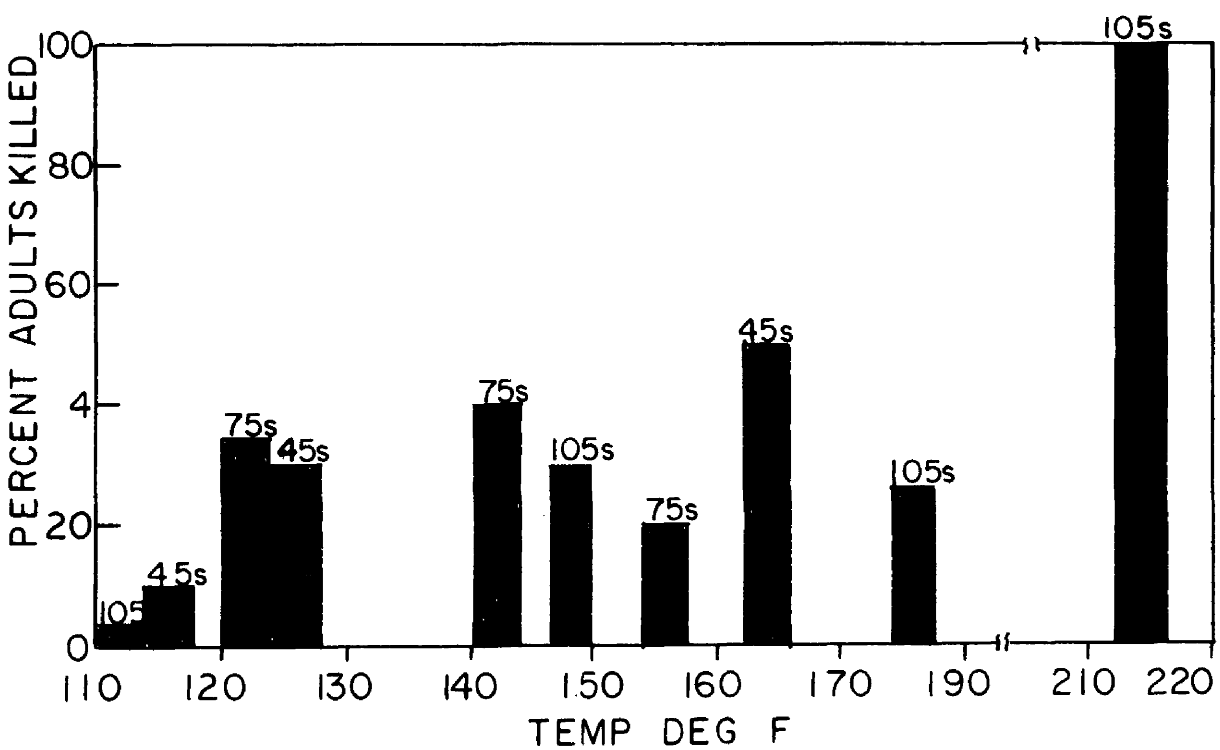


Fig 22 B Partial bar chart for percent Tribolium adults killed for infrared test 4.

Results: The results of infrared test 4 one week after treatment is presented in graphical form in Figs. 22A and 22B. One hundred percent kill was obtained one week after treatment, using an exposure time of 105 seconds and a maximum temperature of 213° F. The number of insects that came to the top of the flour during test 4 is shown in the last column of Table 10. There does not appear to be any relationship between the number of insects killed and the number that came to the top of the sample during the treatment. The insects on top of the flour would receive more energy than the insects buried in the flour.

Infrared Test 5

Infrared test 5 was designed to test further the effects of infrared on the flour beetle adults and eggs, with an increase in time of exposure. The results and data for this test are shown in Table 11 and Figs. 23A, 23B, 24A, and 24B.

Forty adult flour beetles were placed in each of 30 petri dishes containing 10 grams of 13 percent moisture whole wheat flour. The adults remained in the samples for 4 days in order to allow sufficient time for the adults to oviposit. During this 4-day period all samples were incubated in a constant temperature, constant relative humidity oven (80° F, 75 percent RH). At the end of the 4-day incubation period, 25 samples containing adults and eggs were treated with various amounts of infrared energy as

INFRARED TEST 5

Tribolium confusum (Flour Beetle) Adults and Eggs

Sample Number	Lamp Height In Inches	Time In Minutes	Degrees F.	Dead 1 Hour After	24 Hours After	1 Week After	Total	Per Cent Dead	Eggs Hatched 43 Days After	Per Cent Hatched
1	Check	--	--	0	0	0	0	0	150	—
2	10	.5	85	0	0	0	0	0	135	93
3	10	1.0	88	1	1	0	2	5	123	85
4	10	1.5	92	3	3	0	6	15	132	91
5	10	2.0	104	2	0	0	2	5	109	75
6	10	2.5	107	10	1	0	11	27	57	39
7	Check	--	--	0	0	0	0	0	140	—
8	8	.5	89	1	0	0	1	2.5	99	68
9	8	1.0	101	0	1	0	1	2.5	123	85
10	8	1.5	114	3	0	0	3	7.5	79	54
11	8	2.0	120	5	1	0	6	15	47	32
12	8	2.5	127	40	0	0	40	100	11	8
13	Check	--	--	0	0	0	0	0	134	—
14	6	.5	96	0	0	0	0	0	118	81
15	6	1.0	110	9	0	0	9	23	34	24
16	6	1.5	128	25	0	0	25	62	25	17
17	6	2.0	134	30	1	0	31	77	7	5
18	6	2.5	138	40	0	0	40	100	0	0
19	Check	--	--	0	0	0	0	0	157	—
20	4	.5	94	11	0	0	11	27	45	31
21	4	1.0	120	35	2	0	37	92	35	24
22	4	1.5	144	40	0	0	40	100	0	0
23	4	2.0	151	40	0	0	40	100	0	0
24	4	2.5	172	40	0	0	40	100	0	0
25	Check	--	--	0	0	0	0	0	143	—
26	2	.5	118	16	0	0	16	40	34	23
27	2	1.0	144	33	1	0	34	85	6	4
28	2	1.5	162	40	0	0	40	100	0	0
29	2	2.0	174	40	0	0	40	100	0	0
30	2	2.5	184	40	0	0	40	100	0	0

TABLE 11 Infrared Test 5. Forty adult tribolium were placed in 10 grams of whole wheat flour for 4 days in order to have eggs and adults in the same test. Samples were treated in 9 cm petri dishes.

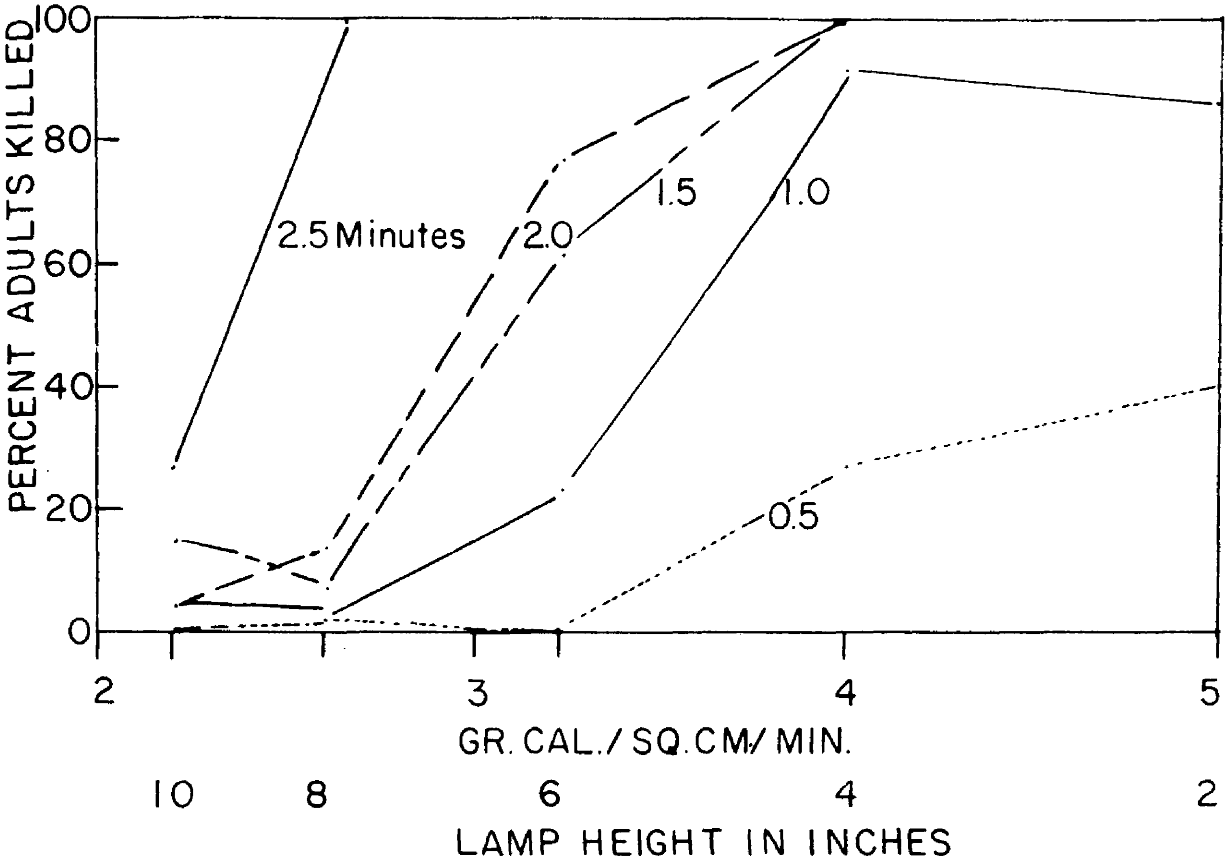


Fig 23A Percent Tribolium killed for infrared test 5.

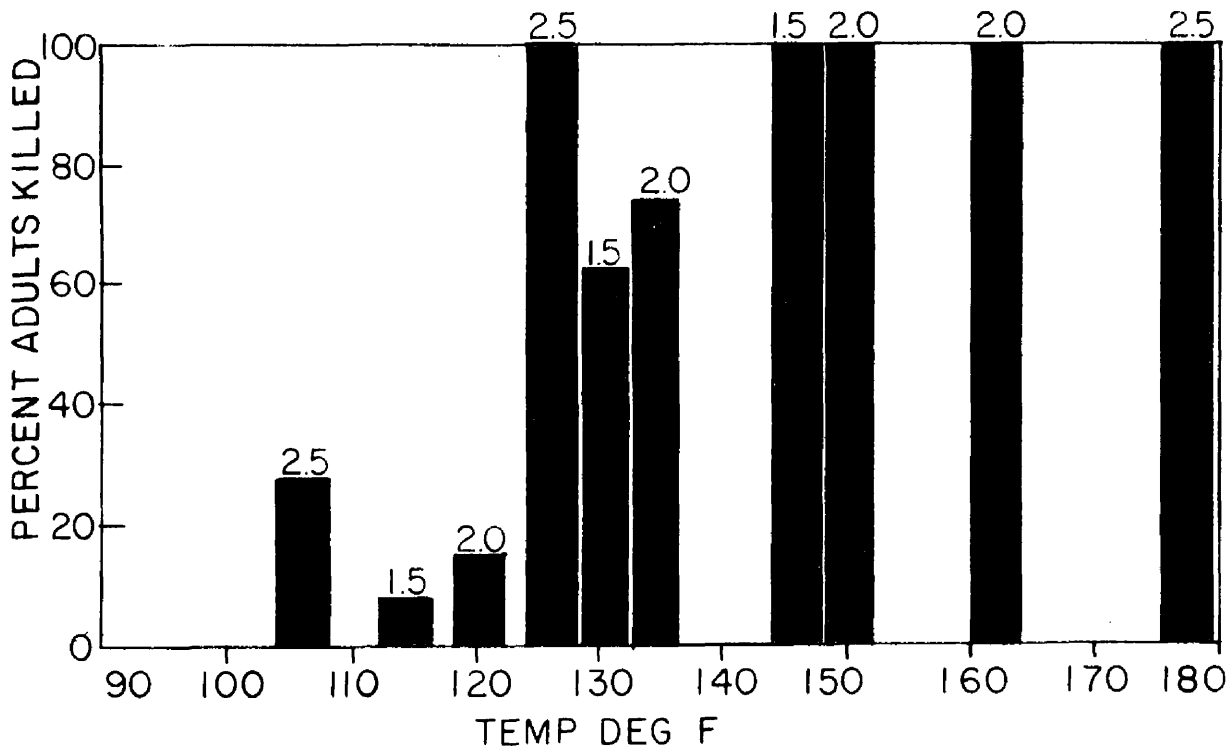


Fig 23B Partial bar chart for percent Tribolium adults killed for infrared test 5.

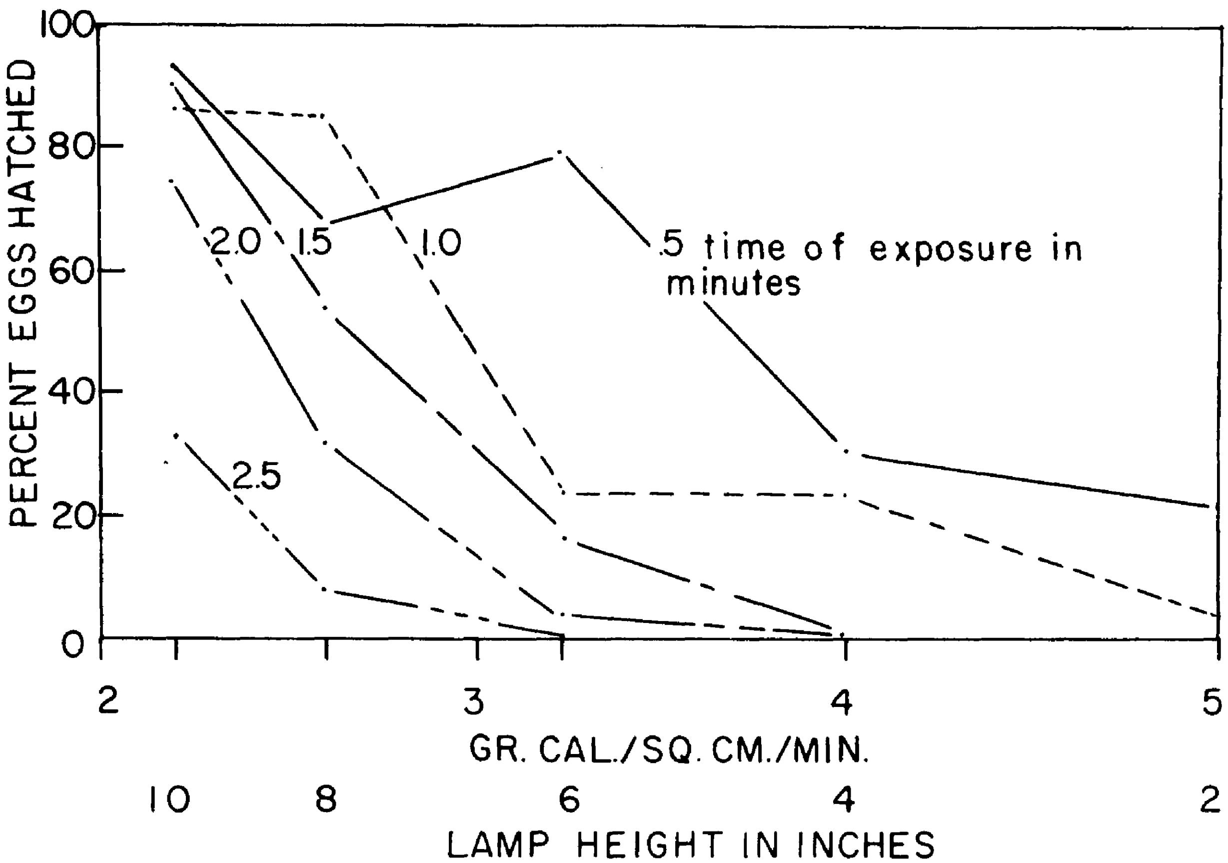


FIG 24A Percent Tribolium eggs hatched for infrared test 5.

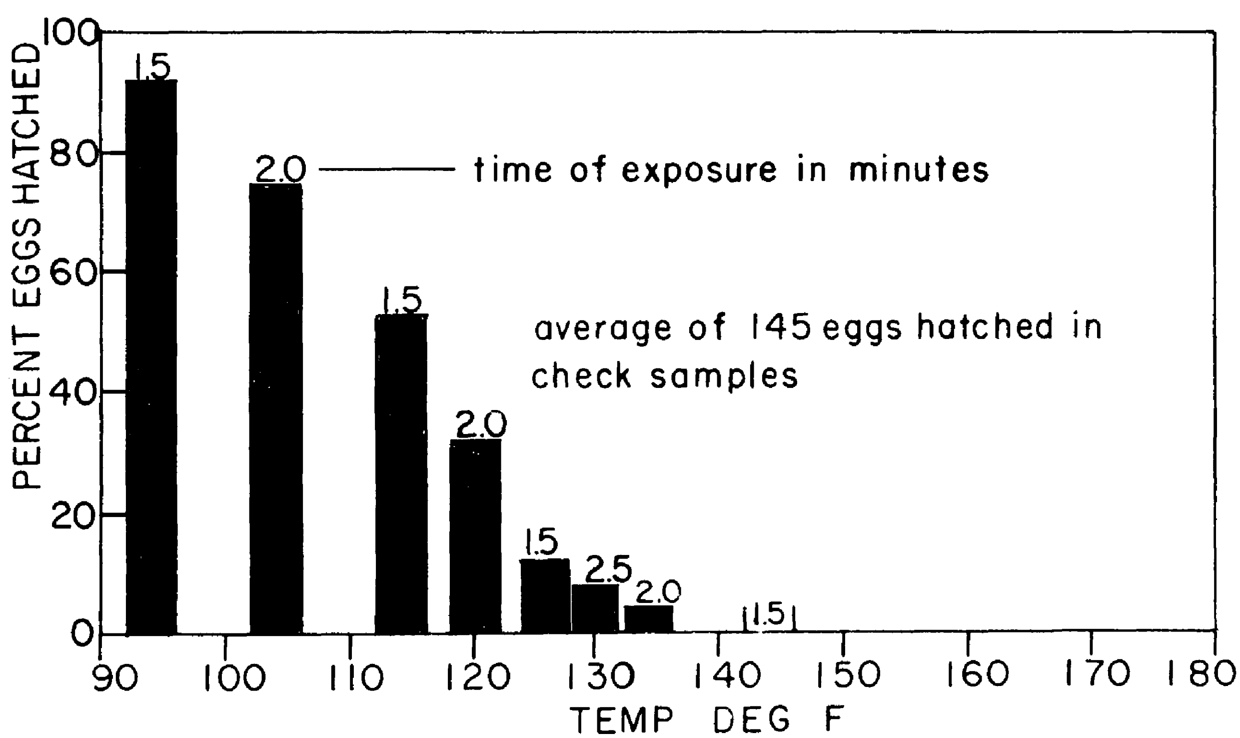


FIG24B Partial bar chart for percent Tribolium eggs hatched for infrared test 5.

shown in Table 11. Five untreated samples were used for check samples.

Before each test the flour was leveled in each dish and the depth was about 1/8 inch. No effort was made to cover the insects with flour. The main reason for having flour in the dishes for this test was to provide sufficient flour for food during the ovipositing period and at the same time supply material in which the adults could deposit their eggs.

The temperature, exposure times, and lamp heights used are shown in Table 11. At the end of each exposure period, the thermocouple attached to the incline rod, Fig. 15, was inserted into the flour so that the thermocouple junction touched the bottom of the petri dish. The maximum temperatures were recorded with the Brown potentiometer, Fig. 15. After the test the samples were incubated for 46 days, and examined at intervals as shown in Table 11.

Results: The results for test 5, presented in charts 23A, 23B, 24A, and 24B, show that a 100 percent kill was obtained one hour after test with an exposure time of 2.5 minutes at a lamp height of 8 inches. The maximum temperature at the end of the test was 127° F. The minimum time required to sterilize 100 percent of the eggs was 2.5 minutes at a lamp height of 6 inches with a maximum temperature of 138° F at the end of the test.

Infrared Test 6

Infrared test 6 was designed to determine the effects of infrared energy on the granary weevil adults and eggs. The data and results for this test are presented in Tables 12 and 13 and Figs. 25A and 25B.

Twenty-five adult granary weevils were placed in each of 12 petri dishes containing 20 grams of Cornell 595 wheat. The moisture content of the wheat was 9.7 percent wet basis. The adults remained in the samples for four days in order to allow time for them to oviposit. During this 4-day period all samples were incubated in an 80° F, 75 percent RH incubator. After the incubation period, 10 samples containing adults and eggs were exposed to various amounts of infrared energy as shown in Table 12. Two samples were not exposed to infrared and were used for check samples. The main reason for having grain in the dishes for these tests was to provide sufficient food for the adults during the incubation period and at the same time provide material in which the adults could oviposit.

The temperature, exposure time, and lamp heights used are shown in Tables 12 and 13. At the end of the exposure period, the grain was poured into the insulated thermocouple cavity shown in Fig. 17. A cork stopper was used to cover the thermocouple cavity. The maximum temperature obtained for each test was recorded by the Brown potentiometer. After the test the adult samples were incubated for one

INFRARED TEST 6A

Sitophilus granarius (Granary Weevil) Adults

Sample Number	Lamp Height In Inches	Time in Minutes	Milli-Volts	Degrees F.	Dead 1 Hour After	Additional Dead After 24 Hours	Additional Dead After 1 Week	Total	Per Cent Dead
1	Check	--	--	--	0	0	1	1	98
2	8	1.0	1.39	95	0	0	0	0	0
3	8	1.5	1.60	104	3	2	0	5	18
4	8	2.0	1.82	113	10	1	0	11	43
5	8	2.5	1.92	117	13	2	0	15	59
6	8	3.0	2.10	125	20	0	0	20	80
7	Check	--	--	--	0	0	0	0	98
8	4	1.0	1.93	118	18	1	0	19	75
9	4	1.5	2.19	128	25	0	0	25	100
10	4	2.0	2.53	142	25	0	0	25	100
11	4	2.5	2.70	150	25	0	0	25	100
12	4	3.0	3.10	166	25	0	0	25	100

TABLE 12 Infrared Test 6A, with 25 adult Granary Weevils placed in 9 cm petri dishes containing 20 grams of Cornell wheat.

INFRARED TEST 6B

Sitophilus granarius (Granary Weevil) Eggs

Sample Number	Lamp Height In Inches	Time In Minutes	Milli-Volts	Degrees F.	Hatched 41 Days After	Hatched 49 Days After	Hatched 56 Days After	Total	Per Cent Hatched
1	Check	--	--	--	35	41	0	76	100
2	8	1.0	1.39	95	25	28	0	53	81
3	8	1.5	1.60	104	10	19	0	29	45
4	8	2.0	1.82	113	7	3	0	10	15
5	8	2.5	1.92	117	10	4	0	14	22
6	8	3.0	2.10	125	1	0	0	1	1.5
7	Check	--	--	--	20	34	0	54	100
8	4	1.0	1.93	118	8	2	0	10	15
9	4	1.5	2.19	128	0	0	0	0	0
10	4	2.0	2.53	142	0	0	0	0	0
11	4	2.5	2.70	150	0	0	0	0	0
12	4	3.0	3.10	166	0	0	0	0	0

TABLE 13 Infrared Test 6B, with eggs laid by 25 adult Granary Weevils in 20 grams of Cornell wheat in 3 days.

