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ELECTRONIC PRODUCT RADIATION and the HEALTH PHYSICIST

Health Physics Society
Fourth Annual Midyear Topical Symposium

U S DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service

DIVISION OF ELECTRONIC PRODUCTS

List of Publications

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ELECTRONIC PRODUCT RADIATION and the HEALTH PHYSICIST

Fourth Annual Midyear
Topical Symposium

Health Physics Society
Louisville, Ky. January 28-30, 1970

October 1970

Sponsored by :

BLUE GRASS CHAPTER, HEALTH PHYSICS SOCIETY

and

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
Rockville, Maryland, 20852

FOREWORD

During recent years, increasing concern about the exposure of man to hazardous ionizing and nonionizing radiation has been manifested in the Unites States and abroad. In pursuing the goal of minimizing such exposure, the Bureau of Radiological Health and the Health Physics Society engage in a continuing program of evaluating sources and conditions of exposure, its hazards, and the development of control measures.

The Fourth Annual Midyear Topical Symposium of the Health Physics Society, cosponsored by the Blue Grass Chapter of the Society and the Bureau of Radiological Health, was held to promote exchanges of information with respect to the status, progress, and future directions in certain areas of radiation exposure. Its subject, "Electronic Product Radiation and the Health Physicist," encompasses a broad range of sources of exposure. Its scope extends over a large portion of the electromagnetic spectrum and includes both ionizing and nonionizing radiation. The individual presentations discuss aspects of electronic product radiation ranging from broad surveys and educational needs to specific considerations of instrumentation and biological effects.

The impact of electronic product radiation on the human condition is becoming increasingly recognized. It is hoped that the papers presented at this Midyear Topical Symposium serve to stimulate both interest and effort to assure that the growth of science and technology in this field will maintain a close concordance with the protection of health.

John C. Villforth
Director
Bureau of Radiological Health

Wordie Parr
Symposium Chairman

PREFACE

The Midyear Topical Symposium on Electronic Product Radiation and the Health Physicist was held to promote an interchange of information, among investigators and health personnel, on various problems related to protection against the hazards of electronic product radiation. Each author was requested to submit a final copy of his paper for publication in these proceedings. In the interest of early publication, these papers are reproduced for the most part from the manuscripts as submitted by the authors.

To the participants, from Government, industry, and educational institutions, who contributed to the program, the Symposium Committee expresses its gratitude.

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ABSTRACT

The Fourth Annual Midyear Topical Symposium of the Health Physics Society, cosponsored by the Blue Grass Chapter of the Society and the Bureau of Radiological Health, was held to promote exchanges of information with respect to the status, progress, and future directions in certain areas of radiation exposure. Its subject "Electronic Product Radiation and the Health Physicist," encompasses a broad range of sources of exposure. Its scope extends over a large portion of the electromagnetic spectrum and includes both ionizing and nonionizing radiation. The individual presentations discuss aspects of electronic product radiation ranging from broad surveys and educational needs to specific considerations of instrumentation and biological effects.

ELECTRONIC PRODUCT RADIATION
and the
HEALTH PHYSICIST

FOURTH ANNUAL MIDYEAR TOPICAL SYMPOSIUM
Health Physics Society

KEYNOTE ADDRESS

John C. Villforth
Director, Bureau of Radiological Health
Environmental Health Service
U.S. Department of Health, Education, and Welfare

KEYNOTE ADDRESS

John C. Villforth
Director, Bureau of Radiological Health
Environmental Health Service
U.S. Department of Health, Education, and Welfare

In January 1969, the Board of Directors of your society passed a resolution recognizing that the scope of interest of the Health Physics Society must necessarily be expanded to include all radiations (except mechanical vibrations) covered by the Radiation Control for Health and Safety Act of 1968, P.L. 90-602.

I wonder if many of you felt as uncomfortable as I did at the prospect of broadening your area of knowledge of radiation effects from those familiar three decades of energy in the ionizing region - between about 10 KeV and 10 MeV (2×10^{18} Hz and 2×10^{21} Hz) - down through the UV visible, infrared, microwave, to the low-frequency range of the spectrum, to 10^6 Hz or lower where biological effects are doubtful. This is an expansion of at least 12 decades of energy and included in it are entirely different phenomena, interactions, and biological effects than there are within the ionizing region. It is, of course, the effects of man that is of concern to us as health physicists. These effects are quite varied depending on the portion of the spectrum one is dealing with.

For example, with regard to laser radiation, the levels that constitute a hazard are difficult to establish because of variations in the type of laser and variations in biological factors. Different wavelengths, intensity levels, pulse durations, and pulse repetition rates all influence directly the possibility of tissue damage. Biological factors applicable to all tissues, such as pigmentation, vascularity, and spectral absorption of the energy influence the degree of damage. In addition, there are organ-specific factors which influence the degree of damage to a particular organ. In the case of the eye, for example, pupil size, convergence power of the cornea and lens, and distance from the lens to the retina all influence the threshold level for damage. Because of the multiplicity of these factors, it is impractical to establish one threshold value for biological damage for all types of laser systems and conditions of operation. Therefore, current guides are based upon the minimum dose required to produce a visible lesion. Unfortunately, very little is known about the possible cumulative effects produced by repeated subthreshold exposures of the eye or skin.