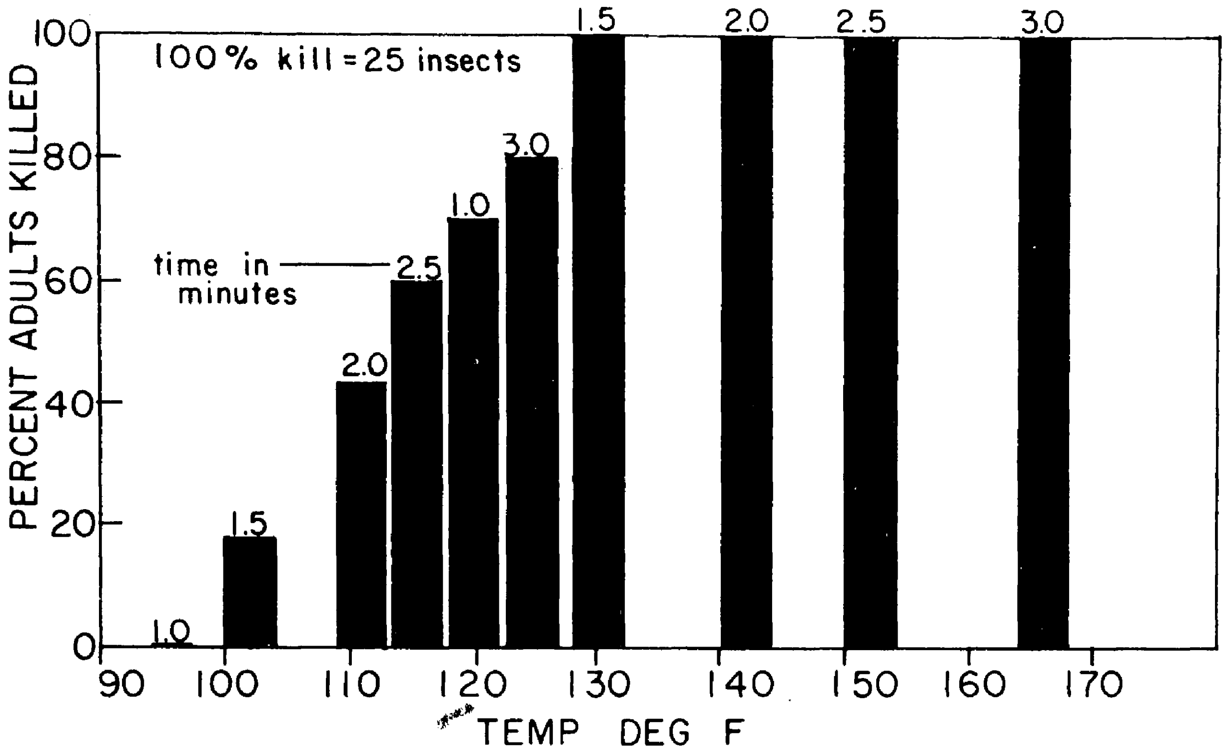


FIG 25 A Percent adult granary weevil killed for infrared test 6A.

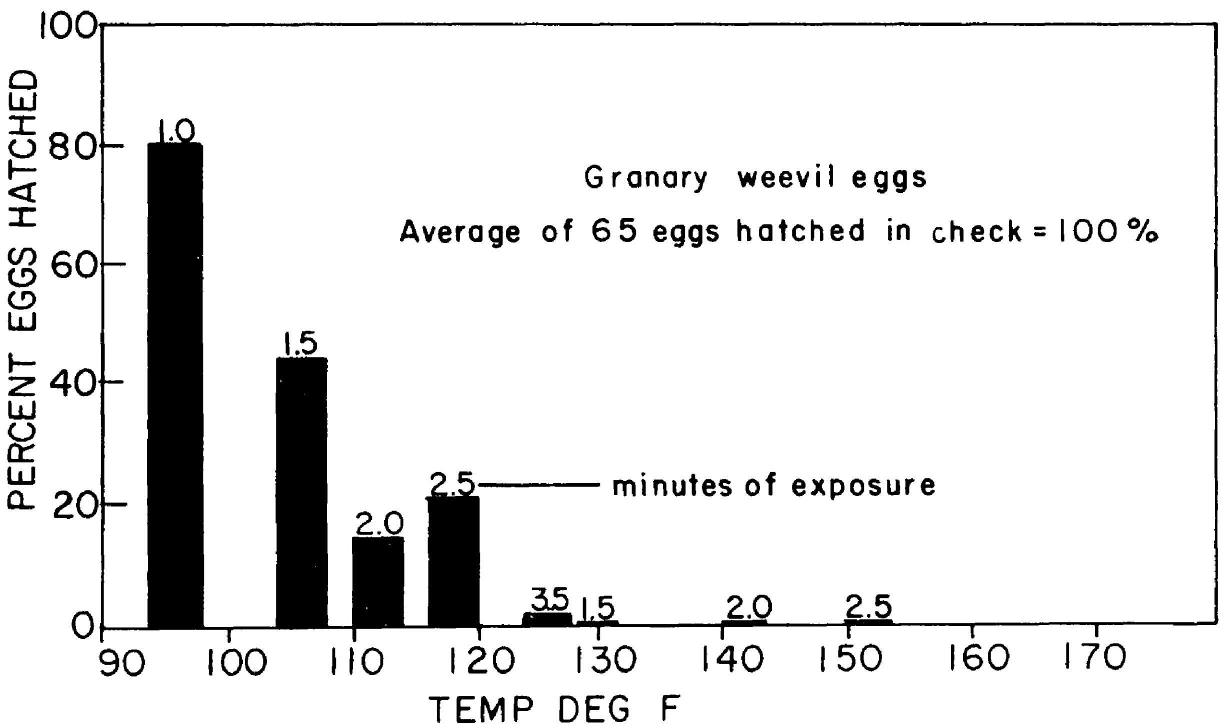


FIG25 B Percent granary weevil eggs hatched for infrared test 6B.

week and the eggs were incubated for 56 days. The adults and eggs were examined at intervals as shown in Tables 12 and 13.

Results: The results for infrared test 6, presented in charts 25A and 25B and Tables 12 and 13, show that a 100 percent kill of adult granary weevils and eggs was obtained with an exposure time of 1.5 minutes at a lamp height of 4 inches and a maximum temperature at the end of the test of 128° F.

Discussion

Infrared radiant energy from an infrared lamp may be used to kill the granary weevil, flour beetle and their eggs. Tests were not conducted on larvae of these two insects, however, work by other investigators has shown that infrared energy can be used to kill the larvae of these insects. Both temperature and exposure time are important factors in determining the amount of energy necessary to cause lethal effects. A high temperature with a short exposure time will be lethal to the insect and a low temperature (considerably above optimal temperature) with a long exposure time will be lethal to the insect. It does not seem that it would make any difference from what source the energy was obtained in order to reach the desired temperature. The energy could be from a radiant, convection or conduction source.

The following factors should be considered before infrared energy is applied on a large scale for killing insects in wheat, flour, beans, and other products.

1. Wheat, flour, and beans are relatively good insulating materials. Infrared energy has only superficial penetration into these materials. After the infrared radiant energy strikes these materials, the infrared energy is changed into heat energy, and any significant penetration into the product is by conduction.

2. The time required for the heat energy to be conducted through a layer of wheat or flour would limit the rate at which a lethal temperature could be obtained in a given thickness of material.

3. Since wheat, flour, and beans are in particle form, it would appear that heat energy convected through the product, or dropping the product through moving, heated air, would be more effective in obtaining the lethal temperature in the product than treating the product with infrared energy alone. A combination of infrared, conducted, and convected energy should possibly be considered. The temperatures shown in Fig. 13 have been effective for destroying insects in continuous processes.

4. There is not enough energy in a quantum of infrared energy to cause ionization of insect tissue, however, some breakdown in the chemical structure of insect tissue

will take place if heat energy is built up in the insect sufficient enough to cause dissociation.

Literature Cited

(1) Hall, J. D., Industrial Applications of Infrared, McGraw-Hill Book Co., New York, N.Y., 1947, p. 164.

(2) Koller, L. R., "Infrared Production and Transmission Reflection and Measurement", General Electric Review, March 1941, pp. 167-173.

(3) Canada, A. H., "Simplified Calculations of Black-body Radiation", General Electric Review, Dec. 1948.

(4) Nicholos, J. E. and Musser, H. B., "Seed Drier Using Infrared Electric Lamps", Agricultural Engineering, Dec. 1941.

(5) Garber, H. J. and Tiller, F. M., "Infrared Radiant Heating", Industrial and Engineering Chemistry, March 1950, pp. 456-463.

(6) Duane, J. P. and Tyler, J. E., "Operation Saurnid", Interchemical Review, Summer 1950, pp. 25-27.

(7) MacLeod, G. F., "Effects of Infrared Radiation on American Cocroach", Journal of Economic Entomology 35(5):728-729, 1941.

(8) Headlee, T. J. and Jobbins, D. M., "Progress to Date on Studies of Radio-waves and Related Forms of Energy for Insect Control", Jour. Econ. Ent. 31(5): 559-563, 1938.

(9) Cotton, R. T., "Heat Sterilization in the Flour Mill", Insects, Pest of Stored Grain and Grain Products, Burgess Publishing Co., Minneapolis, Minn., 1952, p. 226.

(10) Frost, S. W., Dills, L. E., and Nicholos, J. E., "The Effects of Infrared Radiation on Certain Insects", Jour. Econ. Ent. 37(2):287, 1944.

(11) Uvarov, B. P., "The Upper Fatal Limit in Insects", Insects and Climate, Trans. Ent. Soc. London 79(1):17-19, 1931.

(12) Kleis, R. W., "The Development of Engineering Methods for the Treatment of Loose Smut in Wheat", Unpublished M.S. Thesis, Michigan State College, 1951.

(13) Cheklich, G. E., "Further Experiments in the Development of Engineering Methods for the Control of Loose Smut in Wheat", Unpublished M.S. Thesis, Michigan State College, 1953.

PART VI

SOME EFFECTS OF ULTRAVIOLET ENERGY ON CERTAIN INSECTS

Introduction and Review of Literature

Volumes have been written on the various aspects of ultraviolet light. Ellis and Wells (1), Luckiesh (2), and Koller (3) each devote a chapter in their books to the lethal action of ultraviolet rays and sterilization. A number of workers have found the region of bactericidal activity to lie between the wavelength of 2960 and 2100 Angstroms, with maximum germicidal effectiveness at 2537 A. Although the results of many investigations on the lethal effects of ultraviolet energy have been reported in the literature, very little is known yet as to the exact nature of the changes that take place within a living cell when it is exposed to ultraviolet energy.

Ellis and Wells (1) pointed out that the abiotic power of ultraviolet light was the result of photochemical action on certain molecular groupings of the protoplasm and especially the nucleus. They also discuss the effects of ultraviolet on the sterols, ergosterol, and cholesterol, found in plant and animal tissue. They pointed out that the exposure of roundworm eggs to ultraviolet energy from an arc for six to eight hours usually did not kill the eggs at once, but prevented further development if the eggs had been in the two-cell or four-cell stage at the time of exposure. With shorter exposure times, there was observed irregular fragmentation of the chromosomes. Laurens (4) reviews the effects of ultraviolet energy on microorganisms and proteins. Egg albumen coagulated when exposed to ultraviolet as it did when exposed to heat when the pH was between 4.4 and 5.6. It was pointed out that under this condition, the albumen acted like an anhydro-colloid. The final conclusion was that the effects caused by ultraviolet radiation was different from the effects caused by heat. Laurens also pointed out that ultraviolet penetration into tissue was superficial and was from one to two millimeters for rabbit abdominal tissue and not greater than two millimeters for human skin.

MacLeod (5) reported that the eggs and first instar of the bean weevil are killed by light of wavelengths less than 3126 A. Adults showed no visible effects after irradiation but most of their eggs were sterile. Sublethal doses on weevils produced defective metabolic processes.

Martin and Westbrook (6) made histological examinations of _Pulmonaria_ leaves at varying times during irradiation. Lethal changes were first evident in the nuclei of the epidermal cells which coagulated, darkened, and became disorganized into one or more irregular masses. Taylor (7) investigated the effects of ultraviolet on certain insects. He found that more insects were attracted to a lamp which had a peak output at about 3600 A than at any other wavelength. Approximately this same wavelength is listed as the optimum wavelength at which maximum photochemical reaction occurs (8).

It was pointed out in another section of this thesis that there was not enough energy in a quantum of ultraviolet with a wavelength greater than about 2880 A to produce ionization of most of the elements found in insects. With this in mind an effort was made to obtain a source of ultraviolet energy with a considerable amount of radiation of wavelength shorter than 2880 A, so that various insects could be exposed to this radiation. The following section contains a description of equipment and procedure for tests conducted.

Equipment and Procedure

Pictures of the ultraviolet test equipment are shown in Figs. 26 and 27. A sketch of the ultraviolet lamp and circuit used is shown in Fig. 28. Insect specimens were exposed to ultraviolet radiation from the GE type UA-2 UVIARC 250-watt mercury vapor lamp. The energy distribution for this lamp is shown in Figs. 29 and 30. The UA-2 lamp radiates about 12 watts of energy at wavelengths shorter than 2880 A. The UA-2 lamp radiates about 30.6 watts in the total ultraviolet spectrum and about 18.9 watts in the

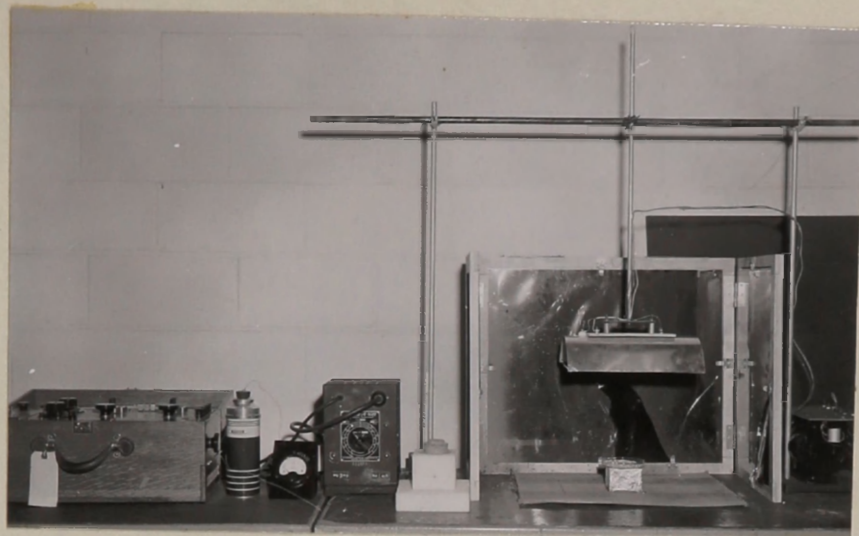


Fig. 26. Ultraviolet test equipment, from left to right, potentiometer, reference junction ice bath, voltmeter, voltage regulator, insulated thermocouple cavity, 250-watt UA-2 UVIARC ultraviolet lamp mounted under aluminum reflector, irradiated sample of wheat in petri dish under lamp. The dark plastic sheet at right was used to shield investigators when samples were exposed.

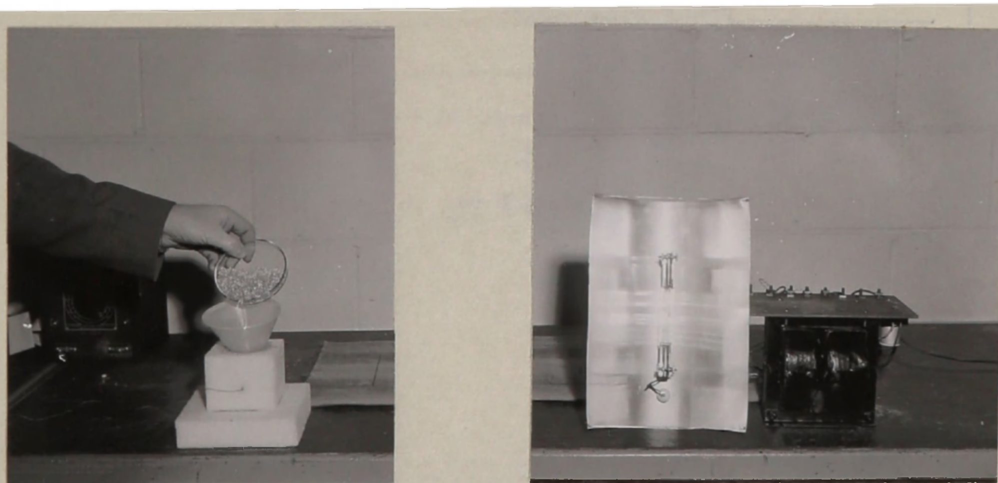


Fig. 27. Left, showing irradiated sample being poured into thermocouple cavity; right, close-up of UVIARC tube and reflector with transformer.

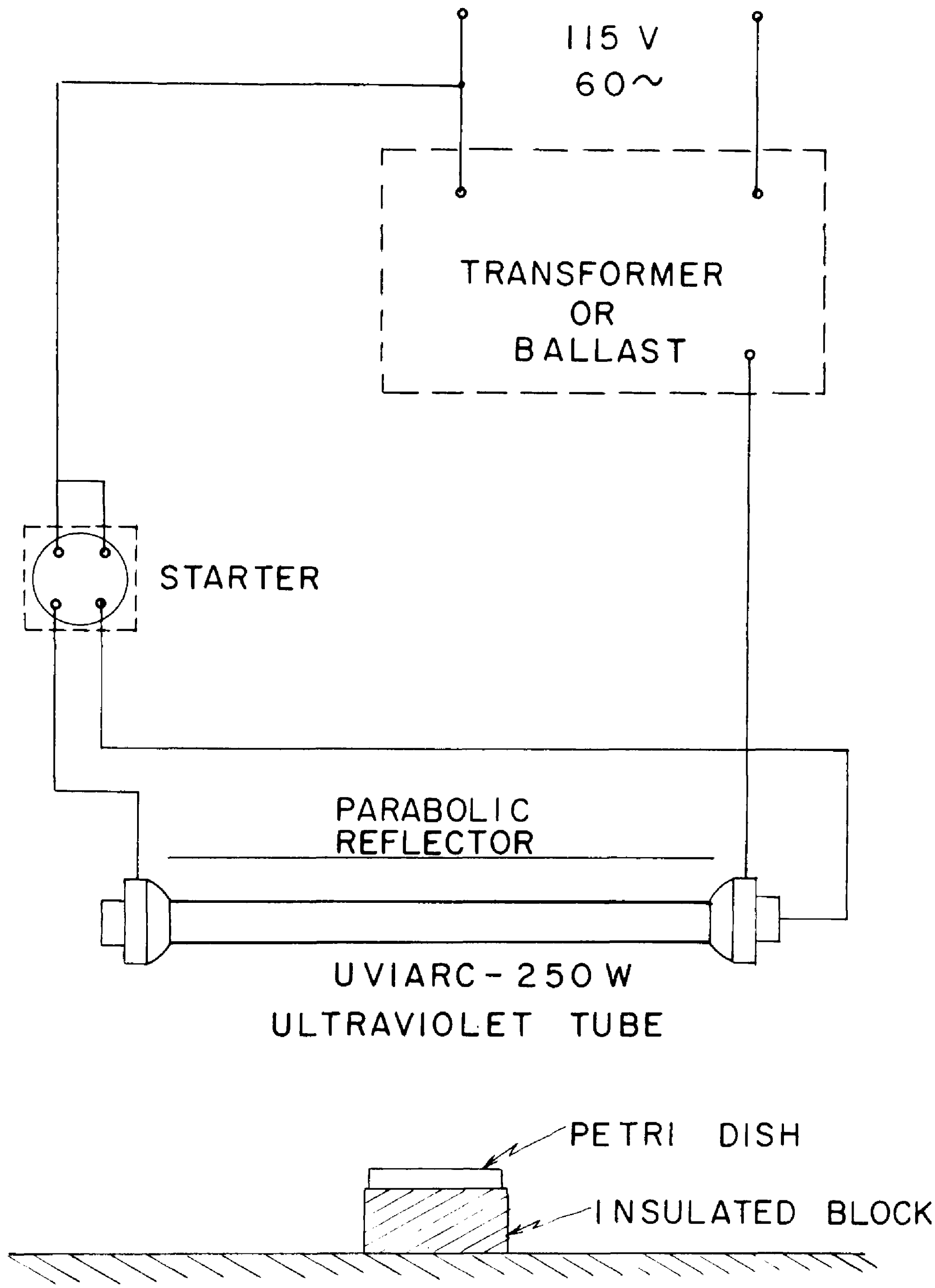


Fig 28 Sketch of ultraviolet test equipment.