In a somewhat different manner, the biological effects produced by microwaves depend on factors such as the frequency of the radiation, intensity of the beam, length of exposure, dielectric constant, and thermal conductivity of the tissue. The depth of penetration of the radiations decreases with increase in frequency (or decrease in wavelength). At frequencies less than 150 MHz, the body is essentially transparent to microwave radiation, with no appreciable absorption. Between 150 and 1,000 MHz, the energy is absorbed in the deeper tissues. From theoretical considerations and experiments on phantoms, it has been shown that the proportion of energy absorbed is approximately 40 percent of the incident energy arriving at the body surface for frequencies in this range. This energy is potentially the most hazardous with respect to internal heating, because at these frequencies there is little or no heating of the skin where thermal receptors would warn the exposed individual of danger. Radiation at frequencies between 1,000 and 3,000 MHz is subject to varying degrees of penetration and is abosrbed in both superficial and deeper tissues, depending upon tissue characteristics. The lens of the eye is a critical target organ at frequencies around 3,000 MHz, at which production of cataracts is an important consideration.

At frequencies below about 30 MHz, no resonant heating occurs and RF energy completely penetrates all body organs. Radiations at these frequencies may produce nonthermal effects which are field dependent and not necessarily related to heating. These effects may be concerned with changes in the central nervous system and peripheral nervous system. In studying subjects working in the environment of less than 30 MHz, the Russian observers have found symptoms of headaches, insomnia, irritability, and fatigue, deviations of brain waves, and slight enlargement of the thyroid gland among others. There is considerable controversy over the validity of these Russian observations. The questions arising from these controversies need resolution.

When we as health physicists begin to look into these nonionizing regions of the electromagnetic spectrum, we find that the relatively poorly understood effects of ionizing radiation loom small compared to the questions that must be answered with respect to the biological effects of nonionizing radiation. Such questions as cumulative effects, threshold effects, genetic effects, and time-intensity relationships must still be worked out for portions of the electromagnetic spectrum. These unanswered questions arise, in part, because of the limited funds available in the past for extensive research in this area as compared to the resources that have been brought to bear on ionizing radiation problems. Another part of the problem relates to the relative newness of the nonionizing radiation field and to its rapid growth. After all, lasers have been with us for only 10 years and there are now 17,000 units in use with an expected growth rate of 130 percent by 1972. Finally, these unanswered questions may be due to the fact that we, as individual health physicists, or we, as a society, have been slow in recognizing our role in researching this portion of the electromagnetic spectrum and consequently have not put enough effort to bear on better understanding of the biological effects, methods of measurement, and, most important, means of control to provide safety to user. Perhaps it is fortunate that P.L. 90-602 is stimulating us to examine these regions.

The Act is doing something else. It is causing us to reexamine the ionizing portion of the spectrum or more specifically those electronic products producing ionizing radiation. (We should keep in mind that, as defined by the Act, electronic product radiation means "...any ionizing or nonionizing electromagnetic or particulate radiation which is emitted from an electronic product as the result of the operation of an electronic circuit in such product." Sometimes we incorrectly use electronic product radiation when we mean only nonionizing radiation.)

It must be admitted that we have a better scientific basis for our activities in ionizing radiation, yet it is unfortunate that we have not made more progress toward reducing unnecessary exposure from electronic products that emit x radiation. I might cite the recent action taken by the Bureau of Radiological Health to restrict exposure from certain cold-cathode gas discharge tubes used for demonstration purposes in educational institutions. (A paper on this will be presented Wednesday afternoon.) These tubes are essentially the same tubes that have been used to describe certain physical phenomena and were in use prior to the time that Roentgen discovered x radiation. No attempt was made in the intervening 80 years to improve the design so that the educational value of these devices could be kept without the unnecessary exposure.

Of course the most significant contribution to population exposure is still from the medical and dental use of x radiation. The 1964 estimates of the genetically significant dose from these sources was 55 millirads - about one-half of natural background. It can be demonstrated that this number could be reduced to about 19 millirads if the primary x-ray beam were limited to the size of the diagnostic film. Further reduction can be achieved through proper radiographic techniques, improved equipment, and the judicious ordering of roentgenograms by physicians. Considerations of education of the user - believe it or not - come within the broad province of "Electronic Product Radiation and the Health Physicist." Our concern is that there aren't enough of us working in these areas to bring about reductions in exposures to compensate for the rapidly increasing uses of radiation in products that emit radiation as a byproduct such as TV receivers, klystrons, vacuum switches, and the like.

In order to appreciate the magnitude of the control and regulation job that must be done, we might look at some data on the electronic products industry. The total dollar value of factory sales of electronic products in 1968 was $24.1 billion of which 51 percent were sales to government, 27 percent to industry, 19 percent to consumers, and 3 percent to the replacement market. In all, about 35 million electronic products with a potential for radiation exposure are in use in the United States. It must be recognized that the health significance of any particular product is based on such factors as (a) number of devices in use, (b) the population at risk, (c) the radiation emission and the biological effect of the emission, and (d) the duration of exposure. Therefore, not all of the 35 million electronic products might present an immediate radiological health problem. Although a paper will be presented this afternoon that will discuss in detail the results of an inventory of some of these products, it might be worthwhile to mention some of these items:

Color TV receivers	24,000,000
Medical-dental x ray	215,000
Microwave ovens	100,000
Lasers	18,000
Industrial x ray	15,000
Diathermy	Several thousand
Accelerator	1,200

It seems to me that as health physicists we have the greatest opportunities ahead of us in the area of electronic product radiation and control and one of the greatest challenges to "protect the health and safety of the population from electronic product radiation." The opportunities will come in trying to solve some of the unknowns in the nonionizing radiation region of the spectrum. These unknowns in biological effect will require an understanding of the basic mechanism of the interaction of radiation at the cellular level, as well as an examination of the gross effect on populations through epidemiological studies. It will require the development of improved or specific instrumentation for some of these products whose radiation we are not able to measure otherwise than in a lab.