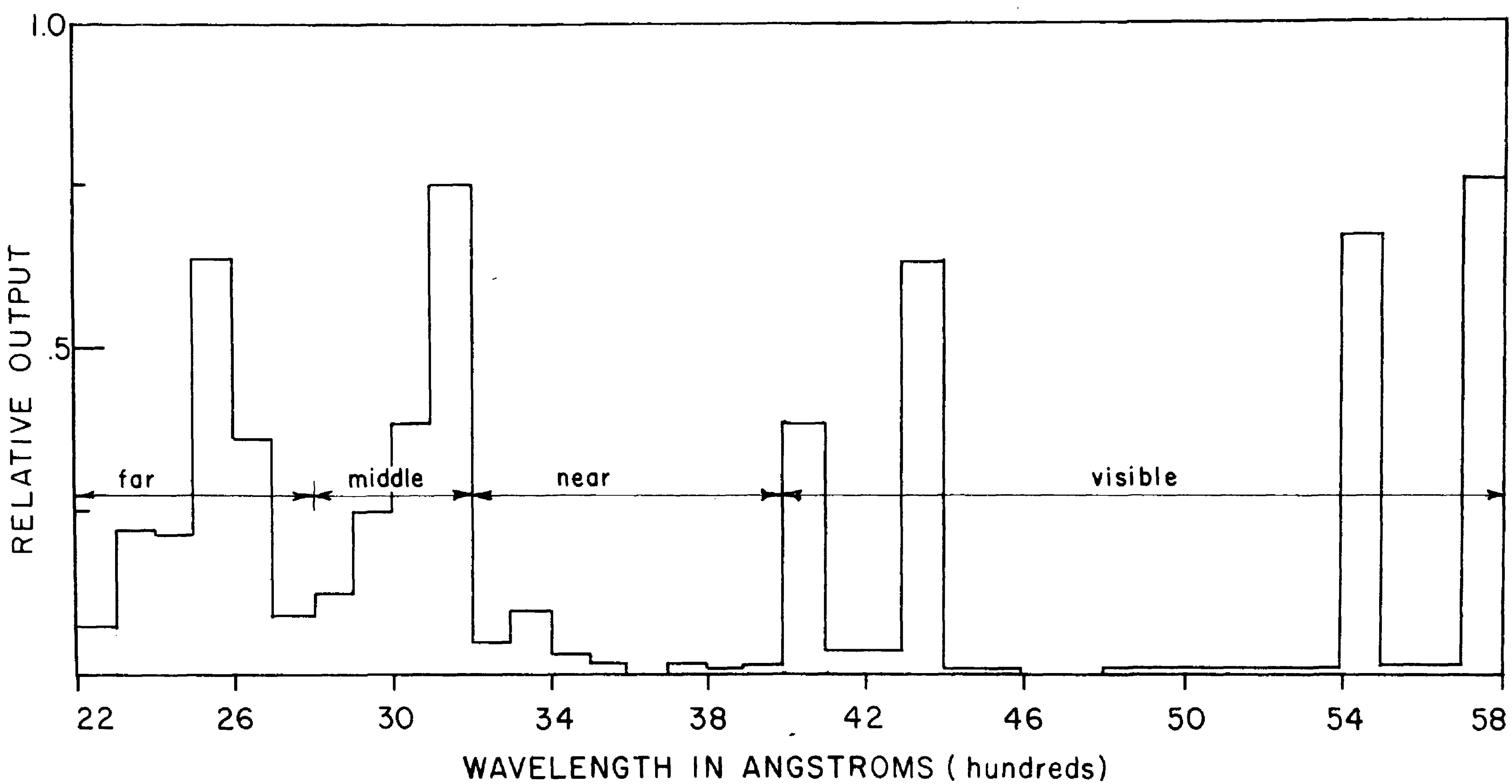


Fig 29 Typical energy distribution for quartz Uviarc lamps, from G.E. Lamp Bulletin LS-104

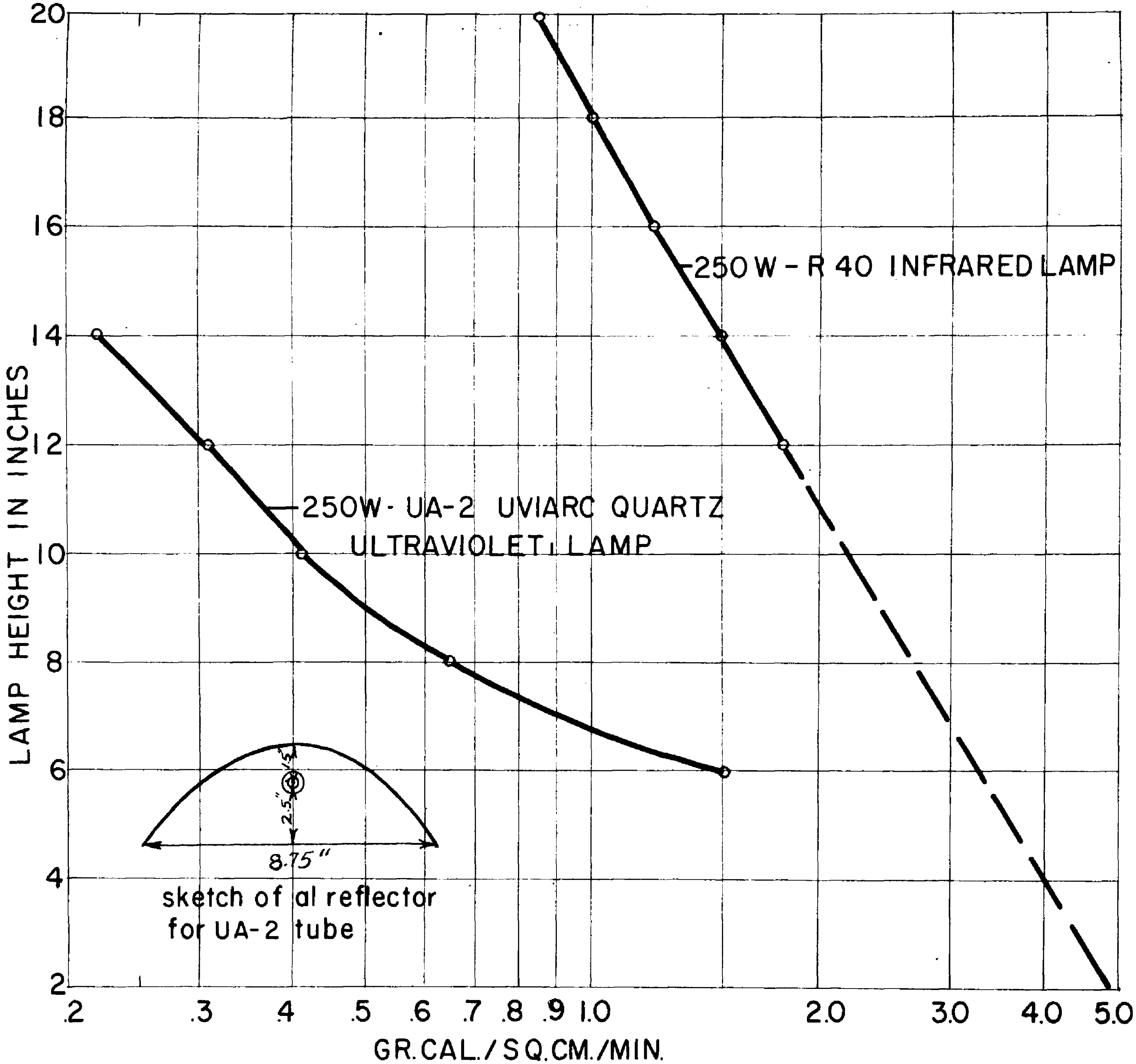


Fig 30 Radiant energy at various lamp heights above GE Type DW-60 radiation meter – for UA-2 and R-40 lamps.

visible spectrum. The remainder of the 250 watts input was radiated as infrared energy or given off as conducted heat to the air. The energy radiated from the UV-2 lamp as ultraviolet is 12.2 percent of the input energy. The voltage on the UA-2 tube was maintained at 117 volts during each test.

The UA-2 lamp was mounted under a parabolic aluminum reflector with dimensions shown in Fig. 30. The length of the quartz section of the UA-2 tube is 3 inches. The height of the lamp above the petri dish, Fig. 26, was measured from the point of maximum curvature of the reflector to the bottom of the petri dish.

Ultraviolet Tests 1A and 1B

The data for tests 1A and 1B, including sample numbers, lamp height, exposure time, and temperatures are recorded in Tables 14 and 15. Forty adult flour beetles were placed in each of 18 petri dishes containing 5 grams of whole wheat flour, and were incubated four days before the test in order to allow sufficient time for the adults to oviposit. The flour was placed in the dishes so that the adults would have food and at the same time have material in which to deposit their eggs. Fifteen of the samples were exposed as shown in Table 14. The data for three untreated samples, containing 40 adult insects in each sample, was averaged and used as a check. Maximum temperatures were recorded

ULTRAVIOLET TEST 1A

Tribolium confusum Adults (Flour Beetle)

Sample Number	Lamp Height In Inches	Time In Minutes	Milli— Volts	Degrees F.	Number Dead 1 Hour After	Number Dead 24 Hours After	Number Dead 1 Week After	Total	Per Cent of Check
1	Check	--	--	--	0	0	0	0	0
2	10	2	1.22	87	0	0	0	0	0
3	10	4	1.40	95	34	0	0	34	85
4	10	6	1.51	100	37	0	0	37	93
5	10	8	1.70	108	40	0	0	40	100
6	10	10	1.32	113	40	0	0	40	100
7	Check	--	--	--	0	0	0	0	0
8	7	2	1.40	95	37	1	0	38	95
9	7	4	1.78	112	40	0	0	40	100
10	7	6	2.15	127	40	0	0	40	100
11	7	8	2.20	129	40	0	0	40	100
12	7	10	2.42	138	40	0	0	40	100
13	Check	--	--	--	40	0	0	0	0
14	4	2	2.44	139	40	0	0	40	100
15	4	4	3.12	166	40	0	0	40	100
16	4	6	3.32	175	40	0	0	40	100
17	4	8	4.08	204	40	0	0	40	100
18	4	10	4.20	209	40	0	0	40	100

TABLE 14 Ultraviolet Test 1A. Forty adult Tribolium confusum were placed in 9 cm petri dishes containing 5 grams of whole wheat flour 4 days before test in order to allow time for adults to oviposit.

ULTRAVIOLET TEST 1B

Tribolium confusum Eggs (Flour Beetle)

Sample Number	Lamp Height In Inches	Time In Minutes	Milli— Volts	Degrees F.	Number of Eggs Hatched After 47 Days	Per Cent of Check
1	Check	—	—	--	73	—
2	10	2	1.22	87	14	22
3	10	4	1.40	95	14	22
4	10	6	1.51	100	7	11
5	10	8	1.70	108	1	1.6
6	10	10	1.82	113	1	1.6
7	Check	—	—	--	54	—
8	7	2	1.40	95	13	21
9	7	4	1.78	112	0	0
10	7	6	2.15	127	0	0
11	7	8	2.20	129	0	0
12	7	10	2.42	138	0	0
13	Check	—	—	—	63	0
14	4	2	2.44	139	0	0
15	4	4	3.12	166	0	0
16	4	6	3.32	175	0	0
17	4	8	4.08	204	0	0
18	4	10	4.20	209	0	0

TABLE 15 Ultraviolet Test 1B. Forty tribolium confusum placed in 5 grams of whole wheat flour 4 days before test in order to allow time for adults to oviposit.

by placing a thermocouple under the layer of flour at the end of each test. The Leeds and Northrup potentiometer, Fig. 26, was used to indicate the voltage readings of the thermocouple after each test.

Results: An exposure time of 8 minutes with a lamp height of 10 inches was lethal to 100 percent of the adult flour beetles one hour after treatment. The maximum temperature recorded was 108° F. An exposure time of 2 minutes with a lamp height of 7 inches was lethal to 97 percent of the adults one week after treatment. No flour beetle eggs hatched, after an incubation period of 47 days, using a lamp height of 7 inches and an exposure time of 4 minutes. Detail results for ultraviolet tests 1A and 1B are shown in Tables 14 and 15.

Ultraviolet Tests 2A and 2B

Tests 2A and 2B were designed to determine the lethal effects of ultraviolet on granary weevil adults and eggs. The data for these tests are presented in Tables 16 and 17. Twenty-five adult granary weevils were placed in each of 12 petri dishes containing 20 grams of Cornell 595 wheat. All samples were placed in an incubator for 4 days before treatment in order to allow sufficient time for ovipositing. The results from two untreated samples were averaged and used as a check. The maximum temperature at the end of each exposure was observed by pouring the wheat into the

ULTRAVIOLET TEST 2A

Sitophilus granarius (Granary Weevil) Adults

Sample Number	Lamp Height In Inches	Time In Minutes	Milli—Volts	Degrees F.	Number Dead 1 Hour After	Number Dead 24 Hours After	Number Dead 1 Week After	Total	Per Cent of Check
1	Check	—	—	—	0	0	0	—	—
2	7	1	1.70	108	6	0	0	6	24
3	7	2	1.95	118	9	1	0	10	40
4	7	4	2.46	140	25	0	0	25	100
5	7	6	2.75	152	25	0	0	25	100
6	7	8	3.40	178	25	0	0	25	100
7	Check	—	—	—	0	0	0	0	0
8	10	1	1.30	90	3	0	0	3	12
9	10	2	1.69	108	6	1	0	7	28
10	10	4	1.82	113	11	0	0	11	44
11	10	6	2.10	125	20	0	0	20	80
12	10	8	2.35	135	25	0	0	25	100

TABLE 16 Ultraviolet Test 2A. Twenty-five adult Granary Weevils were placed in 9 cm petri dishes containing 20 grams Cornell wheat.

ULTRAVIOLET TEST 2B

Sitophilus granarius (Granary Weevil) Eggs

Sample Number	Lamp Height In Inches	Time In Minutes	Milli-volts	Degrees F.	Number of Eggs Hatched After 49 Days	Per Cent of Check
1	Check	—	—	—	123	—
2	7	1	1.70	108	80	57
3	7	2	1.95	118	59	42
4	7	4	2.46	140	0	0
5	7	6	2.75	152	0	0
6	7	8	3.40	178	0	0
7	Check	—	—	—	158	—
8	10	1	1.30	90	162	110
9	10	2	1.69	108	133	95
10	10	4	1.82	113	43	31
11	10	6	2.10	125	12	9
12	10	8	2.35	135	0	0

TABLE 17 Ultraviolet Test 2B. Twenty-five adult Granary Weevils were placed in 9 cm petri dishes containing 20 grams of Cornell wheat. Adults remained in samples 4 days before treatment.

thermocouple cavity (Fig. 27) and immediately observing the indication of the Leeds and Northrup potentiometer in Fig. 26. After the samples were irradiated, the treated and untreated samples were placed in an incubator and observations were made at intervals as shown in Tables 16 and 17.

Results: An exposure time of 4 minutes with a lamp height of 7 inches was lethal to 100 percent adult granary weevils one hour after treatment. No eggs hatched after an incubation period of 47 days, in samples receiving this same treatment. Other results are shown in Tables 16 and 17.

Discussion

From the data collected, there seems to be no appreciable difference between the final results of the ultraviolet test and the infrared test on the granary weevil. In each case a temperature of about 140° F was fatal to eggs and adults. Ultraviolet did seem to have lethal effects on the flour beetle eggs at a much lower temperature than in the infrared tests. This may be due to the fact that the granary weevil eggs are generally deposited inside the wheat berry, whereas the flour beetle eggs are deposited at random in the flour. Since ultraviolet energy has poor penetration into the wheat berry, it would appear that under this condition more energy would be required to kill the granary weevil eggs than the flour beetle eggs.

Before any further work of this nature is attempted, the following points should be considered.

1. Ultraviolet energy has only superficial penetration into wheat, flour, beans, and other relatively opaque materials. This would tend to limit the use of ultraviolet to the application to the surface of these materials.

2. Only the ultraviolet wavelengths shorter than about 2880 A are considered to have any ionization effects.

3. The difficulty of obtaining a pure ultraviolet source at high outputs would make it impractical for use as lethal energy on insects. When present methods of generating ultraviolet are used, such as the gaseous tube and the carbon arc, as a source of relatively large amounts of energy, it would be difficult to separate the effects due to ionization and the effects due to heat.

Literature Cited

(1) Ellis, C. and Wells, A. A., The Chemical Action of Ultraviolet Rays, Reinhold Publishing Co., New York, N.Y., 1941, pp. 692-732.

(2) Luckiesh, M., Application of Germicidal, Erythermal and Infrared Energy, D. Van Nostrand Co., New York, N.Y., 1946.

(3) Koller, L. R., Ultraviolet Radiation, John Wiley & Sons, New York, N.Y., 1952, 270 pp.

(4) Laurens, H., *The Physiological Effects of Radiant Energy*, Chemical Book Co. Inc., New York, N.Y., 1933, pp. 544-546.

(5) MacLeod, G. F., "Effects of Ultraviolet Radiations on the Bean Weevil", *Ann. Ent. Soc. Amer.* 26:605-615, Dec. 1933.

(6) Martin, B. T. and Westbrook, A., "The Effects of Ultraviolet Energy on *Pulmonaria* leaves", *Jour. Exp. Biology* 5:138, 1927.

(7) Taylor, J. G., "Progress Report on Electric Traps for Insects", Paper presented at Winter Meeting Amer. Soc. Agr. Engrs., Chicago, Ill., December 1952.

(8) Buttolph, L. J. and Haynes, H., "Ultraviolet Air Sanitation", *General Electric Lamp Bulletin LD-11*, Nela Park, Cleveland, Ohio, 1950, p. 1.

PART VII

SOME EFFECTS OF X- AND GAMMA RADIATION ON CERTAIN INSECTS

Review of Literature on X-rays

X-rays and gamma rays are electromagnetic waves. X-rays are often referred to as Roentgen rays, named for the discoveror of x-rays, and are formed when an electron with high kinetic energy strikes a target such as copper or tungsten. Part of this energy is dissipated as heat and part goes into the production of x-rays.

A modern x-ray tube is simply a diode across which is applied a high voltage, Fig. 31. Electrons emitted from the heated cathode are accelerated toward the target metal. If the electrons strike the target at a velocity V, their velocity can be calculated by equaling the kinetic energy of the electrons to the work done on the electrons by the electric field in accelerating the electrons across a potential V, i.e., $1/2\ mv^2 = eV$ where e = charge on the electron. If all of the energy of an electron goes into the production of one photon, the wavelength of this radiation will be given by substituting in the equation $E = \frac{hc}{x}$. The minimum wavelength of the x-ray can be calculated by substituting in the equation $x = \frac{12407}{V}$. According to Lapp and Andrews (1), longer wavelength will be produced by electrons that divide their energy and result in two

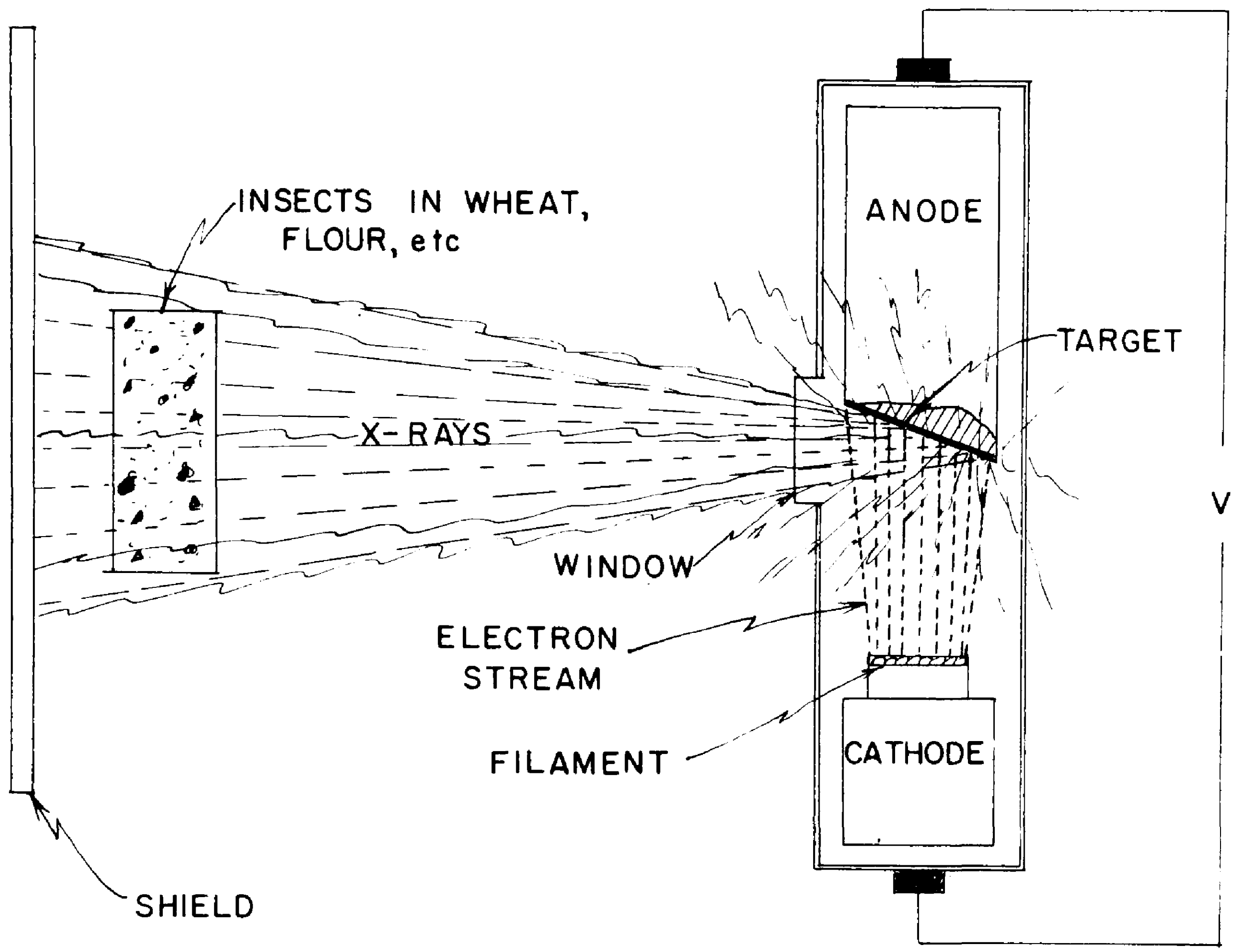


Fig 31 Insect specimen in beam of X-Rays.

or more photons. By observing the equation above it is obvious that as the voltage across the tube is increased, This causes a corresponding decrease in x-ray wavelength.

X-rays are generally propagated from the target in all directions. Because the x-ray distribution cannot generally be controlled in direction or shape, the utilization of x-ray efficiency is very low. Theoretically, the entire x-ray pattern can be useful, but practical target designs and production-line limitations reduce the effective portion to about 50 percent of the total (2). The conversion of electron energy to x-ray energy is a very inefficient process. At 50 kilovolts, the power conversion efficiency is about 0.1 percent for heavy target materials. The power conversion efficiency at 2 million volts is about 5 percent.

X-rays do not have a definite range into matter but are absorbed gradually. Since x-rays radiate in a spherical pattern from the target, the problem of conveying products in order to utilize the full spherical pattern becomes very complex. In practice, if the products are properly distributed around the x-ray source, a total utilization efficiency of about 25 percent can be attained (2).

When matter is transversed by x-rays, energy is absorbed from the x-ray photons by the photoelectric, Compton scattering, or pair production mechanism as shown in Fig. 7. Much is now known about the influence of dosage rate and the linear ion density along the track of the high energy particle. According to Trump (3), physiochemical and biological reactions depend on the number of ionizing electrons produced in the passage of the radiation through the material.

The effects of x-rays on insects has been studied chiefly from a long and short term genetical view point using Drosophila melanogaster (fruit fly) by a number of workers (4, 5, 6). The entomology, genetics, and zoology journals contain many articles on this subject. The main object of x-ray studies here is to determine if any short term lethal effects could be obtained.

Hey (7) conducted preliminary tests with 90 kv x-rays and he found that in general, resistance of the bean weevil to x-rays with doses of 280 to 360 roentgens (r) units induced the development of abnormal larvae and pupae, prolonged the immature stages causing late emergence of adults, and reduced the fertility of adults arising from such treated eggs. Irradiation of larvae, with doses of 507 to 912 r units induced the development of abnormal adults and reduced the fertility of adults. None of the abnormal forms laid any eggs, so it was not possible to determine if such abnormalities would be transmitted to the next generation. The maximum dosage used, 2000 r, was observed to have no lethal effects at all upon the adult weevils.

Tahmisian (4) studied the effects of x-rays on grasshopper eggs. He found that x-radiation dosages ranging from 10,000 to 200,000 r do not completely inhibit respiration in the diapause grasshopper embryo. He also found that irradiation damage can be repressed by subdeveloped temperatures.

Equipment and Procedure for X-ray Test

X-ray Test 1

The data recorded for test 1 is shown in Table 18. The x-ray machine used is shown in Figs. 32A and 32B. The x-ray unit used was a 50 kv Hilger machine in the Physics Department of Michigan State College. Forty adult flour beetles with eggs were placed in 13.5 grams of whole wheat flour in a test box and irradiated as shown in Fig. 16A. The cardboard box was 1.5 inches in diameter and 0.75 inch thick. During the period of irradiation, the test box was mounted 15.5 inches from the target in order to utilize the maximum beam area.

The exposure time for each treatment is shown in Table 18. The Hilger x-ray unit was designed to study crystal structures and the dosage in roentgens was not readily calibrated. A dosimeter was available but unfortunately it was out of order at the time of this test.

Results: The data in Table 18 show that no exposure used was lethal to any adults one hour or one week after

X-RAY TEST 1

Tribolium confusum Adults and Eggs

Sample Number	Time of Exposure In Minutes	Dead After Test		Eggs Hatched After 36 Days	Offspring from Adults 40 Days After Treatment	Adult Offspring From Treated Eggs
		1 Hour	1 Week			
1	Check	0	0	151	99	44
2	1	0	0	81	67	32
3	5	0	0	97	54	31
4	10	0	0	103	37	19
5	20	0	0	87	55	6
6	Check	0	0	120	121	53
7	1	0	0	131	21	63
8	5	0	0	90	72	42
9	10	0	0	101	60	32
10	20	0	0	105	65	54
11	Check	0	0	87	92	37
12	1	0	0	123	56	14
13	5	0	0	93	37	48
14	10	0	0	115	36	35
15	20	0	0	90	43	30

TABLE 18 X-Ray Test 1, with 40 adult tribolium and eggs in 13.5 grams of whole wheat flour, 40 kv, 20 ma strength. Insects placed in round cardboard box 1.5 inches in diameter, .75 inches deep. Box was placed 15.75 inches from copper target.

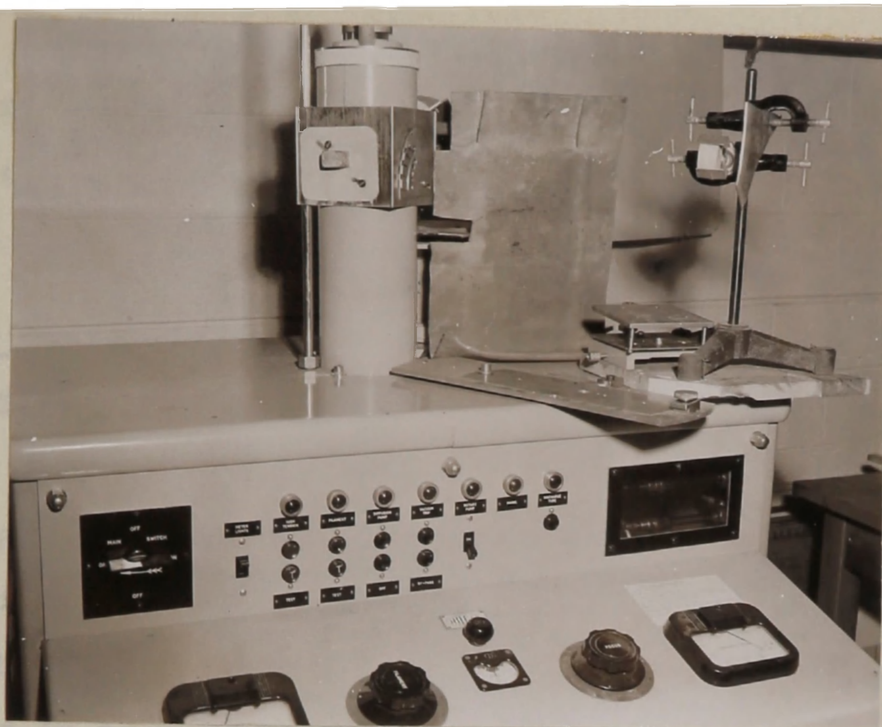


Fig. 32A. Picture of Hilger X-ray unit in the Physics Laboratory. Insect specimens placed in 13.5 gm of whole wheat flour in test box in clamp. Test box distance from x-ray opening is 15.5 inches. Test box is 1.5 inch in diameter and 0.75 inch thick.

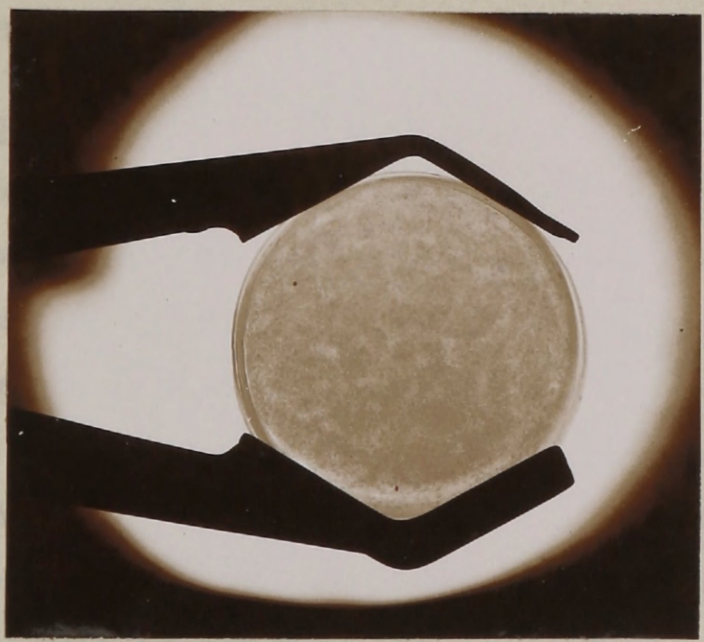


Fig. 32B. X-ray exposure of flour in test box.

treatment. After a period of 36 and 46 days of incubation, some eggs hatched in each sample treated and there appeared to be no trend in the effects on treated and untreated eggs.

X-ray Test 2

The data for test 2 is shown in Table 19. The 250-KV x-ray unit installed in the School of Veterinary Medicine, Michigan State College, was used for this test. Complete specifications for this machine are given in the caption of Table 19. Thirty adult flour beetles with eggs were placed in each of 15 9-cm petri dishes with each dish containing 10 grams of whole wheat flour. Twelve samples were irradiated with doses of energy as shown in Table 19. Three samples were used for checks and were not treated. After the test, the samples were placed in an incubator and observed for lethal effects.

Results: The results of test 2 are presented in Table 19. There were no visible effects on the adults one week after treatment. As many as two adults died after a period of two weeks, but this was not enough to establish a trend, since one adult died in the check samples during this period. The data in Table 19 indicate none of the doses used up to 880 r units had any noticeable effect on the number of eggs hatched after a period of 40 days of incubation, on the offspring from irradiated adults, or on the offspring from

X Ray Test 2

Tribolium confusum (flour beetle) adults and eggs

Sample Number	Time in Minutes	r/air	Total Roentgens	Dead after 24 hours	Dead after 1 week	Total dead after 2 weeks	Offspring from adults	Irradiated eggs hatched	Offspring from irradiated eggs
1	2	100	148	0	0	1	31	17	73
2	2	100	148	0	0	0	50	20	65
3	4	200	296	0	0	1	61	27	89
4	4	200	296	0	0	1	40	23	62
5	6	300	444	0	0	0	29	25	93
6	6	300	444	0	0	2	47	43	59
7	8	400	592	0	0	0	35	56	85
8	8	400	592	0	0	2	32	38	73
9	10	500	740	0	0	0	45	53	90
10	10	500	740	0	0	0	39	19	75
11	12	600	880	0	0	0	55	62	60
12	12	600	880	0	0	0	42	45	81
13	Check	-	-	0	0	0	62	42	68
14	Check	-	-	0	0	0	41	33	79
15	Check	-	-	0	0	1	46	35	95

Table 19 X-Ray test 2 using the G. E. Maximar 250 III, 250 KV X-Ray unit at the School of Veterinary Medicine of Michigan State College, April 14, 1953. Calibrated physical factors - - - total filtration 0.25 cu, 1 al; hvl .78 cu; 15 ma, 200 KV, beam size 400 sq cm; fsd 50 cm; r/min air 50.

irradiated eggs. After this test, it was decided to discontinue the x-ray tests and devote the time to the accelerated electron tests.

Gamma Radiation

No tests were made using gamma rays. However, a brief discussion and a review of literature is presented. Gamma rays are electromagnetic photons identical in nature with x-rays (1). For the same wavelength of radiation, the properties of the two rays are the same, the only difference being that of origin. Photons which originate in the nucleus of an atom (fission products) are known as gamma rays, whereas photons arising from electron transition in the deep-lying electron shells of atoms are x-rays.

There is no reason for maintaining the artificial distinction between x- and gamma rays. Since gamma rays are of the same physical nature as x-rays, all of the characteristics of x-rays discussed in the previous section apply to gamma radiation.

Two units of measurement of gamma radiation intensity are the "curie" and the "rutherford" (rd). The term "curie" is calibrated in terms of the number of radioactive disintegrations occurring per second. The curie may not represent a true basis for comparison, since the ionizing energy available in each disintegration depends on the nature of the radioactive substance. The following conversions have been listed (2).

1 curie = 3.7×10^{10} disintegrations per second

1 rutherford = 10^6 disintegrations per second

200 curies = 1 watt (assuming 1 mev average gamma ray energy)

The roentgen (r) is used also in discussing gamma radiation, however the roentgen is not an intensity unit since a roentgen is independent of time. The term roentgens per second may be thought of as an effective radiation intensity measurement.

Since gamma rays propagate in all directions from a radioactive source, the conveying problems for utilizing all the propagated energy are complex. Long radioactive rods, such as are now in use at the University of Michigan Phoenix project, would appear to present the most favorable shape for irradiation purposes. Cobalt 60 rods, less than one inch in diameter to prevent excessive self-absorption, are made available for this purpose by bombarding ordinary cobalt in a nuclear-reacting pile. The utilization efficiency of cobalt 60 is from 20 to 40 percent.

Gamma Rays for Insect Control

Hassett and Jenkins (8) were probably the first investigators to report on the use of gamma radiation for insect control. They exposed a number of insects among which were the granary weevil and the flour beetle. They first exposed insects to radiation from radioactive tantalum (intensity of 1300 r per hour) by placing insects in a small cylinder and packing tantalum pellets around the walls of the cylinder. The results with Tribolium confusum showed that: 80 percent of adults were killed by 110,000 r, 90 percent were killed by 140,000 r, and 100 percent were killed by 196,000 r. The time of death after exposure was not listed. They pointed out that even though this method produced significant lethal effects, the results were unsatisfactory because of the long exposure time.

Hassett and Jenkins (8) conducted a second group of tests in which a source of cobalt 60, capable of delivering a dose of about 193,000 r per hour, was used. A dose of 16,100 r was lethal to 100 percent of the adult granary weevils and flour beetles 13 days after treatment. A high percentage of each species of insect treated were killed within 24 hours after exposure to 257,000 r. A dose of 193,000 r was very effective also, and only a few insects of three species survived longer than 5 days. At 128,000 r lethal effects varied more noticeably. All adult granary weevils treated with this dose were dead on the fifth day, while on the seventh day 75 percent of the adult flour beetles were dead. A dose of 65,000 r was lethal to most of the specimens 12 to 14 days after treatment.

Hassett and Jenkins also discussed some of the problems involved in the design of an irradiation unit and the cost of fission products.

Conclusions

1. None of the x-ray treatments used, i.e., dosages up to 888 r had any short time lethal effects on flour beetle adults or eggs.

2. The conversion of electron energy into x-rays is a very inefficient process. The conversion varies from 0.1 percent for a 50 kv unit to about 5 percent for a 2 million volt unit.

3. The low utilization efficiency and high sterilization cost of x-rays make it impractical to use x-rays for sterilization of material on a conveyor belt.

4. Since it has been demonstrated (2) that x-ray sterilization costs are several times greater than electron sterilization costs, and since high voltage equipment was not immediately available for test work, it was decided to abandon the x-ray tests and devote time to accelerated electron tests.

5. Fast killing doses of 65,000 r of gamma rays were lethal to the flour beetle and granary weevil adults from 12 to 14 days after exposure. Many problems, including conveying, shielding, and cost of fission products, will have to be worked out before this process can be effective on a large scale.

Literature Cited

(1) Lapp, R. E. and Andrews, H. L., Nuclear Radiation Physics, Prentiss-Hall Co., New York, N.Y., 1949, pp. 42, 69.

(2) X-rays, Radioactivity, and Electrons, Technical Bulletin D-2, High Voltage Engineering Co., Cambridge, Mass., 1952, 6 pp.

(3) Trump, J. G. and Van de Graaff, "Irradiation of Biological Materials by High Energy Roentgen Rays and Cathode Rays", Journal of Applied Physics, July 1948, pp. 599-616.

(4) Tahmisian, T. N., "Effects of X-radiation on the Metabolic Processes of the Resting Cell", Jour. Exp. Zool. 112:449-463, Dec. 1949.

(5) Fano, U., "Theory of Radiation Induced Lethals in Drosophila", Science 106:87-88, July 25, 1947.

(6) Lüning, K. G., "X-ray Induced Mutations in Drosophila melanogaster", Hereditas 38(1):108-109, 1952.

(7) Hey, G. L., "Some Preliminary Experiments Concerning the Effects of X-rays on the Various Stages of the Bean Weevil (Bruchus obtetus (Say)", Jour. Exp. Zool. 64:209-229, November 1932.

(8) Hassett, C. C. and Jenkins, D. W., "Use of Fission Products for Insect Control", Nucleonics, December 1952, pp. 42-46.

PART VIII

SOME EFFECTS OF ACCELERATED ELECTRONS ON CERTAIN INSECTS

Subatomic particles were discussed briefly in Part II under ionization radiation. Accelerated electrons, cathode rays, and beta-particles are used to designate the flow of electrons. The term beta-particle is usually reserved for electrons emitted from a nucleus, whereas the term cathode ray is used to designate the flow of electrons from some mechanical equipment.

In the past few years considerable progress has been made toward the development of high voltage electron acceleration equipment which may be used for the so-called "cold" sterilization of foods and drugs. Trump and Van de Graaff (1, 2), Burrill _et al_. (3) and their associates were among the first to develop equipment for accelerating electrons. Dunn _et al_. (4), Proctor and Goldblith (5, 6) and their associates were among the first investigators to treat various food products with accelerated electrons, and to study the effects on enzymes, microorganisms, molds, and spores. Urbain (7) reported facts about cold sterilization.

Yeomans (8) reported on the exposure of the flour beetle, bean weevil and other insects to impulses of 2.5 Mev electrons from the capacitron. The electron dose ranged from 180,000 rep to 900,000 rep (see appendix for definition of rep). He found that a dose of 310,000 rep was lethal to 100 percent of adult flour beetles 48 hours after treatment, and that a dose of 460,000 rep was lethal to 100 percent of adult bean weevils 48 hours after treatment.

The following points relative to the electron treatment of foods for sterilization are presented (3, 5, 9, 10):

1. From 50 to 75 percent of the electron beam can be utilized.
2. No induced radioactivity is produced in the product at voltages below 21 million volts.
3. The biological and chemical effects of accelerated electrons on matter are the same as those of x-ray and gamma rays.
4. The penetration of accelerated electrons into matter is less than x-rays of corresponding voltages, but their penetration range is of sufficient magnitude to be considered.
5. The rise in temperature of the irradiated product caused by the bombarding electrons is negligible in comparison to the temperatures needed for normal heat sterilization.
6. The electron dose can be metered, thereby providing a continuous record of an uninterrupted flow of product on a conveyor beneath the electron beam.

Equipment and Procedure

This section of the thesis is a report on the investigations being conducted by the Agricultural Engineering and Entomology Departments of Michigan State College in cooperation with The Upjohn Company of Kalamazoo, Michigan. A discussion of electron treatment of the insects which infest wheat, flour, and beans is presented. The section that follows includes a discussion of the types of acceleration equipment available, Van de Graaff generator, units of radiation or dosage, method of calculating dosage, penetration of accelerated electrons into wheat, flour, and beans, test work conducted, and results.

Types of Equipment Available

Three major types of equipment are available for producing accelerated electrons as described by Urbain (7). These are the resonant transformer, the capacitron, and the Van de Graaff generator. Each of these generators include a suitable source of electrons and a source of high voltage. The main difference between these three units is the manner in which the high voltage is obtained. The high voltage for the resonant transformer is obtained from a transformer, and the capacitron receives its voltage from condensers charged in parallel and then discharged in series. The Van de Graaff generator used in this thesis has some advantages over the other two types of equipment.

A brief description of the Van de Graaff generator is presented below.

Van de Graaff generator: A schematic diagram of the Van de Graaff generator is shown in Fig. 33, and photographs are shown in Figs. 34A and 34B. A corona discharge causes electrons to be deposited on a fast moving belt. These electrons are delivered to the spherical shape high voltage terminal. When the potential builds up to two million volts, in the machine which was used, electrons from the heated filament in the evacuated acceleration tube are accelerated down through the acceleration tube through a thin aluminum window and into the product. As the electrons travel down through the acceleration tube they approach the speed of light. The Van de Graaff generator can be thought of literally as an electron gun shooting electron bullets into the product being irradiated.

Units of Radiation or Dosage

The accelerated electron dosage falling upon an absorber can be calculated with accuracy. The dose delivered to materials on a moving belt may be derived more simply by direct comparison with the chemical effects of accelerated electrons as determined on stationary samples.

Accelerated electron doses may be specified in rep (roentgens equivalent physical) for biological studies, whereas the same dose is expressed in ergs and joules for

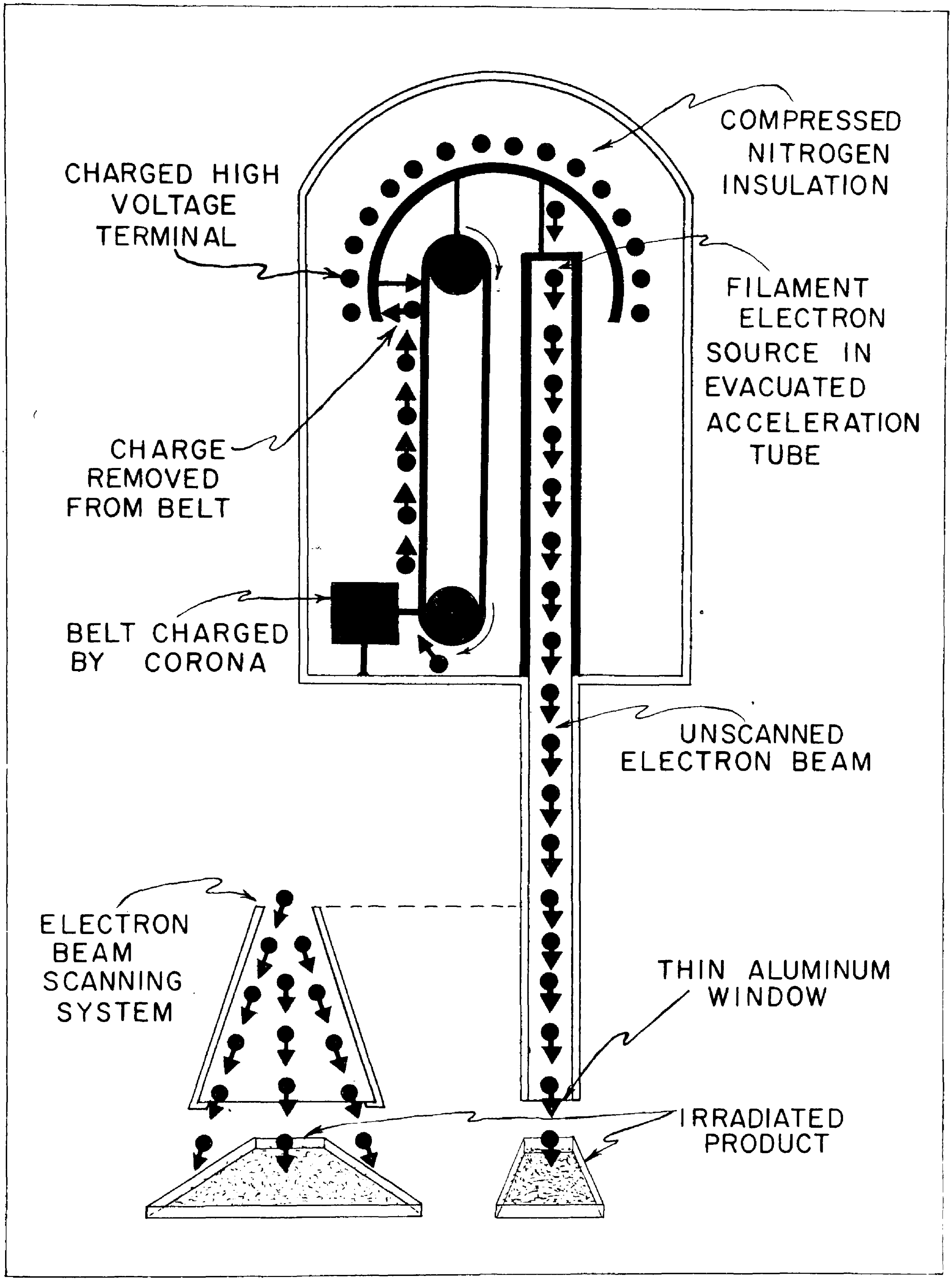


Fig33 Schematic sketch of the Van de Graaff electron accelerator.

Fig. 34A. General view of the Van de Graaff generator and controls. Picture courtesy of The Upjohn Co., Kalamazoo, Michigan.

Fig. 34B. View of converyor belt, shielding blocks and vacuum pump for Van de Graaff generator. Picture courtesy of The Upjohn Company, Kalamazoo, Michigan.

physical studies. One rep represents a very minute quantity of energy.

The conversion factors for these units are:

1 rep = 83.8 ergs per gram of air or

93 ergs per gram of water or tissue*

1 joule = 10^7 ergs = 0.24 calories

1,000,000 rep = 8.38 joules per gram of air

= 2.01 calories per gram of air

Method of Calculating Dosage

The method used for calculating dosage of ionizing electrons was essentially the same as that presented by Trump *et al.*(2). Their formula for dosage calculation is:

$$P = (E\ I/\pi\ (D/2)^2\ R)\ K_1\ K_2 = \frac{4\ EI\ K_2}{\pi\ D^2} \cdot \frac{K_1}{R} \text{ watts per gram} \quad \text{(a)}$$

where: P = power absorbed per gram of material distributed evenly over container of diameter D in cm.

E = accelerating voltage

I = total beam current to container of diameter D

R = depth of material in gram per sq cm

K_1 = fraction of total power absorbed in range R

K_2 = back scatter factor

The value of K_1 may be obtained for 2, 3, 4, and 5 Mev electrons from Fig. 35 by dividing the area under the curve for a sample thickness R in gram per sq cm by the total area under the curve for a given Mev. K_1 and K_1/R have been

*As proposed by Evans (11).