The challenges will come when we direct our efforts at the tremendous number of sources and seek to reduce exposure from these sources by new concepts of design or educational efforts directed toward the user. It is in these areas that the health physicists have worked so effectively to keep exposures from radioactive materials to such an enviably low level. This has been possible because health physics has been a multidisciplined profession that gains its strength from the diversity of interests of its individual members.

In implementing certain provisions of the Radiation Control for Health and Safety Act, the Secretary, Health, Education, and Welfare, is charged with the responsibility of consulting with (among other groups) "appropriate professional organizations and interested persons." I am pleased that our society has taken steps to be responsive to this Act and it is encouraging that so many of our members have been interested enough to explore this new area as evidenced by the attendance at this meeting. I feel that this is the pathway to the reduction of exposure of the public to all unnecessary hazardous radiation from electronic products.

SESSION I: NEW SCOPE FOR HEALTH PHYSICS, INVITED PAPERS

Chairman: John C. Villforth

Energy Pollution of the Environment
K. Z. Morgan

The Impact of the Electronic Product Radiation Control Program (Public Law 90-602)
R. G. Britian, D. J. McConeghy

Educational Needs to Implement New Responsibilities in Radiation Safety
J. N. Stannard

Electronic Product Radiation and the Environmental Engineering Curricula
W. E. Bolch, H. A. Bevis

ENERGY POLLUTION OF THE ENVIRONMENT

Karl Z. Morgan
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Introduction

In discussing the subject of energy pollution, we may define pollution as the act of making components of the environment unhealthy for man and the ecosystem in which he lives. Pollution results when an excess of certain substances--either wanted or unwanted--is added to the environment in such a manner that it causes changes that are considered to be detrimental or deleterious to the health, well being, peace of mind, enjoyment or fulfullment of a normal, productive and happy life of persons who are affected. Energy pollution may affect man directly or indirectly (or both). For example, thermal pollution of a small river by a power plant--burning either fossil or nuclear fuel--may affect man directly by making the water so warm that he considers it unattractive for swimming. It may affect him indirectly by destroying his favorite sport of trout fishing, or if the heat is dissipated in cooling towers, fogs and winter icing may add to the danger of his travel on local highways. It should be noted, also, that often the undesirable consequences of a pollutant are accompanied by desirable and sought after benefits which likewise can be both direct and indirect. In our example, the warmer water may permit this man's neighbor comfortable swimming until late in the fall and to his delight may result in new species of fish in great abundance. The power plant may provide employment for this man and other members of the community, and the entire economy of the area may be improved by the availability of cheaper electrical energy and new, taxable industries which result in a lower tax rate for the average person of the community. Therefore, a vector which from some aspects is a pollutant, may from other considerations be a very desirable and beneficial community asset. All forms of energy when under intelligent control, in appropriate amounts, in the right place, and at the proper time are benefactors of man, but when they are out of control, in excess amount, at the wrong place, and at an improper time, they become energy pollutants. For example, electricity to heat our home is considered a benefit, but electricity in a lightning storm may be very destructive, or a shower bath in water at 30°C. may be just perfect, but if a defect in the hot water system causes a sudden rise in the water temperature to 99°C., the results can be disastrous. Heat, electricity, x-rays, ultrasonic radiation, chemical energy and, in fact, all known forms of energy may be essential to our way of life, but through ignorance, carelessness, selfishness and neglect, they can become pollutants that destroy our property, defile the beauty of our environment and may ultimately cost our lives.

The term "energy" as used in this context includes both kinetic and potential energy, but in order to limit this discussion, I will exclude mass as a form of energy. In high energy physics, however, we must consider mass and energy collectively because in nuclear transformations the sum of energy and mass before a reaction must equal that after the reaction. Either can be converted into the other, i.e., mass to energy or energy to mass, provided the quantum mechanics laws of conservation of leptons, baryons, charge, spin, strangeness and isotopic spin are not violated. Within these quantum restrictions, anything that can happen eventually will happen, and the mass-energy transitions ultimately will tend in the direction of less mass, i.e., toward the production of the massless forms of energy which are photons, neutrinos and anti-neutrinos. In everyday, classical physics we have the somewhat similar, but much more obvious, law of entropy which directs that all forms of energy--electrical, sound, mechanical, chemical, etc.--tend in the direction of heat energy at a uniform temperature where there is less ability to convert energy to mechanical work. Altogether some 80 distinct and individual types of particles or identical building blocks in our universe have been identified. About half of these are resonant particles (i.e., some 40 types) with a lifetime of only about 10^{-23} seconds. Also, half of all particles (or one-half of the mass of the universe) consists of anti-particles which neutralize their mass and an equal amount of ordinary matter whenever contact is made. For example, when an electron and an anti-electron (called a positron) come in contact, they are annihilated, forming two photons and moving each with an energy of 0.51 Mev in the opposite direction in order to conserve momentum. Because neutrinos have zero mass and an exceedingly low cross section for interaction with matter (much lower than that of photons), most of the neutrinos that have been produced since the universe was created some 10 billion years ago probably are still in existence as they dash at terrific speeds (almost with the speed of light) more or less unimpeded in their endless flights through space. Neutrinos together with an equal number of anti-neutrinos probably comprise most of the mass energy of the universe, so in terms of numbers or total energy, they comprise by far the greatest energy pollutant of the universe. All visible stars are intense sources of neutrinos, but because of the comparative nearness of our star, the sun, it is responsible for most of the particle fluence of neutrinos now passing swiftly through our part of space. Some 10^{12} neutrinos penetrate our bodies each second, and for the most part continue unabated in their paths through the earth. This reminds me somewhat of a discussion I once had with Walter S. Snyder about the risks of driving too fast on the highways in small, compact cars. His comment was that the risk of an accident obviously is related to the size of the car and how long it is on the highway. Therefore, a person driving in a small car at a speed approaching infinity should be relatively safe from a collision--just as is the case with a neutrino. I hope none of you will take this jesting comment too seriously. Even though most of these neutrinos probably have millions of ev of energy, they are not considered here as an energy pollutant because with their low cross section, perhaps only one or two of them suffer a collision in our bodies during our lifetime. Even if we were concerned about these particles or considered them a detriment, there is no place we could go to hide from them. Likewise, since half of the universe is made up of anti-matter which annihilates itself in a terrific energy explosion whenever it makes contact with ordinary matter, we might be inclined to list anti-matter as our greatest environmental pollutant. Not so, however, because even though half the matter of the universe is composed of anti-matter, for the most part anti-matter is widely separated in space from ordinary matter and presumably there are infrequent (if any) major annihilation collisions in our part of space. Conceivably such major encounters occur in our solar system with an average frequency of no more than once per million years and except for explosions that may have occurred on the surface of the moon where evidence would be perpetually preserved, we have little opportunity of finding visible remnants from such encounters.