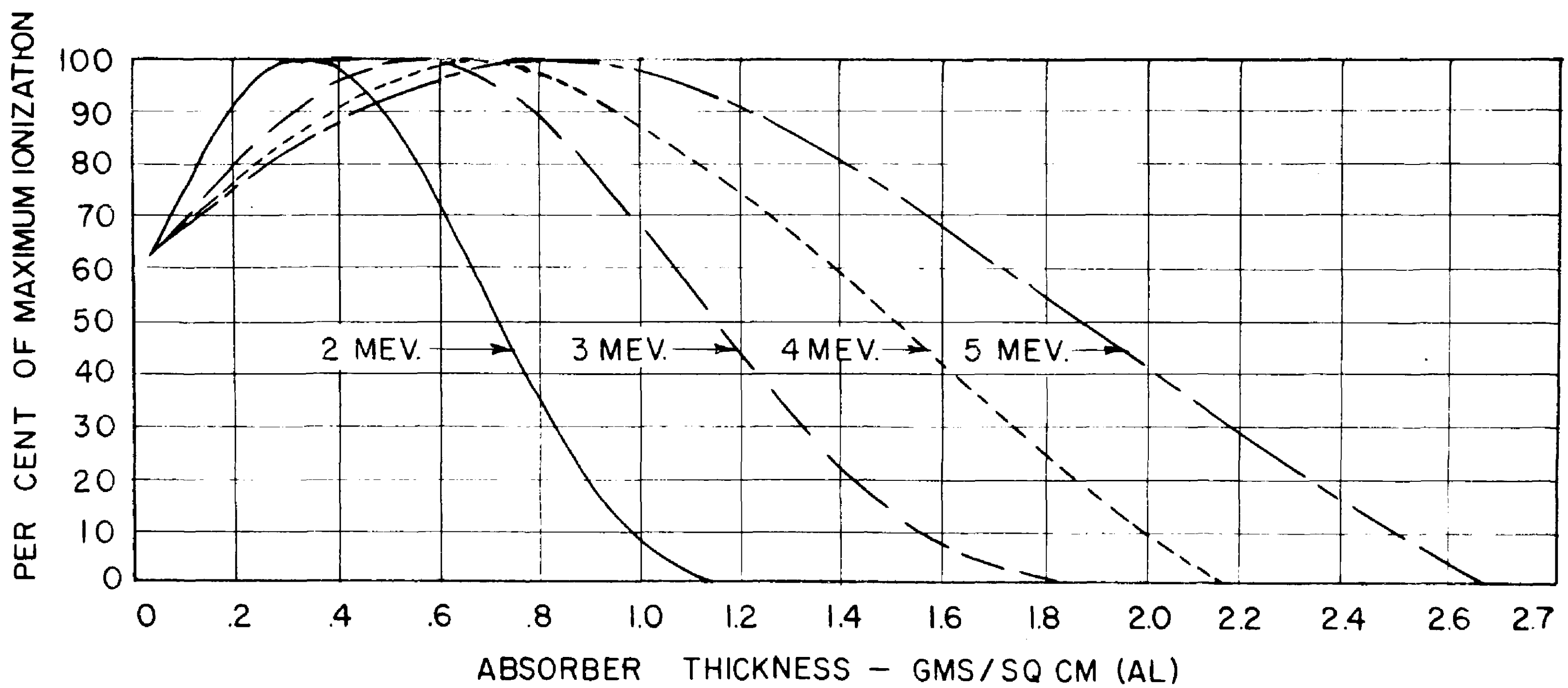


Fig 35 Percent of maximum ionization for 2, 3, 4 and 5 MEV. electrons in aluminum.

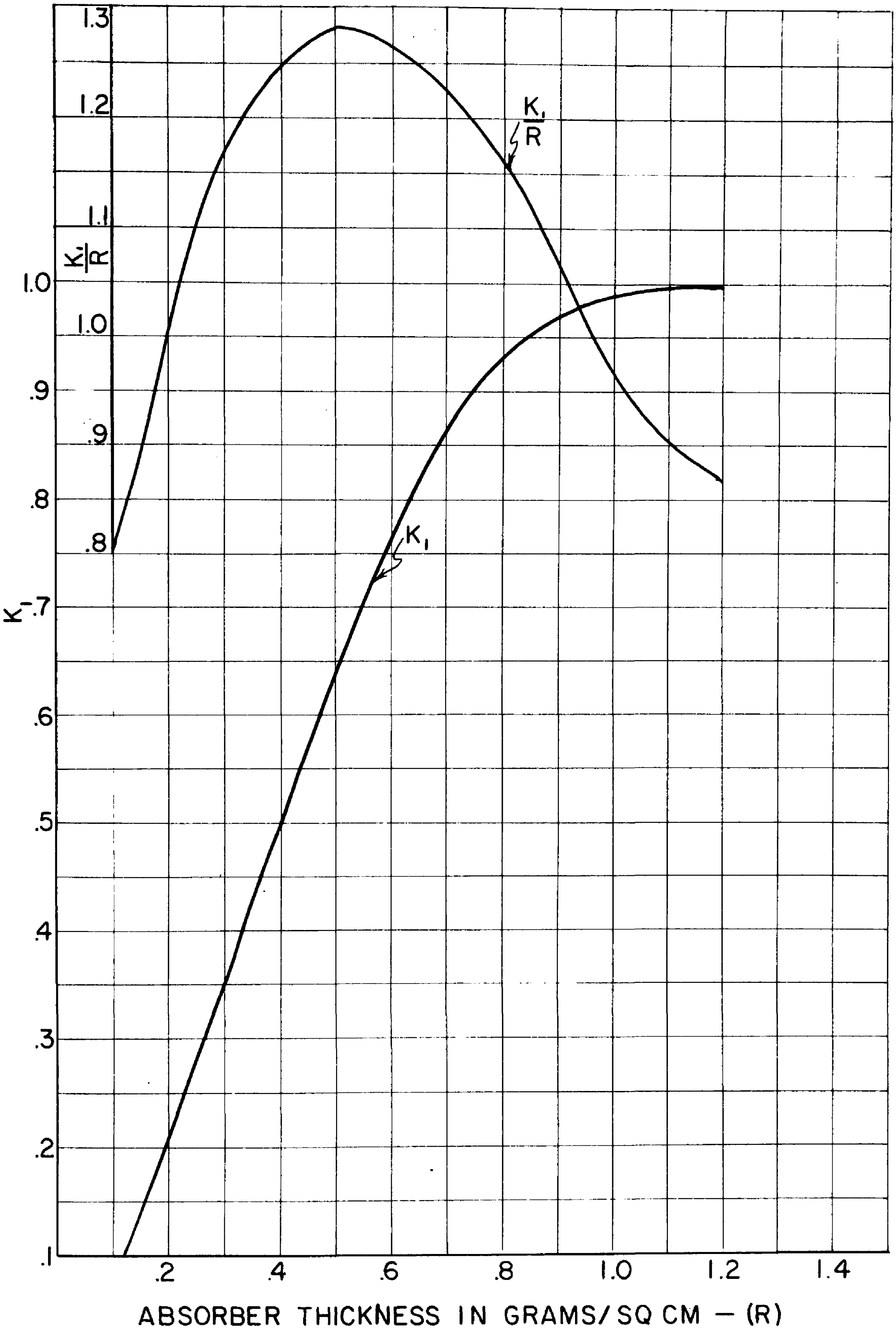


Fig36- K_1 and $\frac{K_1}{R}$ for calculating the dosage of 2MEV electrons.

calculated for 2 Mev electrons by using this method (Fig. 36) and are in use at The Upjohn Company for calculating dosage of 2 Mev electrons (see appendix for definition of Mev). The data in Fig. 35 is based on published data for aluminum. Since R is in grams per sq cm, these curves can be used for most homogenous materials. Trump (2) points out that K_2 can be kept close to unity by making the dish, in which the material is irradiated, of a low atomic number. Before an actual dosage problem is solved, it will be desirable to know the penetration of accelerated electrons into the materials to be irradiated.

Penetration of Electrons into Wheat and Flour

In order for electrons to be effective in ionizing tissue and thus cause lethal effects, the energy of the electron must be absorbed by a material as the electron travels through the material. The actual penetration depths of accelerated electrons into a material is of little value unless some information is available on how the energy is dissipated in the material. The percent of maximum ionization curves for wheat and flour, Fig. 37B, were calculated from ionization curves of aluminum as given in Fig. 35 or Fig. 37A, using a density for wheat and flour of 0.74 gram per cc.

Sample calculation (2 Mev) for converting Fig. 37A to Fig. 37B:

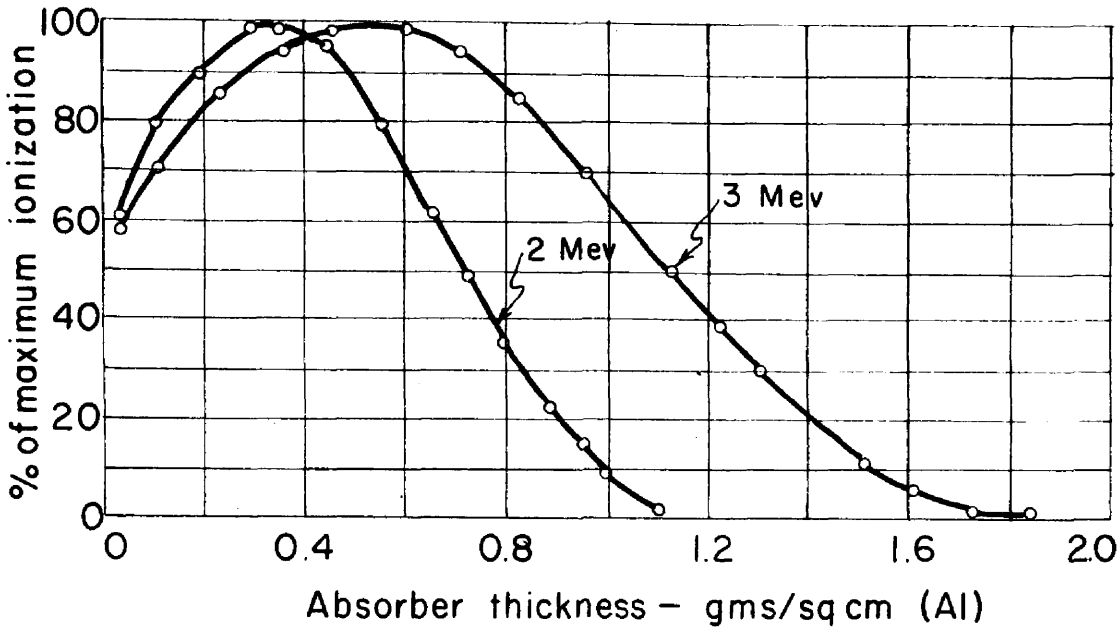


Fig 37A- Distribution of ionization in depths of aluminum irradiated width 2 Mev and 3 Mev cathode rays(2).

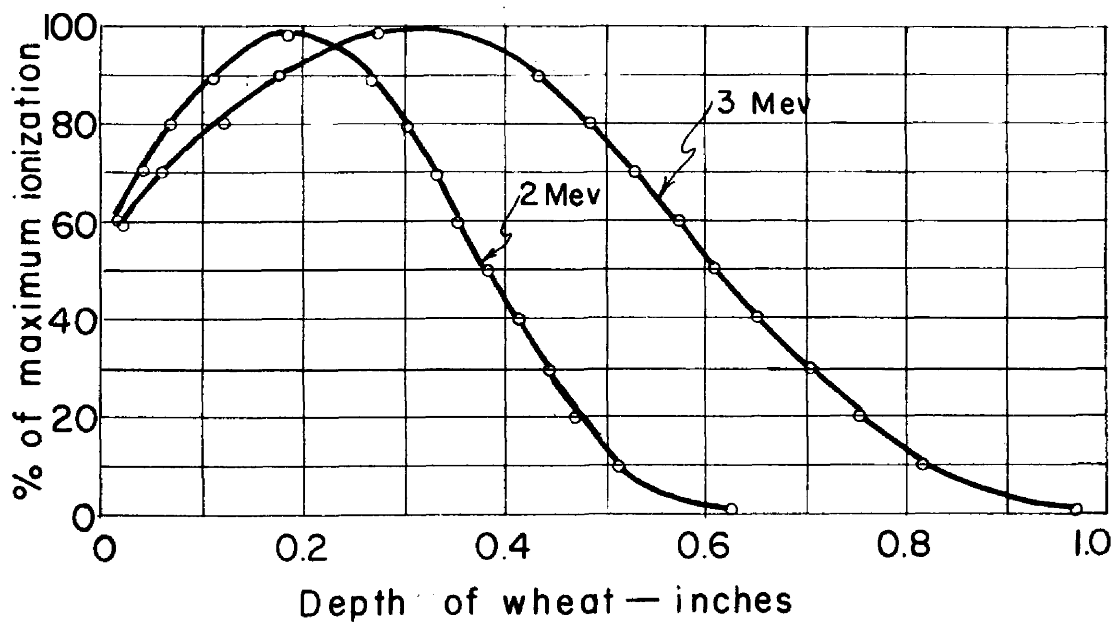


Fig 37B- Calculated distribution of ionization in wheat (density .74 gr/cc) irradiated with 2 Mev and 3 Mev cathode rays.

($0.65\ gr/cm^2$) from Fig. 37A to inches of wheat in Fig. 37B:

$$\frac{0.65\ gr/cm^2}{(0.74\ gr/cm^3)(2.54\ cm/in)} = 0.35 \text{ inch of wheat or flour}$$

If wheat or flour is irradiated on a conveyor belt and 60 percent of maximum ionization is to be obtained in the top layer of flour and in the layer of flour next to the conveyor belt, then the maximum depth which can be treated is about 0.35 inch for 2 Mev electrons, and about 0.57 inch for 3 Mev electrons. These depths may be more than doubled when the material is irradiated from top and bottom. Calculations show that a depth of about 1.0 inch of wheat or flour can be treated if irradiated from top only with 5 Mev electrons, Fig. 38A, or a depth of more than 2.0 inches can be treated if irradiated from top and bottom with 5 Mev electrons. That is, assuming 60 percent of maximum ionization in the top and bottom layers.

Choice of Percent of Maximum Ionization Entering and Leaving Sample

It is desirable to choose a thickness of sample so that the percent of maximum ionization entering and leaving the sample is the same. The percent of maximum ionization for 2 and 3 Mev electrons in wheat and flour is shown in Figs. 38B and 38C. A dose of 60 percent of maximum ionization was chosen for these figures. The physical shape

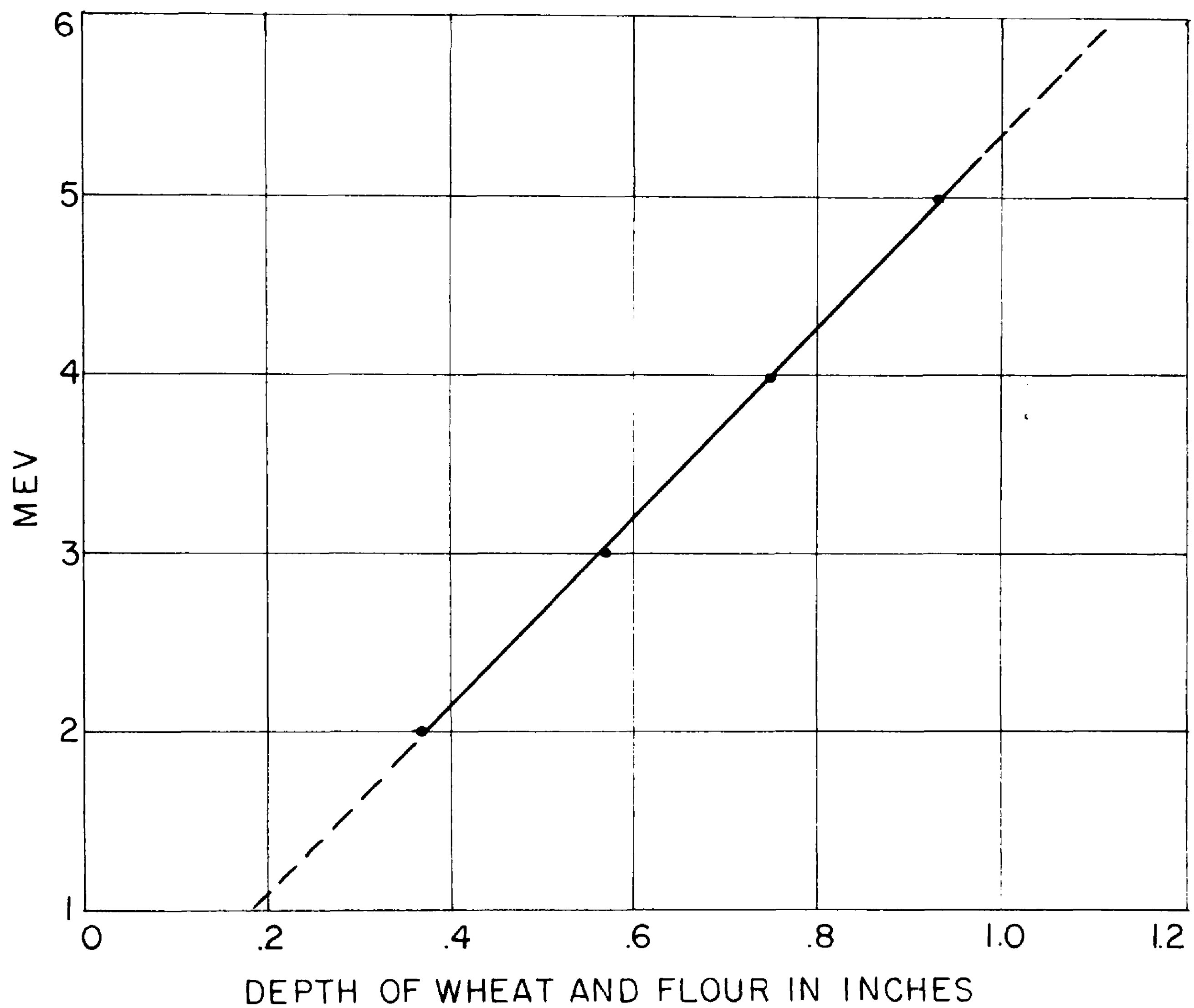


Fig 38A Depth of penetration of accelerated electrons in wheat and flour with a density of .74 gr/cc — — with 60 % of maximum ionization at the top and bottom of the irradiated layer.

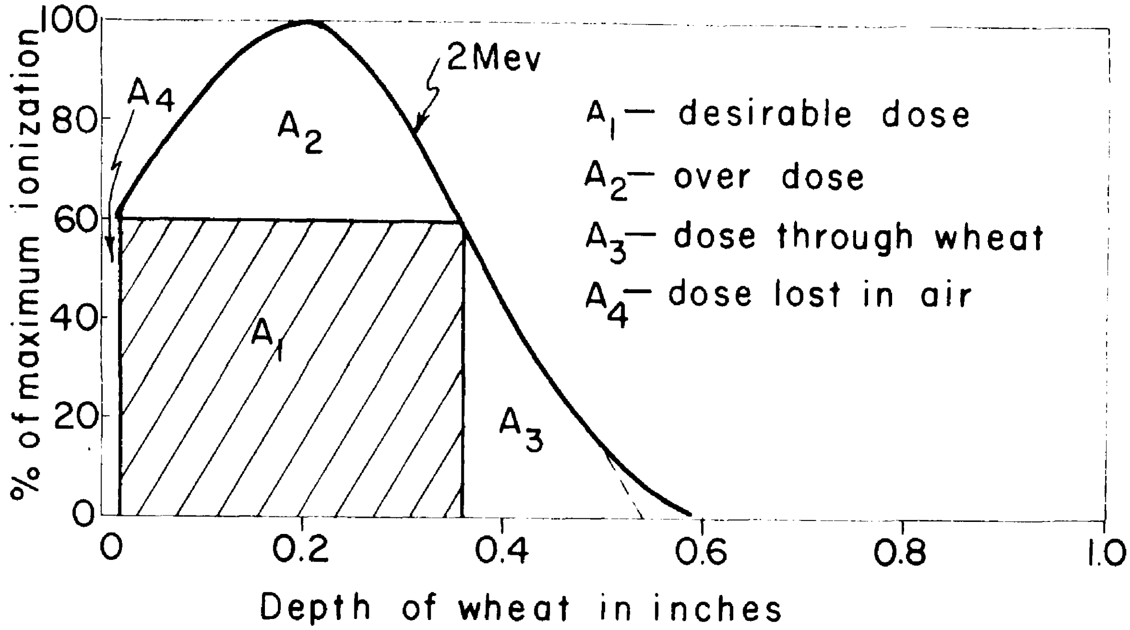


Fig 38B Depth of penetration of 2 Mev accelerated electrons in wheat (density .74 gr/cc) with 60% of maximum ionization at top and bottom layer of wheat.

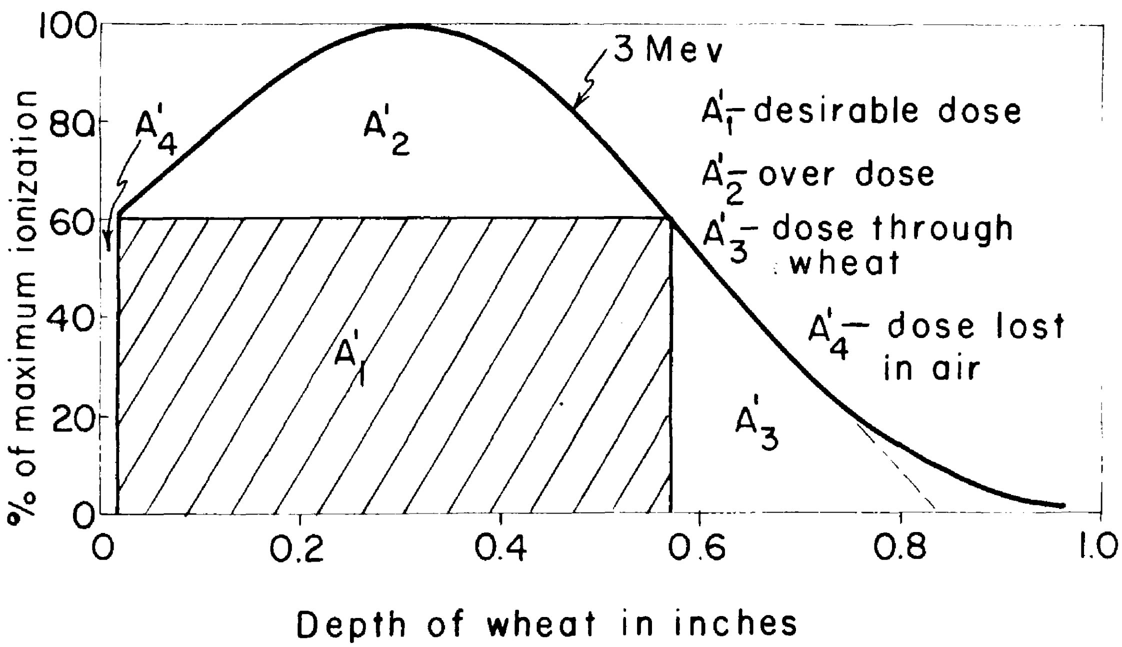


Fig 38C Depth of penetration of 3 Mev accelerated electrons in wheat (density .74 gr/cc) with 60% of maximum ionization at the top and bottom layer of wheat.

of these curves is such that the maximum ionization occurs below the surface of the material irradiated. This is due to the back scattering effect of the electrons.

The area A_1 represents the desirable dose; A_2 represents the over-dose; A_3 is the dose lost through the sample, and A_4 represents the dose lost in the air above the sample. The ideal dose, A_1, should be a value such that A_1 is a maximum with the sum $A_2 + A_3 + A_4$ a minimum. This condition is approximately satisfied when 60 percent of the maximum ionization enters and leaves the sample. Maximum energy can be transferred to the sample, i.e., K_1/R is a maximum in equation (a) and Fig. 36 for 2 Mev electrons by using a depth of product between 0.4 and 0.65 gram per sq cm or say about 0.35 inch of wheat and flour as an upper limit of depth for 2 Mev electrons.