In this discussion, then, we will set aside further consideration of energy problems of mass-energy and quantum physics and devote the remainder of this discussion to classical physics or health physics and to energy sources of pollution which I include broadly under the headings of (1) mechanical, (2) chemical, and (3) electromagnetic and elementary particles. In order to show what we might include under these three general headings, we can list, respectively, for illustration sources of these three forms of energy as follows: (1) an ultrasonic machine or a falling body; (2) atmospheric pollutants such as SO_2 and NO which I consider as chemical sources of potential energy which may react in the atmosphere, in the ecosystem, or in our bodies to bring about undesirable changes; (3) an x-ray machine, radar antenna or alpha source such as plutonium-239. In some respects, each of these classes of energy pollutants is so different from the others that it is hardly comparable, but in other ways the similarity of the three is striking, and their effects on man are not completely independent. In fact, there appears to be a synergistic relationship in the ways some of these affect man and his environment. For example, SO_2 (a chemical pollutant) in the presence of ultraviolet radiation (an electromagnetic pollutant) can be converted in the atmosphere to SO_3 and, in turn, to H_2SO_4. It is fairly well established that some of these forms of sulphur pollutants in association with other energy pollutants lead to synergistic effects where the total damage to man and his environment is much worse than that from the sum of the damage produced by either alone. Likewise, nitric oxide can be converted in the atmosphere into nitrogen dioxide which is a lung irritant.

One surprising observation is that in some typical situations of exposure from several kinds of energy, the amount of energy absorbed from each by man at the maximum permissible level or at a level of comparable damage is about the same, but with other forms of energy, the amount of energy absorbed is very much different. Figure 1 was prepared by G. S. Hurst for his freshmen students in order to emphasize some of these comparisons and striking differences. This figure indicates that a total body dose of 10^4 rad which would be expected to kill a man in minutes to hours corresponds to a temperature rise of 0.024°C., and from the law of conservation of energy, we find, likewise, that a 32 ft. fall (also ordinarily lethal) corresponds to the same temperature rise of 0.024°C. However, a temperature rise of 0.024°C. when one is taking a bath would not be perceptible.

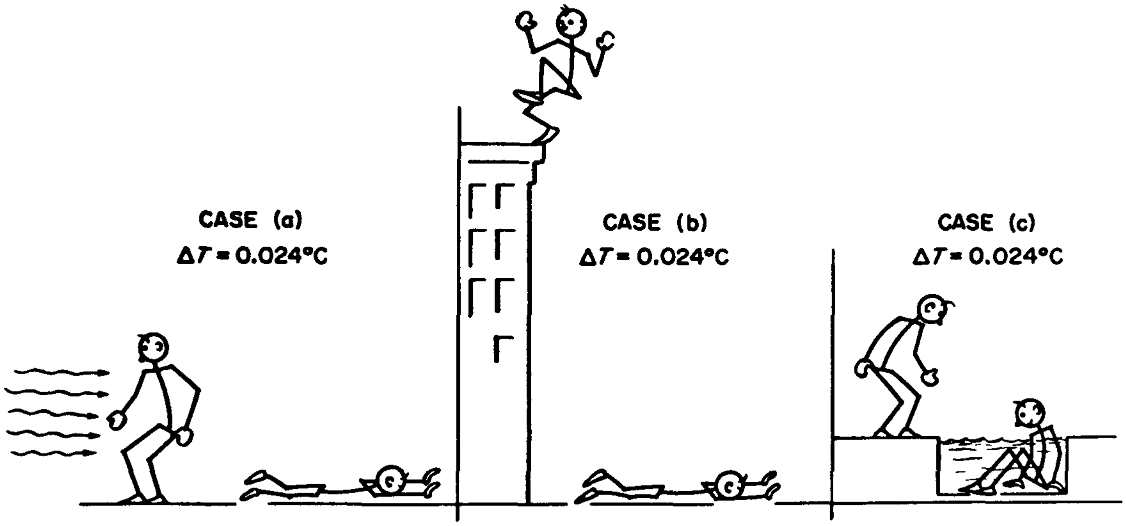
Perhaps a much simpler designation of the types of energy pollutants under discussion here is that we are reviewing briefly all those types covered by Public Law 90-602 (1968). This also means we are including all forms of energy pollutants defined by the Board of the Health Physics Society in 1969 as coming under the purview of the health physicists except in this case we are not excluding mechanical forms of energy. In fact, we are expanding the forms of energy discussed here even beyond the inclusions of PL 90-602 and adding chemical energy to our list. I should emphasize at this point that most of the discussion will deal with Class 3 above, i.e., electromagnetic and elementary particles, since only this form of energy pollution comes under the purview of health physics. Also, because this health physics conference is devoted to extensive discussions of microwave, RF, lasers and ultraviolet radiations, I will mention these radiations only briefly and leave their discussion to the experts who follow me on this program. Before proceeding beyond the introduction to this paper, I wish to state that I do not consider myself an expert on the subject of environmental pollution by all forms of energy. The only firsthand knowledge I have concerns ionizing radiation as it relates to health physics. Therefore, views I express on this broad subject of energy pollution assigned me by the Program Committee are my own and may conflict with opinions of some of the experts.