Further Information on Dosage Calculations

An example of calculations used to obtain the exposure time for a dose of 1,000,000 rep of 2 Mev electrons in a stationary 9-cm diameter sample is presented. Suppose that the beam current is 50 microamperes and that the depth of wheat or flour chosen to be irradiated is about 0.65 gram per sq cm (from Fig. 35). From Fig. 36,

$$\frac{K_1}{R} = 1.25, \qquad \text{assume } K_2 = 1 \qquad \text{Then from equation (a)}$$

$$P = \frac{4\ (50 \times 10^{-6})(2 \times 10^{6})\ 1}{\pi\ (9)^2}\ (1.25) = 1.96 \text{ watts per gram}$$

The time required to deliver an average dose of 1×10^6 is

$$\frac{8.38 \text{ joules/gram}}{1.96 \text{ joules/sec/gram}} = 4.27 \text{ sec}$$

By this same formula, with the same conditions, the time required for 500,000; 100,000; and 10,000 rep is 2.13, 0.427, and 0.0427 seconds respectively. By knowing the time required for a given dose to a stationary sample, it is a simple matter to calculate the belt speeds for products to be treated on a conveyor belt. In actual practice the belt speed may be set, which in turn would set the exposure time. If this be the case then the beam current could be adjusted to obtain the desired dose in rep.

Suppose that it is desired to calculate the rate of flour or wheat receiving a dose of 100,000 rep. Assume that a 2 Mev generator is available and that 200 microamperes of beam current is dissipated in the wheat. This would be 400 joules per second or a power of 400 watts. Using the value of 8.38 joules per gram for 10^6 rep, then the rate of flow is about:

$$\frac{400 \text{ joules/sec}}{0.838 \text{ joules/gram}} = 478 \text{ grams per second or}$$

$$\frac{478\ (60)\ (60)}{453.9} = 3800 \text{ pounds per hour}$$

If the dosage be reduced to 10,000 rep, the rate of flow would be 38,000 pounds per hour. The cost of electrical energy, assuming 2¢ per KWH, and a dose of 1×10^5 rep at an efficiency of 10 percent, is about:

$$\frac{400 \text{ watts x 1 hr}}{1000 \text{ x } 0.10} \text{ x } \frac{0.02}{\text{KWH}} \text{ x } \frac{3800}{2000} = 15.2¢/\text{ton or } 0.076¢/100 \text{ lbs}$$

With a dose of 10,000 rep, the cost of energy is about 1.52¢ per ton.

The Distribution of Current Density

Curves for the distribution of 2 Mev cathode rays in a traverse plane 40 cm from the 3-mil aluminum window for the Van de Graaff generator have been presented (2). Data from these curves enable one to calculate the maximum and minimum doses distributed across a given sample. The distribution of the dose across the object may be controlled by selecting the thickness of scattering window, absorber depth, and irradiation distance. The thickness of the scattering window installed in the 2 Mev Van de Graaff generator at The Upjohn Company was chosen so that the distribution of the unscanned cathode ray beam across the samples being irradiated was rather uniform.

It should be pointed out here that when calculating the dose of accelerated electrons on insects in this thesis, the density of the insect was assumed to be 0.74 gram per cc when the insects were mixed with the flour and wheat, and an insect density of 1.0 was assumed when the insects were irradiated in plain dishes with no flour. Under these conditions the actual dose received may or may not be valid since by definition: 1 rep = 83.8 ergs per gram of air at

0° C and 760 mm Hg or about 93 ergs per gram of water or tissue. Perhaps terms such as rei (roentgen equivalent insect) or rew (roentgen equivalent wheat) should have been used, because the insect and wheat are different from water and tissue.

Calculations for Temperature Rise in a Given Sample

The calculations for determining the temperature rise in a given material receiving a dose of accelerated electrons is a straightforward and simple process. The following well known formula is used:

$$Q = W\ (s.h.)\ (T_2 - T_1) \qquad \text{(b)}$$

Suppose it is desirable to calculate the temperature rise for one gram of wheat or flour receiving a dose of 100,000 rep using equation (b) and a value of

Q = 100,000 rep = 0.20 calories per gram

s.h. = 0.4

then:

$$T_2 - T_1 = \frac{Q}{W\ (s.h.)} = \frac{0.20}{0.4(1)} = 0.5^{\circ}\text{ C temperature rise}$$

The temperature rise for one gram of flour receiving a dose of 500,000 rep would be about 2.5 degrees Centigrade.

Tests Conducted

A total of ten tests were conducted using the Van de Graaff generator. These tests include data for one germination test and the two irradiations for the wheat and flour used in the baking tests. Insects were irradiated in the first seven tests. Since the procedure for each test was similar, a general description of procedure will be given for all tests, with a specific procedure for two tests. This description should suffice, since the procedure given, together with the tabulated data for each test, should enable one to repeat the tests.

The insects for all tests were grown in constant temperature, constant humidity incubator in the Entomology Department at Michigan State College. More information will be presented on this phase of the work in the next part of this thesis. The samples for each series of tests were prepared in the Entomology Laboratory (12). After preparation, the samples were placed in an insulated box and transported by car from East Lansing to The Upjohn Company at Kalamazoo, Michigan. The samples were then irradiated and returned to East Lansing the same day and again placed in the incubator. Some observations were made for lethal effects immediately after each test, however, most of the observations were made at various intervals, as is indicated in the data tables for each test.

The First Seven Tests

The data for the first seven tests are presented in Tables 20 through 26 inclusive. A detailed description of tests 2 and 3 is presented below. The procedure for the other tests can be easily determined by observing the general test information together with that given in the data table for each test.

The samples for the granary weevil test three were prepared by placing 50 adults in each of 25 9-cm petri dishes containing 30 grams of Cornell 595 wheat. The wheat had a moisture content of 10 percent wet basis, a density of 0.74 gram per cc, and a specific gravity of 1.33. These samples were then placed in a constant temperature, constant humidity incubator (80° F, 75 percent RH) for about 3 days before treatment to allow sufficient time for the adults to oviposit. The samples were then treated with dosages of 2 million volt unscanned electrons as shown in Table 22. Four petri dishes containing a total of 200 adults were placed on the Van de Graaff generator conveyor belt and received treatments as shown in Table 21A. The dosages were calculated according to the method presented under the section on dosage calculations. Five petri dishes containing a total of 250 adults were used as check or control samples and were not treated. The treated and untreated samples were observed for effects immediately after treatment, 24 hours after treatment, 48 hours after treatment, and one week after treatment.

The procedure for treatment for test two using the *Tribolium confusum* flour beetle differed slightly from the procedure listed above. Twelve samples each containing

100 adult flour beetles and 30 grams of whole wheat were placed in 9-cm petri dishes and irradiated. A total of 5 dosages were used with two petri dishes containing a total of 200 adults receiving each dose. The remaining samples of 200 adults each were used as controls and were not treated. The remainder of the procedure for test two was essentially the same as that listed for the granary weevil in test three.

Results: The complete results for the first seven accelerated electron tests are presented in Tables 20 through 26 inclusive. Bar charts for tests 1, 2, and 3 are presented in Figs. 21, 42, and 43. The effects of granary weevil, *Sitophilus granarius*, infestation on treated (100,000 rep) and untreated samples are shown in Figs. 39A and 39B. The effects of bean weevil, *Acanthoscelides obtectus*, and untreated beans are shown in Figs. 40A and 40B. A summary of the results is also presented here.

Brief summary of results:

1. An electron dose of 10,000 rep will sterilize flour beetle and granary weevil eggs, and this same dose will prevent the adults from reproducing. Thirty percent of flour beetle eggs hatched when irradiated with a dose of 1000 rep.

2. A dose of 5.0×10^5 rep was lethal to 100 percent of adult flour beetles (treated in flour) immediately after

Fig. 39A. Wheat artificially infested with granary weevils, treated with accelerated electrons (100,000 rep) from the Van de Graaff accelerator. Picture taken after an incubation period of about 43 days from date of treatment.

Fig. 39B. Wheat artificially infested with granary weevils, used as a check sample (untreated). Picture taken after an incubation period of about 43 days from date of treatment.

Fig. 40A. Beans artificially infested with bean weevils, treated with accelerated electrons (100,000 rep) from the Van de Graaff accelerator. Picture taken after an incubation period of about 43 days from date of treatment.

Fig. 40B. Beans artificially infested with bean weevils, used as a check sample (untreated). Picture taken after an incubation period of about 43 days from date of treatment.

ACCELERATED ELECTRON TEST 1

Tribolium confusum (Flour Beetle) Adults and Eggs

Sample Number	rep	Number Dead 3 Hours After	Additional Dead After 24 Hours	Additional Dead After 1 Week	Total	Per Cent Dead	Eggs Hatched	Per Cent of Check	Offspring from Treated Adults
1	Check	0	0	0	0	0	112	—	34
2	1.45×10^6	40	0	0	40	100	0	0	0
3	1.45×10^6	40	0	0	40	100	0	0	0
4	1.45×10^6	40	0	0	40	100	0	0	0
5	1.45×10^6	40	0	0	40	100	0	0	0
6	720,000	40	0	0	40	100	0	0	0
7	Check	0	0	0	0	0	16	—	41
8	720,000	40	0	0	40	100	0	0	0
9	720,000	40	0	0	40	100	0	0	0
10	720,000	40	0	0	40	100	0	0	0
11	72,000	0	0	0	0	0	0	0	0
12	72,000	0	1	0	1	2.5	0	0	0
13	Check	0	0	0	0	0	33	—	20
14	72,000	0	2	0	2	5	0	0	0
15	72,000	5	3	0	8	12.5	0	0	0
16	10,000	0	0	0	0	0	0	0	0
17	10,000	0	0	0	0	0	0	0	0
18	10,000	0	1	0	1	2.5	0	0	0
19	Check	0	0	0	0	0	25	—	18
20	10,000	0	0	0	0	0	0	0	0
21	1,000	0	0	0	0	0	13	28	29
22	1,000	0	1	0	1	2.5	16	35	21
23	1,000	0	0	0	0	0	19	41	23
24	1,000	0	0	0	0	0	11	25	19

TABLE 20 Accelerated electron test 1 using Van de Graaff generator at Upjohn Company February 6, 1953. Forty adult Tribolium were placed in 9 cm petri dishes containing 15 grams whole wheat flour on February 3, 1953, which allowed about 2½ days for the adults to oviposit.

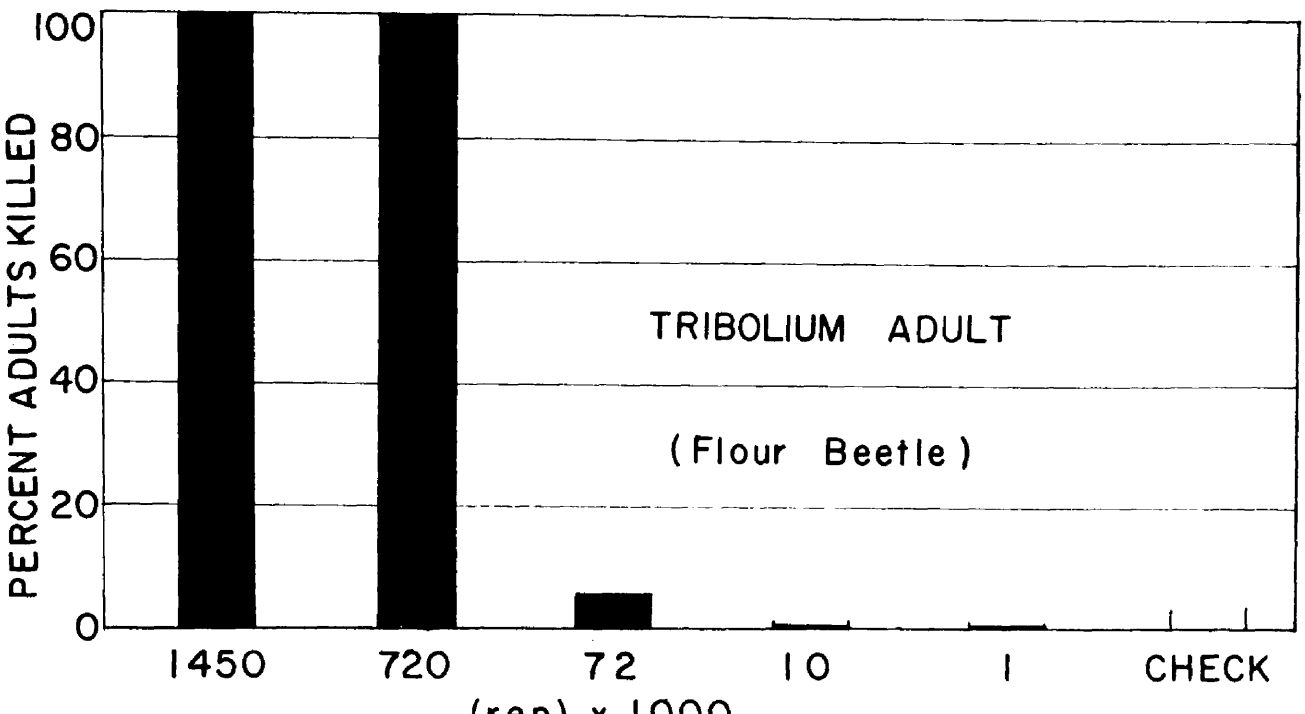


Fig41A

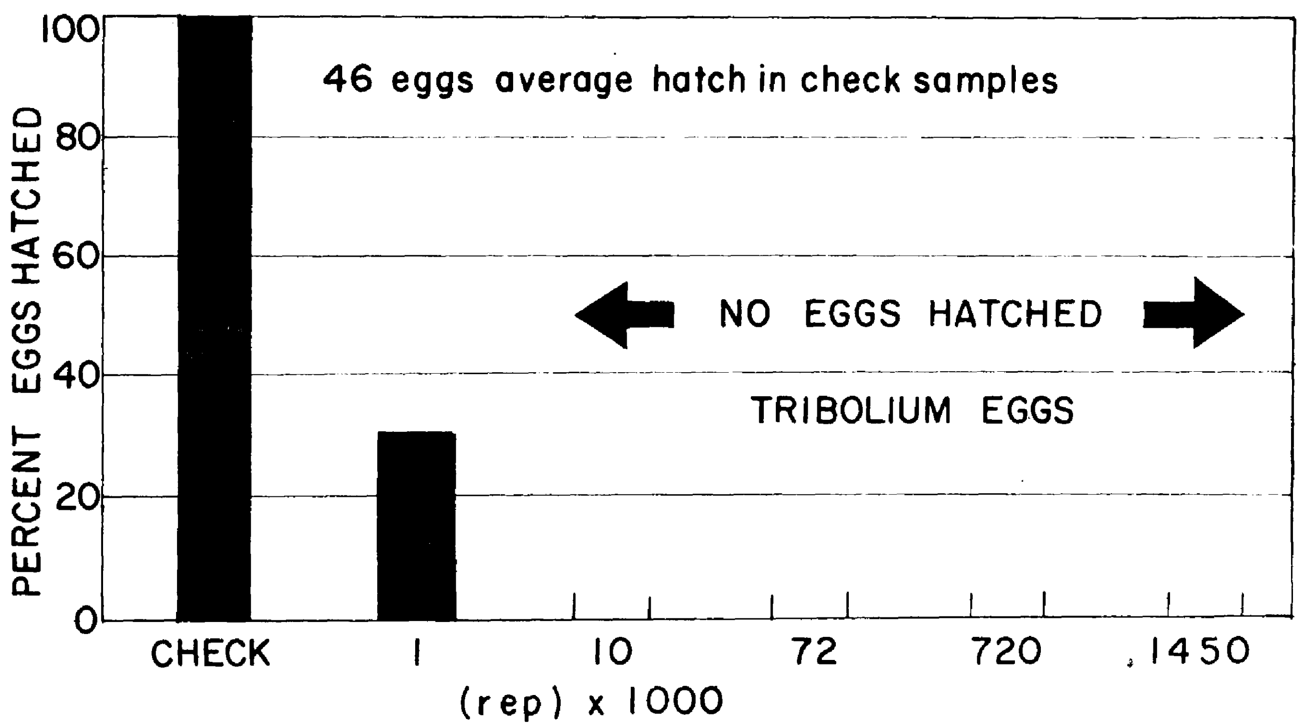


Fig41 B

Fig41 A-B Percent Tribolium confusum adults killed and eggs hatched for accelerated electron test 1 using Van de Graaff generator at UPJOHN CO. Feb 5, 1953 - Data in table 20.

ACCELERATED ELECTRON TEST 2A

Tribolium confusum Adults

Sample Number	rep	Beam Current Microamperes*	Belt Speed Feet Per Minute	Number Dead 1 Hour After	Additional Dead After 24 Hours	Additional Dead After 48 Hours	Additional Dead After 1 Week	Total	Corrected Per Cent
1	1×10^6	26.0	1	100	0	0	0	100	100
2	1×10^6	26.0	1	100	0	0	0	100	100
3	$.5 \times 10^6$	26.0	1	100	0	0	0	100	100
4	$.5 \times 10^6$	26.0	1	100	0	0	0	100	100
5	$.25 \times 10^6$	13.0	1	32	6	30	23	91	90.5
6	$.25 \times 10^6$	13.0	1	19	9	40	27	95	95.0
7	100,000	5.2	8.3	1	0	0	3	4	9.5
8	100,000	5.2	8.3	0	0	1	1	2	9.8
9	50,000	2.6	8.3	0	0	1	0	1	1
10	50,000	2.6	8.3	0	0	0	0	0	0
11	Check	--	--	0	0	1	0	1	1
12	Check	--	--	0	0	0	0	0	0

*Samples 1 and 2 through beam twice to make total beam current 52 microamperes.

TABLE 21A Accelerated electron test 2 using Van de Graaff generator at Upjohn Company, March 13, 1953. One hundred Tribolium adults were placed in 9 cm petri dishes containing 30 grams of whole wheat flour 3 days before test date.

ACCELERATED ELECTRON TEST 2B

Tribolium confusum Eggs

Sample Number	rep	Beam Current Microamperes	Belt Speed Feet Per Minute	Trips Through	Total Beam Current Microamperes	Eggs Hatched After 43 Days	Per Cent of Check
1	1×10^6	26	1	2	52	0	0
2	1×10^6	26	1	2	52	0	0
3	$.5 \times 10^6$	26	1	1	26	0	0
4	$.5 \times 10^6$	26	1	1	26	0	0
5	$.25 \times 10^6$	13	1	1	13	0	0
6	$.25 \times 10^6$	13	1	1	13	0	0
7	100,000	5.2	8.3	1	5.2	0	0
8	100,000	5.2	8.3	1	5.2	0	0
9	50,000	2.6	8.3	1	2.6	0	0
10	50,000	2.6	8.3	1	2.6	0	0
11	Check	--	--	--	--	69	--
12	Check	--	--	--	--	81	--

TABLE 21B Accelerated electron test 2 using Van de Graaff generator at Upjohn Company, March 13, 1953. One hundred adult Tribolium were placed in 9 cm petri dishes containing 30 grams of whole wheat flour 3 days before test date.

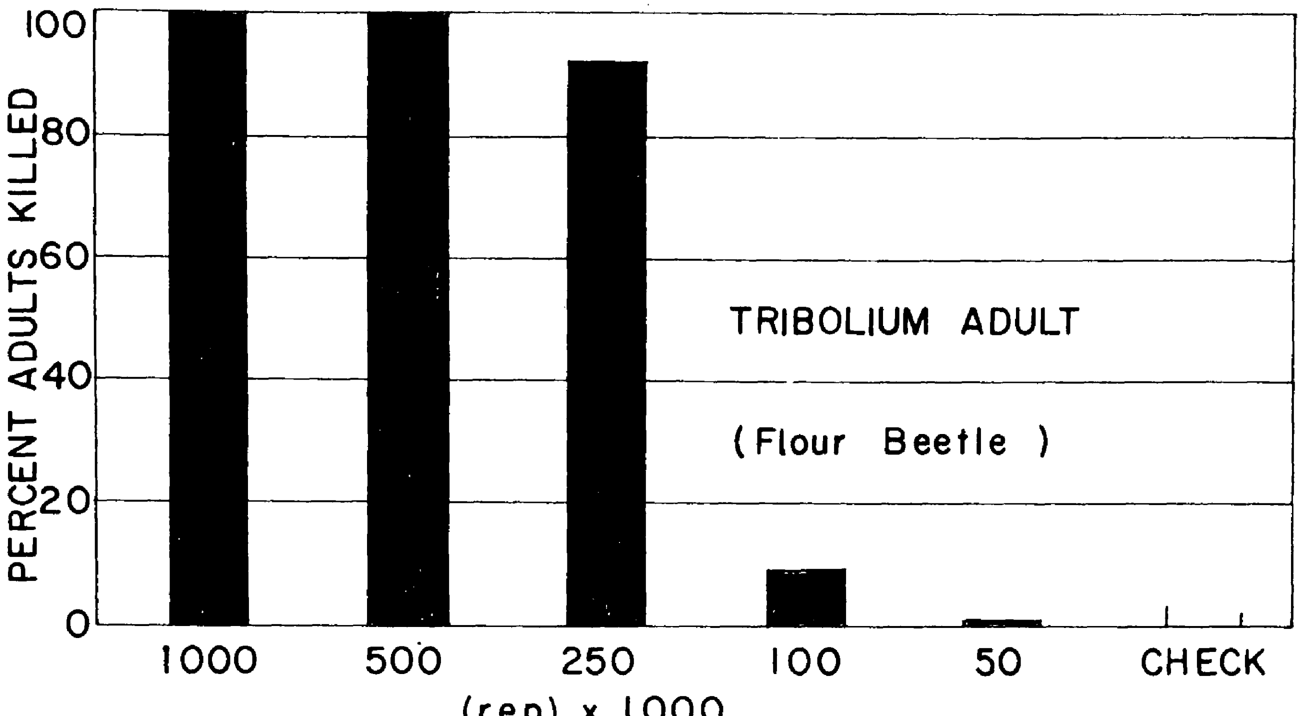


Fig42A

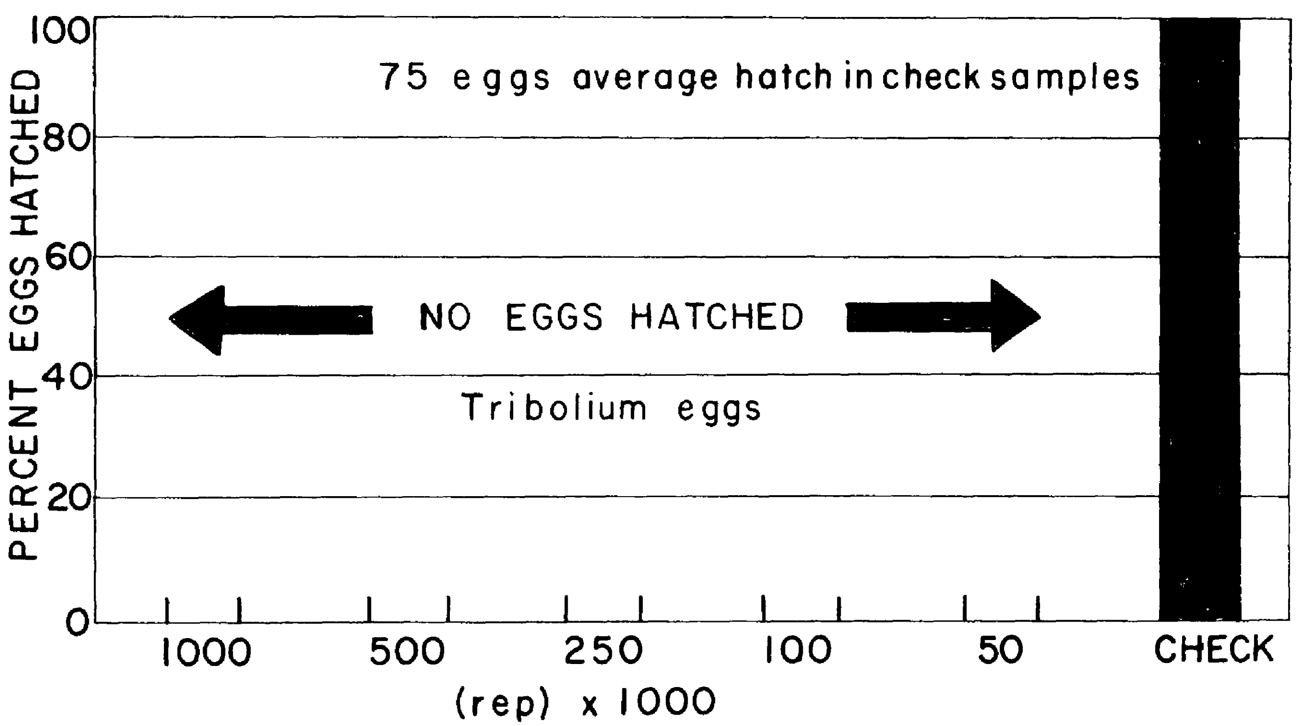


Fig42B

Fig42 A-B Percent Tribolium confusum adults killed and eggs hatched for accelerated electon test 2 using Van de Graaff generator at UPJOHN CO. March 13, 1953 Data in tables 21A and 21B.