Mechanical Energy

Some of the most important forms of mechanical energy which result in energy pollution are associated with changes in linear and angular momentum, mechanical vibrations, sound, ultra-sound and infra-sound. This would include the energy involved in automobile collisions, plane crashes, the noisy hotel room in which you may be staying, the ultrasonic machine you use to remove radioactive contaminants from clothing and the sonic boom which is expected to thunder much louder when the taxpayers bring to fruition one of their "objectives" of providing a few, select individuals with the opportunity of traveling in American-made supersonic transports.

I do not think it would take much argument to convince anyone that automobiles, in addition to being the major source of atmospheric pollution, are pollutants of our environment from the standpoint of filling stations on every street corner of some parts of our cities, unsightly parking lots, ugly, crowded roads and highways, and finally the junkyards and graveyards where each year seven million U. S. cars find their resting place to display their broken, rusting skeletons and to spoil our once beautiful landscape. My intention here, however, is to consider automobiles as an energy pollutant in that last year in our country through sudden changes in momentum during collisions, they killed over 50,000 people and severely injured, maimed and disabled 12 million persons. All of us should be proud that Ralph Nader, the customer's champion, has done so much to show how this situation can and must be improved, but I think we should be ashamed of the lack of support our government, industry and our profession have given him toward implementing the numerous safety programs for which he is crusading.

I think most people will agree that man himself is one of the most destructive of all pollutants as he dashes madly down city streets, through the long passageways of the airports, into the packed and smoke-filled buses and subway trains. The farmer's children move to the cities where their homes are crowded together, and they finally move into small and even more crowded apartments. Man visits the national parks and forest areas but clutters them with rubbish and soon he wants more roads, motels, shops, amusement places and golf courses. Then, it is only a matter of time until the forests and parks have lost their beauty and charm. The dashing, white waters where we used to fish and enjoy camping are mostly gone, and in many cases they are replaced



Case (a) Person receives a total body absorbed dose of 10^4 rad of x-rays over a period of time of a few minutes. Energy absorption 10^6 ergs/g and temperature rise ~0.024°C. Death in minutes to hours.

Case (b) Person falls from a 32′ building. Energy absorption 10^6 ergs/g and temperature rise ~0.024°C. Death in minutes to hours.

Case (c) Person sits in a tub of water to which 10^6 ergs/g of heat is supplied or a temperature rise of ~0.024°C. Person not aware of temperature rise.

Figure 1. Effects of energy absorption.

by hydroelectric ponds. The mountains, once the pride of God's handiwork, are scarred and barren from fires and strip mining. Man is the prime example, epitome and principal cause of all forms of pollution. Even worse, man is polluting this planet through overpopulation, and unless he applies more rigid and effective methods of birth control, we can expect millions of people in South America, India, and China to starve in the decades immediately ahead.

Another form of mechanical energy pollution is mechanical vibrations (often below the audible range) in many buildings from heavy city traffic on nearby highways and subway trains, etc., or in vibrations which are produced by medical and industrial equipment to produce impaction or settling in various fluids. Very few studies have been carried out to determine the biological significance of the infrasonic vibrations to the well being of man, but certainly they result in structural damage to many types of buildings, bridges, utilities, etc.

Sound is becoming an increasingly important form of mechanical energy pollutant. It has been known for a long time that certain workplaces such as roller mills, blast furnaces and construction of bridges, buildings and highways are very noisy and lead to hearing damage to thousands of workmen each year. In addition, this noise is moving much closer to the general population. Increasing street traffic has been raising city noise levels by one decibel (1 db) a year for the past 35 years. In many city business districts, the level is above 70 db, and in subway stations it often rises above 95 db. A recent report by Mayor John V. Lindsey's Task Force on Noise Control says that noises in parts of New York regularly go above 85 db. Figure 2 (taken from the textbook, Medical Physics(1)) indicates the noise levels in several of man's environments. The Labor Department Health Code has set 90 db as the loudest noise to which a workman can be subjected continuously for an eight-hour day. This corresponds approximately to the noise level of a motorcycle or boiler factory. Eighty-five decibels is the threshold at which it is believed injury begins to be quite significant. Some city streets are so noisy that hearing becomes difficult and leads to accidents of those pedestrians who unwisely place too much reliance on their sense of hearing to warn of oncoming traffic. In some cities, the use of car horns, factory whistles, portable public address systems, cutouts on car mufflers, grass mowers with ineffective mufflers, etc., is limited, but usually the laws and their enforcement are very poor, and year by year the noise level increases. Even the office worker finds no refuge from noise because here the typewriter, telephone, intercom, etc., produce a constant clutter of sound which intermingles with those of the noisy garbage collectors, the blaring horns, droning buses, the air compression machine with its banging jackhammer as it cracks the cement, or the construction workman pounding on steel rivets. Only the exceptional workplace has adequate soundproofing to keep out the outside noises and appreciably attenuate those from the inside. Added to this, we have the sonic boom from aircraft, the noisy airports and low-flying aircraft. Worst of all, noise has moved into our homes where we find droning airconditioners, furnace blowers, refrigerators, deep freezers, clanking dishes, dishwashers, food blenders, alarm clocks, carpet sweepers, electric razors, screaming