ACCELERATED ELECTRON TEST 3

Sitophilus granarus (Granary Weevil) Adults and Eggs

Sample Number	reps	Beam Current Microamperes	Number dead 1 hour after	Additional dead after 24 hours	Additional dead after 48 hours	Additional dead after 1 week	Total Dead	Corrected percent dead	Eggs Hatched	Percent of check
1	1×10^6	79*	40	0	0	0	40	100	0	0
2	1×10^6	79*	40	0	0	0	40	100	0	0
3	1×10^6	79*	40	0	0	0	40	100	0	0
4	1×10^6	79*	40	0	0	0	40	100	0	0
5	$.5 \times 10^6$	79	40	0	0	0	40	100	0	0
6	$.5 \times 10^6$	79	37	2	1	0	40	100	0	0
7	$.5 \times 10^6$	79	40	0	0	0	40	100	0	0
8	$.5 \times 10^6$	79	40	0	0	0	40	100	0	0
9	$.25 \times 10^6$	40	0	2	25	13	40	100	0	0
10	$.25 \times 10^6$	40	2	5	30	3	40	100	0	0
11	$.25 \times 10^6$	40	0	7	24	9	40	100	0	0
12	$.25 \times 10^6$	40	0	3	27	10	40	100	0	0
13	$.10 \times 10^6$	16	0	0	20	7	27	66	0	0
14	$.10 \times 10^6$	16	0	0	27	12	39	97.4	0	0
15	$.10 \times 10^6$	16	0	0	15	20	35	87.4	0	0
16	$.10 \times 10^6$	16	0	0	10	23	33	80.0	0	0
17	$.50 \times 10^5$	8	0	0	2	5	7	16.5	0	0
18	$.50 \times 10^5$	8	0	0	7	3	10	23.6	0	0
19	$.50 \times 10^5$	8	0	0	3	2	5	11.4	0	0
20	$.50 \times 10^5$	8	0	1	1	2	4	8.9	0	0
21	Check	--	0	0	0	1	1	2.5	91	--
22	Check	--	0	0	0	0	0	0	135	--
23	Check	--	0	0	0	1	1	2.5	106	--
24	Check	--	0	0	0	0	0	0	86	--
25	Check	--	0	0	0	0	0	0	99	--

* Samples 1-4 through beam twice.

Table 22 Accelerated electron test 3 using Van de Graaff generator at Upjohn Company, March 13, 1953. Forty adult **Sitophilus granarus** placed in 9 cm petri dishes containing 30 grams of Cornell wheat on March 10, 1953. This allowed about 3 days for the adults to oviposit.

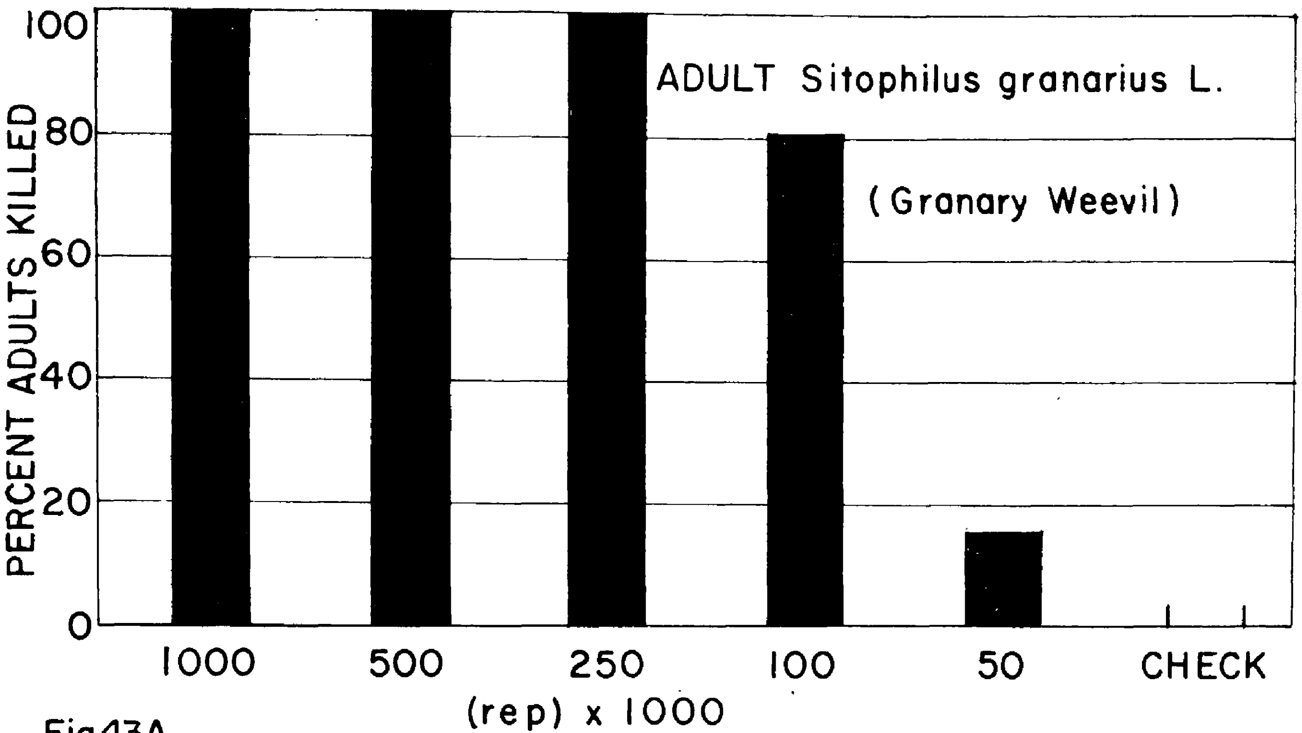


Fig 43A

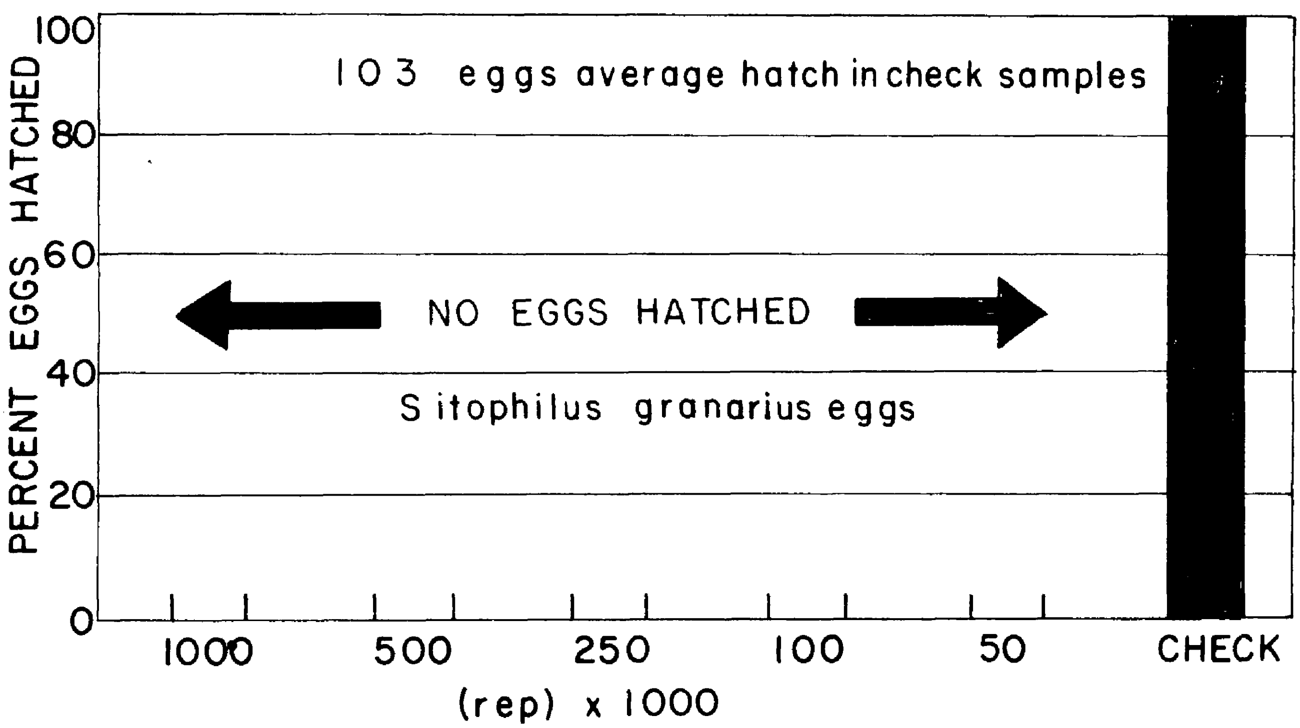


Fig 43B

Fig 43 A-B Percent Sitophilus granarius adults killed and eggs hatched for accelerated electron test 3 using the Van de Graaff generator at UPJOHN CO. March 13, 1953 - Data in table 22.

Accelerated Electron Test 4

Tribolium confusum (flour beetle)

Sample Number	Dose in rep	No. dead immediately after test	Additional dead 24 hours after test	Additional dead 48 hours after test	Additional dead 1 week after test	Total dead	Offspring from adults after 30 days
1	500,000	50	-	-	-	50	0
2	500,000	50	-	-	-	50	0
3	500,000	50	-	-	-	50	0
4	500,000	50	-	-	-	50	0
5	400,000	50	-	-	-	50	0
6	400,000	50	-	-	-	50	0
7	400,000	50	-	-	-	50	0
8	400,000	50	-	-	-	50	0
9	300,000	50	-	-	-	50	0
10	300,000	50	-	-	-	50	0
11	300,000	50	-	-	-	50	0
12	300,000	50	-	-	-	50	0
13	200,000	50	-	-	-	50	0
14	200,000	50	-	-	-	50	0
15	200,000	50	-	-	-	50	0
16	200,000	50	-	-	-	50	0
17	100,000	19	1	1	28	50	0
18	100,000	18	0	0	28	46	0
19	100,000	11	0	0	37	48	0
20	100,000	16	2	2	30	50	0
21	Check	0	0	0	0	0	61
22	Check	0	0	0	0	0	53
23	Check	0	0	0	1	1	65
24	Check	0	0	0	0	0	54

Table 23 Accelerated electron test 4 using the Van de Graaff generator at Upjohn Co. April 20, 1953. Fifty adult Tribolium confusum were irradiated in 9 cm petri dishes with no flour.

Accelerated Electron Test 5

Tribolium confusum (flour beetle) larvae

Sample Number	Dose in rep	Activity after test	1 week after	2 weeks after	3 weeks after	4 weeks after	dead larvae after 5 wks.	alive adults after 5 weeks	offspring from adults
1	75,000	—	—	—	—	—	14	0	0
2	75,000	—	—	—	—	—	30	0	0
3	75,000	—	—	—	—	—	40	0	0
4	75,000	—	—	—	—	—	58	0	0
5	50,000	—	—	—	—	—	50	0	0
6	50,000	—	A	—	A	A	67	8	0
7	50,000	—	—	—	—	—	19	0	0
8	50,000	A	A	A	—	—	81	0	0
9	25,000	—	—	—	—	—	39	0	0
10	25,000	—	A	A	A	A	20	4	0
11	25,000	—	A	—	—	—	31	0	0
12	25,000	A	AA	A	AA	A	52	18	0
13	10,000	A	A	—	A	A	28	2	0
14	10,000	A	A	—	—	—	17	0	0
15	10,000	A	A	A	—	—	25	0	0
16	10,000	A	A	—	—	—	43	0	0
17	1,000	AA	AA	AA	A	—	61	0	0
18	1,000	AA	AA	AA	A	A	48	2	7
19	1,000	A	AA	A	A	A	28	2	0
20	1,000	AA	AA	A*	A	A	33	6	31
21	Check	AAA	AAA	AAA*	AAA	AAA	0	80**	80
22	Check	AAA	AAA	AAA*	AAA	AAA	0	32	97
23	Check	AAA	AAA	AAA*	AAA	AAA	0	49	91
24	Check	AAA	AAA	AAA*	AAA	AAA	0	60	102

Legend: —......No Activity A.....Little Activity
AAA......Very active *.....Adults began to appear
AA......Active **.....Only 30 adults tested

Table24 Accelerated electron test 5 using the Van de Graaff generator at Upjohn Co. April 20, 1953. Tribolium larvae were irradiated in 9 cm petri dishes containing 13.5 grams of whole wheat flour.

ACCELERATED ELECTRON TEST 6

Sitophilus granarius adults (granary weevils)

Sample Number	Dose in rep	No. dead immediately after test	No. dead 24 hours after test	No. dead 48 hours after test	No. dead 1 week after test	Total
1	250,000	50	-	-	-	50
2	250,000	50	-	-	-	50
3	250,000	50	-	-	-	50
4	250,000	50	-	-	-	50
5	125,000	0	8	4	38	50
6	125,000	0	6	9	35	50
7	125,000	0	9	2	39	50
8	125,000	0	10	8	32	50
9	75,000	0	6	4	40	50
10	75,000	0	2	3	45	50
11	75,000	0	5	2	43	50
12	75,000	0	1	5	44	50
13	50,000	0	2	0	36	38
14	50,000	0	0	1	41	42
15	50,000	0	0	0	30	30
16	50,000	0	0	1	33	34
17	10,000	0	0	0	13	13
18	10,000	0	0	0	7	7
19	10,000	0	0	0	8	8
20	10,000	0	0	0	9	9
21	-	0	0	0	2	2
22	-	0	0	0	1	1
23	-	0	0	0	1	1
24	-	0	0	0	0	0

Table25 Accelerated electron test 6 using the Van de Graaff generator at Upjohn Company April 20, 1953. Fifty adult granary weevils were irradiated in 9 cm petri dishes containing no wheat. There were no offspring from the adults that survived except for the check samples.

Accelerated Electron Test 7

Acanthoscelides obtectus Say (bean weevil) adults

Sample Number	Dose in rep	No. dead immediately after test	No. dead 24 hours after test	No. dead 48 hours after test	No. dead 1 week after test	Total dead after one week
1	500,000	15	-	-	-	15
2	500,000	15	-	-	-	15
3	250,000	13	2	0	0	15
4	250,000	10	4	0	0	14
5	100,000	1	9	4	1	15
6	100,000	2	5	4	4	15
7	10,000	1	5	1	8	15
8	10,000	0	4	8	3	15
9	Check	0	0	2	1	3
10	Check	0	0	1	3	4

Table26 Accelerated electron test 6 using the Van de Graaff generator at Upjohn Company April 20, 1953. Fifteen adult bean weevils were irradiated in 9 cm diameter petri dishes containing 20 grams of Michigan navy beans.

treatment, whereas a dose of 2.5×10^5 rep (treated in wheat) was lethal to 100 percent adult granary weevils immediately after treatment. A dose of 2.5×10^5 rep was lethal to 92 percent of adult flour beetles one week after treatment and a dose of 1×10^5 rep was lethal to 82 percent of adult granary weevils one week after treatment.

3. An electron dose of 75,000 rep was lethal to 100 percent of flour beetle larvae (treated in flour) one week after treatment. The adult flour beetles which emerged from larvae that had received a dose of 10,000 rep did not produce any offspring.

4. An electron dose of 2×10^5 rep was lethal to 100 percent of adult flour beetles (treated in plain petri dishes, assuming a density of one), immediately after treatment. A dose of 1×10^5 rep was lethal to 98 percent of adult four beetles (treated in plain petri dishes) one week after treatment. A dose of 75,000 rep was lethal to 100 percent of granary weevils (treated in plain petri dishes, assuming a density of one), one week after treatment.

5. An electron dose of 10,000 rep was lethal to 100 percent of adult bean weevils one week after treatment.

Baking Tests

Procedure and results: Preliminary baking tests were conducted using about 38 pounds of whole wheat flour irradiated with 5×10^5 rep and about 38 pounds of whole wheat flour made from irradiated Cornell 595 wheat receiving a treatment of 5×10^5 rep. The wheat and whole wheat flour were irradiated in 46.7 x 15.3 x 2.75 cm aluminum trays, placed on the conveyor belt of the Van de Graaff generator. The depth of the flour and wheat for each test was about 0.6 gram per sq cm. The density of the wheat and flour was about 0.74 gram per cc.

The treated flour was baked into a one hundred percent whole wheat loaf. The flour from the treated wheat was more nearly the consistency of a meal and required some white flour for satisfactory fermentation. This was the result of the grinding. Both products produced a satisfactory loaf of bread though there appeared to be some effect on tenderness, flavor, and moistness in the bread from treated flour or grain. Further baking tests are planned.

Bread baked from 75 percent treated whole wheat flour and 25 percent plain flour is shown in Fig. 44A, left. The treated whole wheat flour was ground from wheat irradiated with a dose of 5×10^5 rep. Bread baked from 75 percent untreated whole wheat flour and 25 percent plain white flour is shown in Fig. 44A, right. Bread baked from 100 percent whole wheat flour irradiated with an electron dose of 5×10^5 rep is shown in Fig. 44B, left. Bread baked from 100 percent untreated whole wheat flour is shown in Fig. 44B, right.

Fig. 44A. Bread made from 75 percent whole wheat flour made from treated (5×10^5 rep) wheat and 25 percent plain white flour.

Fig. 44B. Bread made from 100 percent whole wheat treated (5×10^5 rep) and untreated flour.

Germination Tests

<u>Procedure and results:</u> Tests indicate that germination may not be a criterion for determining the effects of accelerated electrons on wheat. The majority of the samples tested with doses of 5×10^5, 2.5×10^5, 1×10^5, and 1×10^4 rep germinated when wrapped in a damp towel; however, no emergence was obtained when the seeds receiving a dose of 1×10^5 rep or above were planted in a greenhouse. Seeds receiving 1×10^4 rep were definitely retarded in growth as compared to untreated seed growth two weeks after emergence. The effect of two doses on the growth of wheat is shown in Fig. 45. In Fig. 45, left, Cornell 595 treated and untreated wheat is shown two weeks after emergence. The wheat receiving a dose of 1×10^5 rep did not emerge and grow under the same conditions of moisture and temperature as the untreated wheat. The Cornell 595 wheat irradiated with an electron dose of 1×10^4 rep, Fig. 45, left, did emerge and grow under the same conditions of moisture and temperature as the untreated wheat, however, plants from the treated seed appeared to be retarded in growth. The germination results for the beans tested were essentially the same as for the wheat. The growth of treated and untreated beans is shown in Fig. 45, right.

Fig. 45. Growth of treated and untreated Cornell 595 wheat (left) and Michigan Navy beans (right) two weeks after planting in greenhouse.

Literature Cited

(1) Trump, J. G. and Van de Graaff, R. J., "Irradiation of Biological Materials by High-energy Roentgen Rays and Cathode Rays", Journal of Applied Physics 19(7), July 1948.

(2) Trump, J. G., Wright, K. A., and Clarke, A. M., "Distribution of Ionization in Materials Irradiated by Two- and Three-million-volt Cathode Rays", Journal of Applied Physics, 21(4), April 1950.

(3) Burrill, A. E. and Gale, A. J., "Electron Beam Sterilized Food and Drugs", Electronics, Nov. 1952.

(4) Dunn, C. G., Campbell, W. L., Fram, H., and Hutchins, A., "Biological and Photo-chemical Effects of High Energy Electrostatically Produced Roentgen Rays and Cathode Rays", Journal of Applied Physics 19(7), July 1948.

(5) Proctor, B. E. and Goldblith, S. A., "Electromagnetic Radiation Fundamentals and Their Application in Food Technology", Advances in Food Research, Vol. III, E. M. Mark and G. P. Stewart, ed., Academic Press, Inc., New York, N.Y., 1951, 78 pp., containing 174 individual references.

(6) Goldblith, S. A., Proctor, B. E., and Hammerle, O. A., "Evaluation of Food Irradiation Procedures", Industrial and Engineering Chemistry, Feb. 1952, pp. 310-314.

(7) Urbain, W. M., "Facts about Cold Sterilization", Parts I, II, Food Engineering, March and April 1953.

(8) Yeomans, A. H. and Rogers, E. E., "The Second Experiment Using the Capacitron Treatment on Various Insects", Mimeograph Special Report No. IN2-21, Bureau of Entomology, USDA, January 1950.

(9) Huber, W., "Radiation Sterilization", Drug and Allied Industries, November 1952.

(10) Proctor, B. E. and Goldblith, S. A., "Food Processing with Ionizing Radiations", Food Technology 5(9).

(11) Evans, R. D., Nucleonics 1:39, October 1947.

(12) Taboada, Oscar, "Some Effects of Radiant Energy on The Beetles, Tribolium confusum, Duv., Sitophilus granarius (L.); and Acanthoselides obtectus (Say), Thesis for M.S. Degree, Department of Entomology, Michigan State College, 1953.

Related Literature

(1) Lea, D. E., "Actions of Radiations on Living Cells", MacMillan Company, New York, N.Y., 1947.

(2) Proctor, B. E. and Goldblith, S. A., "Effect of High-voltage X-rays and Cathode Rays on Vitamins (Niacin)", Nucleonics, August 1948, pp. 32-43.

(3) Proctor, B. E. and Goldblith, S. A., "The Effect of High-voltage X-rays and Cathode Rays on Vitamins (Riboflavin and Carotene)", Nucleonics, August 1949.

(4) Brasch, A., Huber, W., et al., "Action of High Intensity Electrons on Biological Objects", Proceedings of Rudolf Virchow Medical Society, Vol. 8, Brooklyn Medical Press, Brooklyn, N.Y., 1949.

(5) Proctor, B. E. and Goldblith, S. A., "Effect of Soft X-rays on Vitamins (Niacin, Riboflavin, and Ascorbic Acid)", Nucleonics, September 1949.