NEW YORK CITY DATA	NOISE LEVEL	DATA FROM OTHER SOURCES
	100	
		Boiler factory*
Subway--local station with express passing	95	
	90	
	85	Some factories are as high as this**
	80	Very loud radio music in home‡
	75	
Noisiest non-residential building location measured		
	70	Stenographic room*** Very noisy restaurant‡
Average of 6 factory locations		
	65	
	60	
Information booth in large railway station		Noisy office or department store*
	55	
		Moderate restaurant clatter‡
Average non-residential location	50	Few places where people work are below this**
		Average office*
Noisiest residence measured	45	
	40	Very quiet radio in home‡
		Quiet office*
	35	Soft radio music in apartment***
Quietest non-residential location measured		
Average residence		
	30	
		Country residence*
	25	County court, Chicago, room empty windows closed**
Quietest residence measured		
	20	Quiet garden, London‡

-Sources-

*H. Fletcher, "Speech and Hearing"
**D. A. Laird, Scientific American, Dec. 1928
***W. Waterfall, Engineering News Record, Jan. 10, 1927
‡A. H. Davis, Nature, Jan. 11, 1930

Figure 2. Typical indoor noise levels.(1) (In this case, 0 db corresponds to 10^{-16} w/cm^2).

children, neighborhood dogs and, most of all, blasting radios and television sets without which the younger and brainwashed generations claim they cannot concentrate. Silence may be golden but is becoming more difficult to obtain than gold. Many writers(2) have pointed out that noise is not just a distraction and irritating disturbance, but it brings about psychological and physiological changes--cardiovascular, glandular, respiratory, generalized stress and damage to blood vessels, nerves and to the fetus.

Figure 3 (from Medical Physics(1)) indicates the threshold of human hearing and how it varies with frequency. It is to be observed that man's hearing is much better at about 3,000-4,000 Hz (i.e., the threshold drops to -10 db) but is very poor below about 20 Hz or above about 18,000 Hz (i.e., the threshold approaches infinity very rapidly). The human ear has a remarkable range of sensitivity and can detect sound corresponding to changes of less than 10^{-4} dynes/cm^2 and can accommodate pressure changes up to 10^3 dynes/cm^2. The hearing of most persons degenerates rapidly with age, and a noisy environment accelerates this degeneration process, often resulting in almost complete loss of hearing.

As indicated in Figure 3, the human auditory range is limited to a rather narrow band of frequencies. Low frequencies below this range (less than 20 Hz) are sometimes sensed as mechanical vibrations, and those considerably above (greater than 18,000 Hz) can be heard by a few persons and many animal species (dogs, bats, etc.). These ultrasonic frequencies have a practical range from about 20 Khz to 5 Mhz, but, theoretically, much higher frequencies could be attained. Supersonics, although beyond the range of the human ear, have many practical applications such as degasing of melts, coagulation of smoke, flaw detection in non-destructive testing, echo sounding, surface cleaning, medical diagnosis, therapy, etc. The secondary effects of ultrasonics that may affect biological organisms and man are heat production, mechanical action and chemical changes. When ultrasonic radiation passes through man, a reflection and momentum transfer occurs at each interface or organ structure. The magnitude depends on the frequency and amplitude of the radiation and the change in density and rigidity of the structure. At large amplitudes (greater than 1 watt/cm^2) cavitation is produced in liquids and may be produced in soft tissue during the negative pressure cycle. These cavities tend to become filled with dissolved gases and may be accompanied by a large temperature rise and electrical discharges in the cavity which lead to oxidation and other chemical changes. Levels of 1 to 3 watts/cm^2 at 1 Mhz have been used extensively in therapy with no evidence of harmful effects other than a temporary disturbance in auditory nervous systems in a few cases. Ultrasonics, when carefully focused, can be used as a valuable therapeutic tool in producing localized lesions and for cauterization. These high-powered machines could be very dangerous if operated by non-experts. Much progress has been made in the use of ultrasonics as a method of diagnosis of soft tissues and organ systems. Like all other sources of energy, sound, infra-sound and ultra-sound have become pollutants only where they have been misused or there has been a lack of proper control.

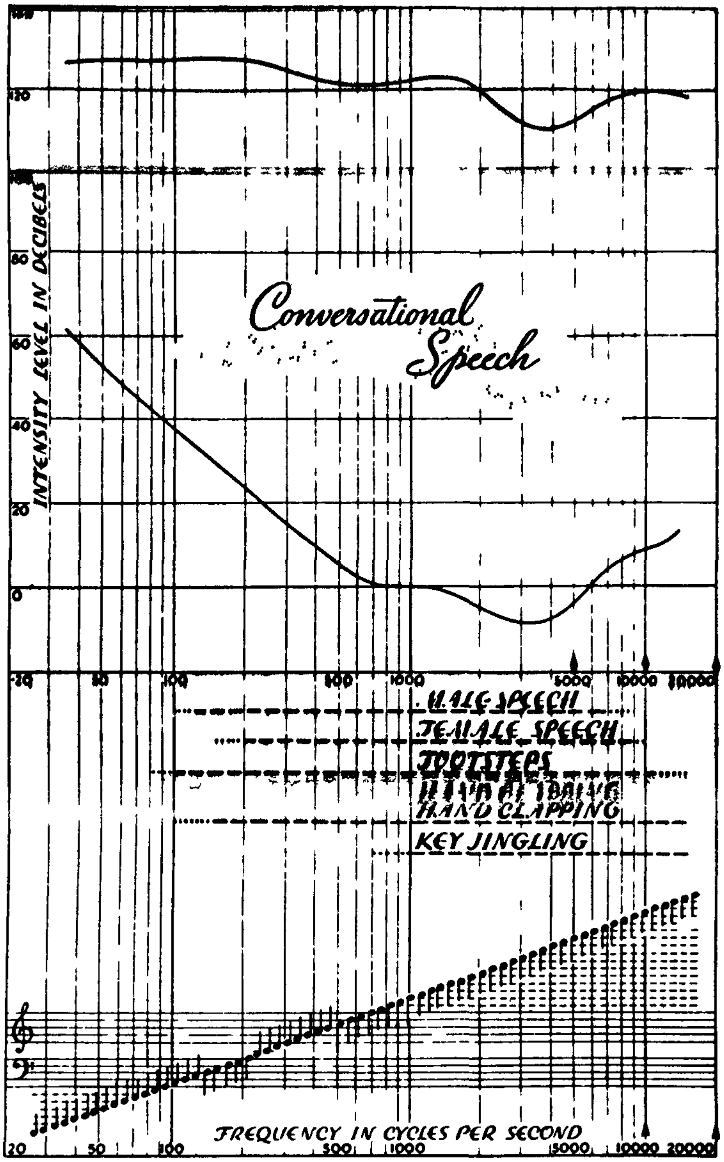


Figure 3. Range of sound intensity of speech and other sounds. (In this case, 0 db corresponds to 10^{-16} w/cm^2. The curve at middle of graph is lower limit of human hearing.)

Chemical Energy

As mentioned above, when considering energy pollution of man's environment, we must consider both kinetic and potential energy. In the case of chemical energy, I am considering it primarily from the standpoint of various chemicals in the air, water and food which serve as sources of potential energy in the ecosystem and in our bodies. For reasons mentioned above, I do not intend to more than mention a few of the problems associated with chemical energy pollution; I will suggest enough perhaps to justify the broad title assigned me for this lecture. Pollution of our atmosphere, rivers, farms, lakes, cities, homes and bodies by almost countless chemicals--many of them unknown--and by various energy exchanges they bring about is, I believe, the most serious pollution problem next to overpopulation facing this so-called civilized society in which we live. P.H. Abelson(3) indicated that as many as 500,000 different chemicals are finding their way into our water systems. Many of these in sufficient amount are known to be toxic and believed to be carcinogenic and/or mutagenic. Many of them are harmful to man's environment such that their indirect damage may be as great or greater than the direct damage to man. For example, excess phosphates and nitrates probably are at the top of the list as the most harmful chemical pollutants of our rivers and lakes. For the past decade, I have flown frequently into Los Angeles, Chicago and New York, and have seen the clouds of smoke and smog become more and more dense over these cities. I have had a sense of pity for my fellow Americans who must live in such an unpleasant atmosphere. However, now that the TVA Bull Run coal-burning power plant has been in operation at the edge of my hometown, Oak Ridge, I frequently see a great cloud of smoke extending from the stack at Bull Run toward Oak Ridge and get a firsthand impression of the great harm these chemical pollutants bring to our home communities; many times I wish this might have been a nuclear fuel plant instead.

As indicated in Table 1,(4) motor vehicles discharged over 60%, or 8.6×10^7 tons of the principal atmospheric pollutants in the United States in 1966. The pollution control devices being required on cars in the State of California represent an important step forward, but I believe since this only partially solves the chemical pollution problem and in no wise reduces mechanical pollution discussed above (congested traffic, highway accidents, parking, etc.), other means of clean, fast and efficient transportation must be developed during this decade for our big cities; just to add to our throughways more lanes--4, 8, 12, etc.--is a poor and, at best, a temporary expediency. Although 60% of the total mass of man-made atmospheric pollution derives from motor vehicles, they contribute only 4% of the SO_2 which in some respects may be our most harmful chemical pollutant. Fossil-fueled power plants, on the other hand, contribute 50% of this pollutant. B. R. Fish(5) has called attention to the fact that for many of the world's major air pollution disasters--Muse Valley, Belgium (1930), Donora, Pa. (1948), London, England (1952)--SO_2 was present in high concentrations along with the other atmospheric pollutants and may have been the major cause of the large number of fatalities. I do not believe we can at present assess with any accuracy the relative risks from CO, CO_2, SO_2, O_3, NO, NO_2, hydrocarbons, particulates, etc.,

Table 1

SOURCE OF AIR POLLUTION
(in millions of tons annually (1966))