(6) Robinson, R. F., Phillips, M. D., and Nagelsen, M. G., "A Brief Bibliography on the Effects of X-ray on Bacteria", Battelle Memorial Institute, 1951, contains 178 references.

(7) High Voltage Engineering Corporation, "Bulletins D and D-1 - High-voltage Electron Sterilization", 7 University Road, Cambridge 38, Mass., 1951, 1952.

(8) Corson, M., Proctor, B. E., Goldblith, S. A., Hogness, J. R., and Langham, W. H., "The Effect of Supervoltage Cathode Rays on p-Aminobenzoic Acid and Anthranilic Acid Labeled with C^{14}", Archives of Biochemistry and Biophysics 33(2), 1951.

(9) Sparrow, A. H. and Rubin, B. A., "Effects of Radiation on Biological Systems", Bulletin BNL-97, Technical Information Services, AEC, Oak Ridge, Tennessee, 1951, 53 pp.

(10) Stanford Research Institute, "Industrial Uses of Radioactive Fission Products, A Report to the United States Atomic Energy Commission", Stanford, California, 1951, 102 pp.

(11) Bhatia, D. S. and Proctor, B. E., "Effects of High-voltage Cathode Rays on Aqueous Solutions of Histidine Monohydrochloride", The Biochemical Journal 49(4), 1951.

(12) "Death Rays for Bacteria", Industrial and Engineering Chemistry, March 1951, p. 17A.

(13) Proctor, B. E. and Goldblith, S. A., "A Critical Evaluation of the Literature Pertaining to the Application of Ionizing Radiations to the Food and Pharmaceutical Fields", Technical Report No. 1, prepared under Contract No. AT(30-1)-1164 with the United States Atomic Energy Commission, January 1952.

(14) Astrack, A., Sorbye, O., Brasch, A., and Huber, W., "Effect of High Intensity Bursts Upon Various Vegetable and Fish Oils", Food Research 17(6):571-583, 1952.

(15) Trump, J. G., "Electron Sterilization", Machlett Cathode Press, Machlett Laboratories, Springdale, Connecticut, Winter issue 1951-1952.

(16) Proctor, B. E., Goldblith, S. A., et al., "Biochemical Prevention of Flavor and Chemical Changes in Foods and Tissues Sterilized by Ionizing Radiation", Food Technology, July 1952, pp. 237-242.

(17) "X-rays, Radioactivity and Electrons", Technical Bulletin D-2, High Voltage Engineering Corporation, Cambridge, Mass., 1952.

(18) Symposium on Radiobiology, sponsored by AEC and ONR, held at Oberlin College, June 14-18, 1950. John Wiley & Sons, New York, N.Y., 1952, 465 pp.

(19) Proctor, B. E. and Goldblith, S. A., "Prevention of Side Effects in Sterilization of Foods and Drugs by Ionizing Radiations", Nucleonics 10(4), April 1952.

(20) United States Atomic Energy Commission, "List of Research Reports for Sale", Office of Technical Services, Department of Commerce, Washington 25, D.C. (Many of the large number of reports listed in this bibliography are directly pertinent to irradiation sterilization.)

(21) Brownell, L. E. *et al.*, "Sterilizing Foods by Cold Gamma Rays", Paper presented before American Society of Refrigeration Engineers, Atlanta, Georgia. 1952.

(22) Lawrence, C. A., "Effect of Cobalt-60 Gamma Radiation on Microorganisms", *Nucleonics*, January 1953, pp. 9-11.

(23) "Utilization of Gross Fission Products, Project Report 4", Engineering Research Institute, University of Michigan, March 1953, 112 pp.

(24) Proctor, B. E. *et al.*, "Elimination of *Salmonella* in Whole Egg Powder by Cathode Ray Irradiation of Egg Magma Prior to Drying", *Food Technology*, July 1953.

PART IX

CULTURE OF INSECTS FOR EXPERIMENTS

Only a brief description of the procedure used with the insects is presented here. A more detailed discussion of this subject will be found in a thesis by Taboada (1). The insects for all tests reported in this thesis were reared in the Entomology Department Laboratory of Michigan State College. Pictures of the constant temperature, constant humidity incubators used for rearing the insect specimens are presented in Figs. 46A and 46B.

The bean weevil, flour beetle and granary weevil reproduce rapidly at an incubator temperature of 75 to 80° F and a relative humidity of about 70 percent. A saturated solution of sodium chloride in an open pan on the bottom shelf of the incubator maintained the relative humidity at about 70 percent. A culture of the above insects were maintained in the incubators during the test period.

The definition of the word <u>lethal</u> in this work is taken to mean death of the exposed insect immediately or some time after exposure to electromagnetic energy or accelerated electrons.

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1. Taboada, Oscar, "Some Effects of Radiant Energy on the Beetles, <u>Tribolium confusum</u>, Duv., <u>Sitophilus granarius</u>, (L.), and <u>Acanthoscelides obtectus</u> (Say)", Unpublished M.S. Thesis, Department of Entomology, Michigan State College, 1953.

Fig. 46A. View of a constant temperature, constant humidity oven used to incubate insects. Saturated NaCl solution was maintained in the bottom of the oven in order to give 70 percent RH at 75° F.

Fig. 46B. View of three insect incubators in an air conditioned room in the Natural Science Building, Michigan State College.

THE "ENTOLATOR" PROCESS FOR DESTROYING INSECTS

The "Entolator" process is a mechanical method of killing insects in cereal products. Although mechanical methods for destroying insects were not a part of this investigation, it was felt advisable to describe this process briefly. This process may be more practical and more economical for destroying insects in certain products than any electronic process which has been developed to date. All forms of insect life have been killed in flour, wheat, and other cereal products by passing these products through the "Entolator" machine. The insects are killed by mechanical impact, and the insect fragments are then removed by aspiration. This process is now in use in a number of modern flour mills. Up to 15,000 pounds of flour per hour can be treated with a 7.5 hp unit. Breaking or cracking of wheat berries may be excessive when wheat is treated with this machine at certain critical moisture contents.

"The "Entolator" device is a centrifugal machine, manufactured by the Safety Car Heating and Lighting Company of New Haven, Connecticut. Further information on the "Entolator" process may be found in the following references:

1. Cotton, R. T. and Frankenfeld, J. C., "Mechanical Force for the Control of Flour Mill Insects", American Miller, October 1942.

2. Cotton, R. T., "Producing Insect Free Flour", Northwestern Miller, April 11, 1945.

3. Hibbs, A. N., and Dobbs, R. B., "Continuous Insect Infestation and Insect Fragment Control", Modern Sanitation, February 1950.

GENERAL SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDY

Much attention was given to the status of the use of radiant energy for controlling insects by A. H. Yeomans who summarized much of the previous research in The 1952 Yearbook of Agriculture. This summary is based on the results of this study as well as results from earlier studies.

A number of investigators have made worthwhile contributions to electrical insect control by developing the electrical insect trap, the electric fly screen, etc. Other inventors and investigators have proposed various electrical equipment for insect control. Most of them were probably sincere in their efforts, but some equipment was undoubtedly designed to fool the public. One machine, which is nothing more than a resistance coupled amplifier, has been used recently to fool farmers into believing that various insecticides could be broadcast by means of radio waves. At least one farmers' organization actually paid money into the development and use of the machine. There is no scientific evidence, hypothesis, or theory which hints that such a machine will work, and the inventors of the process have not demonstrated that the process is effective.

In analyzing any electrical insect control problem, the following points merit consideration:

1. The effect of electromagnetic energy (including radio waves, microwaves, infrared, and ultraviolet up to a frequency equivalent to a wavelength of about 2880 Angstroms) on living tissue is a heating effect. The effect of electromagnetic energy (including ultraviolet energy with a wavelength of less than 2880 Angstroms, x-rays and gamma rays) on tissue is chemical in nature with some heating effect.

2. No particular resonance effect due to radio waves or microwaves has been observed in tissue. The only effect observed was that of heating caused by molecular agitation. There does not appear to be any particular frequency that would have selective effects on insects.

3. The tremendous amount of energy required to kill insects in free space with electromagnetic waves from an antenna would be so high as to make this process impractical. The high field strengths required would undoubtedly cause a corona discharge which would heat the plants as well as other animals in the area.

4. Radio frequency dielectric heating between the plates of a condenser is an excellent process for penetrating into non-conductors and causing high temperatures through the mass in a short time. Some machines have been developed which will penetrate as much as one foot or more of wheat, and cause a temperature rise of 100° F in a few seconds.

Wheat, flour, and other similar products are good absorbers of radio frequency dielectric energy. The hypothesis that there would be selective heating between the wheat and the insects in the wheat does not appear to have merit, because it was necessary to raise the temperature of the mass to the lethal temperature of the insect before a 100 percent kill was obtained. The cost of energy and equipment for the dielectric process, for treating large masses of grain, as compared to the cost of conducted energy from a coal furnace, would make this process impractical to use for insect control at the present time.

5. Infrared energy can be used to kill insects, provided that the lethal temperature of the insect is obtained. Since infrared energy has only superficial penetration into matter, and a relatively high cost of operation per pound of product heated, these facts will limit the use of infrared energy for insect control.

6. It is a well known fact that visible light and ultraviolet light will attract insects. It has been found that the optimum wavelength for attracting insects is about 3600 Angstroms. This happens to be about the optimum wavelength for photochemical effects. Visible and ultraviolet light can be used to attract insects to an area, but some means such as electric high voltage grids or some type of mechanical trap must be used to kill the insect. It was found that ultraviolet energy will sterilize insect eggs,

however, since ultraviolet has only superficial penetration into wheat, flour, and many other materials, this fact will make it impractical to use ultraviolet as a direct lethal agent for insects. Furthermore, the present sources for producing ultraviolet energy, such as carbon arcs and gaseous discharge tubes are relatively inefficient producers of ionizing ultraviolet energy. Even if enough ionizing energy could be obtained from these sources, it would be difficult to separate the effects caused by heating and those caused by ionization.

7. X- and gamma rays are electromagnetic radiation, and have the same effect on biological tissue. X-rays have been used to create short and long range mutations in insects. This process is mostly of academic interest and does not appear to have any practical application as far as insect control is concerned. The generation of x-rays is a very inefficient process. Even though x-rays do have relatively deep penetration into materials which insects infest, it is likely that a dose sufficiently strong to cause short time lethal effects to the insects will also cause damage to the material which the insects infest. The inefficiency of x-ray generation, together with the fact that x-rays radiate in a more or less spherical pattern, will make it very improbable that x-rays can be efficiently used for economical insect control.

8. Somewhat the same problems exist with gamma

radiation as with x-rays. Energy from gamma radiation has been used to kill insects as well as molds and bacteria. Gamma radiation is emitted from disintegrating radioactive isotopes such as cobalt 60. Cobalt 60 has a half life of 5.3 years and may be formed by bombarding ordinary cobalt 59 with neutrons in an atomic reactor.

When radiation from long rods of cobalt 60 are used to irradiate food and other products, cylindrical coordinates must be used in order to effectively utilize all the gamma radiation. The problem of adapting this type of radiation so that food can be irradiated on conveyor belts would appear to be complex. Perhaps passing the food around the radioactive material in cylindrical bands or spirals would be an effective process. If the conveying, shielding, and cost of effective isotopes can be worked out satisfactorily, this process would appear to have significant possibilities in the future.

9. The problem of effectively utilizing accelerated electrons for treating foods appears to be closer to being solved than for other types of radiation. It was found in this study that a dose of 10,000 rep will sterilize insect eggs and prevent adults from reproducing. Higher doses were required to kill adults. Accelerated electrons can be efficiently applied to products on a conveyor belt, and there is no radioactivity involved at energies below 21 Mev. Accelerated electrons present interesting possibilities for

food preservation, such as the surface treatment of meats, bread, and vegetables, and the penetration into such products as flour and wheat. Color and flavor changes may vary greatly with the product treated, but means of minimizing certain of the undesirable changes have been found. The installation and maintenance costs involved may limit the extent of the use of accelerated electrons in the immediate future, but this fact should not stop research workers from investigating further the use of accelerated electrons in food processing.

10. In the final analysis the application of any electrical method for destroying insects in products must be better than or as good as present mechanical methods of performing the same operation. One fact which must not be overlooked is that even if insects can be killed in stored products by electrical means, some mechanical means must be used to remove the insect fragments before the food can be lawfully sold for human consumption.

11. It is recommended that further studies be conducted with accelerated electrons in order to determine the effects on the nutritional values of wheat, flour, and other foods, with doses less than 500,000 rep. Further information is needed on the effects of treating the surface of meats and vegetables in order to kill molds and bacteria.

12. Somewhat the same information is needed for gamma radiation as suggested for accelerated electrons. The

technique and equipment used for the two studies would be different as gamma ray treatment would require special shielding, conveying, and exposure time techniques.

APPENDIX

13736. Adulteration of flour. U. S. v. 108 Bags * * *. (F. D. C. No. 25051. Sample No. 23233–K.)

LIBEL FILED: July 21, 1948, Western District of Louisiana.

ALLEGED SHIPMENT: On or about May 20, 1948, from Fort Worth, Tex.

PRODUCT: 108 25-pound bags of flour at Crowley, La.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the article consisted in whole or in part of a filthy substance by reason of the presence of weevils. (The article was adulterated while held for sale after shipment in interstate commerce.)

DISPOSITION: August 22, 1948. Helo Bros. Wholesale Co., Crowley, La., claimant, having consented to the entry of a decree, judgment of condemnation was entered and the product was ordered released under bond to be denatured for use as hog feed, under the supervision of the Federal Security Agency.

13715. Adulteration of corn meal. U. S. v. Lynchburg Milling Co. and Thomas K. Scott. Plea of nolo contendere. Corporation and individual each fined $75. (F. D. C. No. 25305. Sample Nos. 40212–K to 40214–K, incl.)

INFORMATION FILED: September 23, 1948, Western District of Virginia, against the Lynchburg Milling Co., a corporation, and Thomas K. Scott, president.

ALLEGED SHIPMENT: On or about April 26 and May 7, 1948, from the State of Virginia into the State of North Carolina.

LABEL, IN PART: "10 Lbs. Net Weight Old Fashion Stone Ground Corn Meal."

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in part of a filthy substance by reason of the presence of insect larvae, larval heads, a larval head capsule, insect fragments, rodent excreta pellet fragments, and rodent hair fragments; and, Section 402 (a) (4), it had been prepared and packed under insanitary conditions whereby it may have become contaminated with filth.

Nos. 13720 to 13748 report actions involving flour that was insect- or rodent-infested, or both. (In those cases in which the time of contamination was known, that fact is stated in the notice of judgment.)

13720. Adulteration of flour. U. S. v. Lakeview Milling Co., Inc., and Harry A. Wolf. Fine of $100 per count against each defendant on first 3 counts (total $600). Sentence suspended on count 4. Corporation and individual placed on probation for 1 year. (F. D. C. No. 25326. Sample Nos. 5062–K, 5074–K, 5076–K, 40129–K.)

INFORMATION FILED: October 21, 1948, Middle District of Pennsylvania, against Lakeview Milling Co., Inc., a corporation, Chambersburg, Pa., and Harry A. Wolf, vice-president, secretary-treasurer, and manager.

ALLEGED SHIPMENT: On or about February 28, May 19, and June 2, 1948, from the State of Pennsylvania into the States of Massachusetts and Maryland.

LABEL, IN PART: "100 Lbs. Net Wholewheat Flour," "100 Lbs. Venus Whole Wheat Flour," "Bleached 100 Lbs. Fancy Pastry Flour," or "100# Fine Ground Whole Wheat Flour."

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in part of a filthy substance by reason of the presence of larval insect head capsules, insect fragments, rodent hair fragments, insect larvae, a larval cast skin, mites, and a rodent excreta pellet fragment; and, Section 402 (a) (4), the product had been prepared and packed under insanitary conditions whereby it may have become contaminated with filth.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in whole or in part of a filthy substance by reason of the presence of rodent urine and rodent excreta; and, Section 402 (a) (4), it had been held under insanitary conditions whereby it may have become contaminated with filth. The product

18303. Adulteration of flour. U. S. v. 38 Bags, etc. (F. D. C. No. 32041. Sample Nos. 22128–L to 22130–L, incl.)

LIBEL FILED: October 23, 1951, Southern District of Mississippi.

ALLEGED SHIPMENT: On or about February 13, May 28, and June 30, 1951, from Fort Worth, Tex.

PRODUCT: 158 25-pound bags and 244 10-pound bags of flour at Gulfport, Miss.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the article consisted in whole or in part of a filthy substance by reason of the presence of insects. The article was adulterated while held for sale after shipment in interstate commerce.

13719. Adulteration of corn meal, corn grits, and flour. U. S. v. 16 Bales, etc. (and 3 other seizure actions). (F. D. C. Nos. 25137 to 25139, incl., 25356. Sample Nos. 60–K to 65–K, incl., 69–K to 71–K, incl., 166–K, 167–K, 362–K, 363–K, 373–K.)

LIBELS FILED: August 2, 4, and 13, 1948, Southern District of Georgia; amended libel on one lot filed on September 14, 1948.

ALLEGED SHIPMENT: Between the approximate dates of March 24 and July 15, 1948, by the Manning Milling Co., from Manning, S. C.

PRODUCT: 214 bales and 110 bags of corn meal, 46 bales and 10 bags of corn grits, and 5 bales and 158 bags of flour at Savannah and Augusta, Ga. The bales contained from 4 to 20 bags. The bags were in 2-, 5-, 10-, 25-, 50-, and 100-pound sizes.

LABEL, IN PART: "Corn Meal Enriched," "Corn Grits Enriched by Nature," and "White Eagle Flour [or "Self Rising Flour"]."

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the articles consisted in whole or in part of filthy substances by reason of the presence of insects, insect fragments, rodent hairs, rodent hair fragments, and rodent excreta; and, Section 402 (a) (4), they had been prepared under insanitary conditions whereby they may have become contaminated with filth.

DISPOSITION: September 23 and 24, 1948. The Manning Milling Co., claimant, having consented to the entry of decrees, judgments of condemnation were entered and the products were ordered released under bond for conversion into animal feed, under the supervision of the Federal Security Agency.

13721. Adulteration of flour. U. S. v. 83 Bags * * *. (F. D. C. No. 25175. Sample No. 2806–K.)

LIBEL FILED: On or about July 20, 1948, Western District of Virginia.

ALLEGED SHIPMENT: On or about June 7, 1948, from Greeley, Colo.

PRODUCT: 83 100-pound bags of flour at Harrisonburg, Va.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in whole or in part of a filthy substance by reason of the presence of larvae and larvae parts. The product was adulterated while held for sale after shipment in interstate commerce.

DISPOSITION: October 27, 1948. Default decree of condemnation. The product was ordered delivered to a charitable institution, for use other than for human consumption.

18304. Adulteration of flour. U. S. v. 66 Bags * * *. (F. D. C. No. 32052. Sample Nos. 22109–L, 22110–L, 22351–L.)

LIBEL FILED: On or about November 7, 1951, Southern District of Mississippi.

ALLEGED SHIPMENT: On or about May 11, 1951, from Claflin, Kans., and on or about August 3, 1951, from Wilson, Kans.

PRODUCT: 66 bags, each containing 10 pounds, of flour at Vicksburg, Miss.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in whole or in part of a filthy substance by reason of the presence of insects. The product was adulterated while held for sale after shipment in interstate commerce.

DISPOSITION: November 20, 1951. A decree of condemnation was entered ordering that the product be denatured for use as animal feed and that it be delivered to a charitable institution.

13723. Adulteration of flour. U. S. v. 37 Bags * * *. (F. D. C. No. 25449. Sample No. 19947–K.)

LIBEL FILED: September 9, 1948, Southern District of Ohio.

ALLEGED SHIPMENT: On or about April 24, 1948, from Wabasha, Minn.

PRODUCT: 37 100-pound bags of flour at Portsmouth, Ohio.

NATURE OF CHARGE: Adulteration, Section 402 (a) (3), the product consisted in whole or in part of a filthy substance by reason of the presence of insects and insect fragments. (The article was adulterated while held for sale after shipment in interstate commerce.)

DISPOSITION: October 13, 1948. The International Milling Co., claimant, having admitted the allegation of the libel, judgment of condemnation was entered and the product was ordered released under bond, conditioned that it be denatured and converted into stock feed, under the supervision of the Federal Security Agency.

Fig. 47. Selected notices of judgments under the Federal Food, Drug, and Cosmetic Act -- released by the Federal Security Agency, Food and Drug Administration.

UNITS

Length or Distance	Symbol	
1 Meter	M	100 cm
1 Angstrom	A	10^{-8} cm
1 Micron	U	10^{-4} cm
1 Millimicron	Mu	10^{-7} cm
1 Centimeter	cm	0.3937 in
1 Foot	ft	12 in
Weight		
1 Pound	lb	453.9 gr

DEFINITIONS

Force -- mass x acceleration

Work -- force x distance

Energy and work are expressed in the same units. An agent is said to possess energy if it is able to do work. When an agent does work, its energy is reduced by an amount equal to the work done.

Power -- $\frac{\text{Energy}}{\text{Time}} = \frac{\text{Work}}{\text{Time}}$

Dyne -- unit of force in the C.G.S. system of physical units. It is such a force that under its influence a particle whose mass is one gram would experience during each second an acceleration of one centimeter per second.

<u>Newton</u> -- unit of force in the MKS system of units and is defined as that unbalanced force which will give a mass of 1 kg an acceleration of 1 meter per second.

<u>Work</u> or <u>energy in MKS units</u> is the work done by a force of one newton acting on a body through a distance of 1 meter in the direction of the force, and is expressed as the newton-meter. Since the newton is 10^5 dynes, and the meter is 10^2 centimeters, the newton-meter of work is equal to 10^7 dyne-cm = 10^7 ergs = 1 Joule; 1 watt sec = 2.78×10^{-7} kwh = 6.24×10^{12} Mev.

<u>Joule</u> = 10^7 ergs = 0.24 calories = 0.738 ft lbs = to the energy expended in one second by an electric current of one ampere in a resistance of one ohm.

<u>Electron volt</u> -- energy acquired when an electron is accelerated through a potential of one volt.

ev -- 1 electron volt

Kev -- 1000 electron volts

Mev -- 1,000,000 electron volts

<u>Power</u>

1 watt = 1 Joule/sec MKS system = 10^7 ergs/sec CGS system

$$1 \text{ hp} = 550 \frac{\text{ft lbs}}{\text{sec}} = 33{,}000 \frac{\text{ft lbs}}{\text{min}}$$

1 hp = 746 watts

1 kw = 1000 watts = 1.34 hp

1 ft lb per sec = 1.356 watts

Relation of heat to mechanical work

Quantity of heat	Equivalent amount of mechanical work
1 calorie	4.186×10^7 ergs
1 calorie	4.186 Joules
1 BTU	778 ft lbs
0.239 calorie	1 Joule

Radiation Equivalents

1 Roentgen = 1.61×10^{12} ion pairs/gram air

= 6.77×10^4 Mev/cc std air

= 5.24×10^7 Mev/gram air

= 83.8 ergs/gram air

= 93 ergs/gram water or tissue

1 rep (roentgen-equivalent-physical) -- 1 roentgen

1×10^6 rep

1 mega rep

8.38 Joules/gram air

8.38 watt sec/gram air

9.3 Joules/gram tissue

9.3 watt sec/gram tissue