	Carbon Monoxide	Sulfur Oxides	Nitrogen Oxides	Hydro-carbons	Particulate Matter	Totals
Motor vehicles	66	1	6	12	1	86
Industry	2	9	2	4	6	23
Power plants	1	12	3	1	3	20
Space heating	2	3	1	1	1	8
Refuse disposal	1	1	1	1	1	5
Total	72	26	13	19	12	142

in the atmosphere, and we probably know even less about the effects of some of the metals (Pb, Sb, As, Be, Cd, Bi, Cr, Hg, etc.) and their compounds which reach high concentrations in some human environments. We do know that the lungs of a normal, healthy adult processes 40-60 pounds of air per day, i.e., 600 tons of air in a lifetime, which is an order of magnitude greater than the combined intake of food and water. Thus, the lungs of the average person living in a big city must bring into the body many pounds and tremendous assortments of unwanted and harmful chemicals along with the dust, tobacco smoke, gasoline fumes, aldehydes, acids, phenols, bacteria and viruses. Often, essential elements are ingested in excess or even in dangerous amounts. Among these, we might mention two--iodine and fluorine. Pittman et al(6) point out that more than 40% of all bread produced in the U.S. will increase the chance of toxic thyroid gland enlargement as a result of the large amount of iodine added to bread in the new, continuous mix process where 150 µg is added to the average slice of bread. Adult daily requirement of iodine is between 150-300 µg, and normally a person obtains what he needs by eating a balanced assortment of natural foods. However, many persons are obtaining what may be a harmful excess of iodine from eating bread and iodized salt. Similarly, now that many city fathers can point with pride to the fact that the water in their city systems is fluorinated, and the children should have "no-cavity" teeth, many of them are forced to have second thoughts. It is reported(7) that fluorine may injure especially the older members of the population and that it is damaging to the kidneys and liver and produces many undesirable side effects. Some are claiming that its use provides little evidence of improved teeth in children. It is difficult to evaluate such claims, but it seems very probable again that too much of a good thing--even iodine and fluorine--may be harmful. Many of the airborne pollutants are harmful not only to man but also to his buildings, bridges, automobiles and to his forests, agriculture and farm animals. For example, J. G. Terrill et al(8) point out that 0.3 to 0.5 ppm of SO_2 is the threshold for alfalfa, and 0.3 ppm is regarded by the State of California as an "adverse" effect level for humans. Carbon dioxide is not ordinarily thought of as a harmful environmental vector (it promotes deeper breathing) but rather as an essential component of our atmosphere for photosynthesis to function and for plant life to be possible. However, again, too much of a good thing (e.g., fertilizer, cars, liquor, women, etc.) can bring about the spoilation of man's environment and eventually his undoing. Terrill et al(8) point out that the average worldwide concentration of CO_2 has increased 8% since 1890, and the Environmental Pollution Panel of the President's Science Advisory Committee states by the year 2000 there will be a 25% increase in CO_2 over the present level. There is good cause for concern that this increase in CO_2 may result in a serious "greenhouse" effect that will bring about marked changes in the world climates. The increase in CO_2 in the atmosphere "captures" solar heat much as does a greenhouse, resulting in an increase in the average temperature of the earth which in turn would cause the polar ice caps to melt and raise the sea level to flood many of the major cities of the world. Abelson(3) points out, however, that man's atmospheric pollution with dust particles may counteract this effect in that solar energy striking these particles is diffracted and reflected away from the earth and back into space. In addition to inhalation of chemical pollutants, man ingests thousands of contaminants as additives in his food and water. J. J. Hanlin(9) points out that one of two Americans is served drinking water that either does not measure up to federal standards or is of unknown quality. Man must contend with fungicides, insecticides, fertilizers, preservatives, detergents, birth control pills, cosmetics, antibiotics, drugs, sewage, etc., that are taken in with his food. It is amazing that our bodies have been able to cope as well as they have with all of these insults. I am afraid, however, in this business of chemical energy pollution we have been pushing our luck too far and must mend our ways unless we pass the point of no return for our descendants.

Electromagnetic and Elementary Particle Energy

As indicated above, I am including elementary particles in this category because electrostatic forces are always associated with charged particles, and magnetic forces are always associated with the spin or translatory motion of these particles. I include also all the neutral particles (i.e., the mesons, π^o and k^o, and the baryons, n^o, Σ^o and Ξ^o) as well as their anti-particle counterparts because they are usually associated with the production of charged particles. Figure 4 shows the wide range of the electromagnetic energy spectrum, all of which produces energy pollution in our modern world. Even the radiations of the lower portion of the cosmic ray spectrum (from about 10^6 to 10^{10} ev) are now produced artificially as intense sources of radiation by present-day, high voltage accelerators. Likewise, astronauts are concerned about these cosmic radiations as they pass through streams of them trapped in the Van Allen belts, and they must feel some apprehension when they are in space or walking on the moon far beyond the earth's protective, magnetic field which quietly traps or turns away most of the ionizing particles headed toward the earth or moves them toward the earth's geomagnetic poles. Man in space is outside the blanket of air about the earth which absorbs and degrades the energy of the cosmic ray particles which penetrate the earth's first line of defense--its magnetic lines of force. Except for the earth's defenses in depth from the bursts of protons and electrons that periodically shoot out from the sun at the peak of the 11-year sunspot cycles (sometimes reaching very high intensities), survival on this earth through ages past might have been far more difficult.

When our assortment of high voltage accelerators consisted of relatively small Van de Graaffs, Cockcroft-Waltons, betatrons, and cyclotrons and when the electrons and protons, alpha particles and neutrons they produced were confined mostly to the basement accelerator rooms of the university physics department, we thought radiation protection problems were difficult enough for the health physicist. Today, however, our problems are far more challenging with the large synchrotrons and linear accelerators that have racetracks stretching out for miles. These monstrous machines, in addition to photons, can produce the whole array of leptons, mesons, baryons and resonant particles; every now and then new particles are reported. Thus, it is sometimes difficult for the health physicist just to keep track of the many particles, their classifications and the principal reactions they are expected to undergo in the body. The health physicist

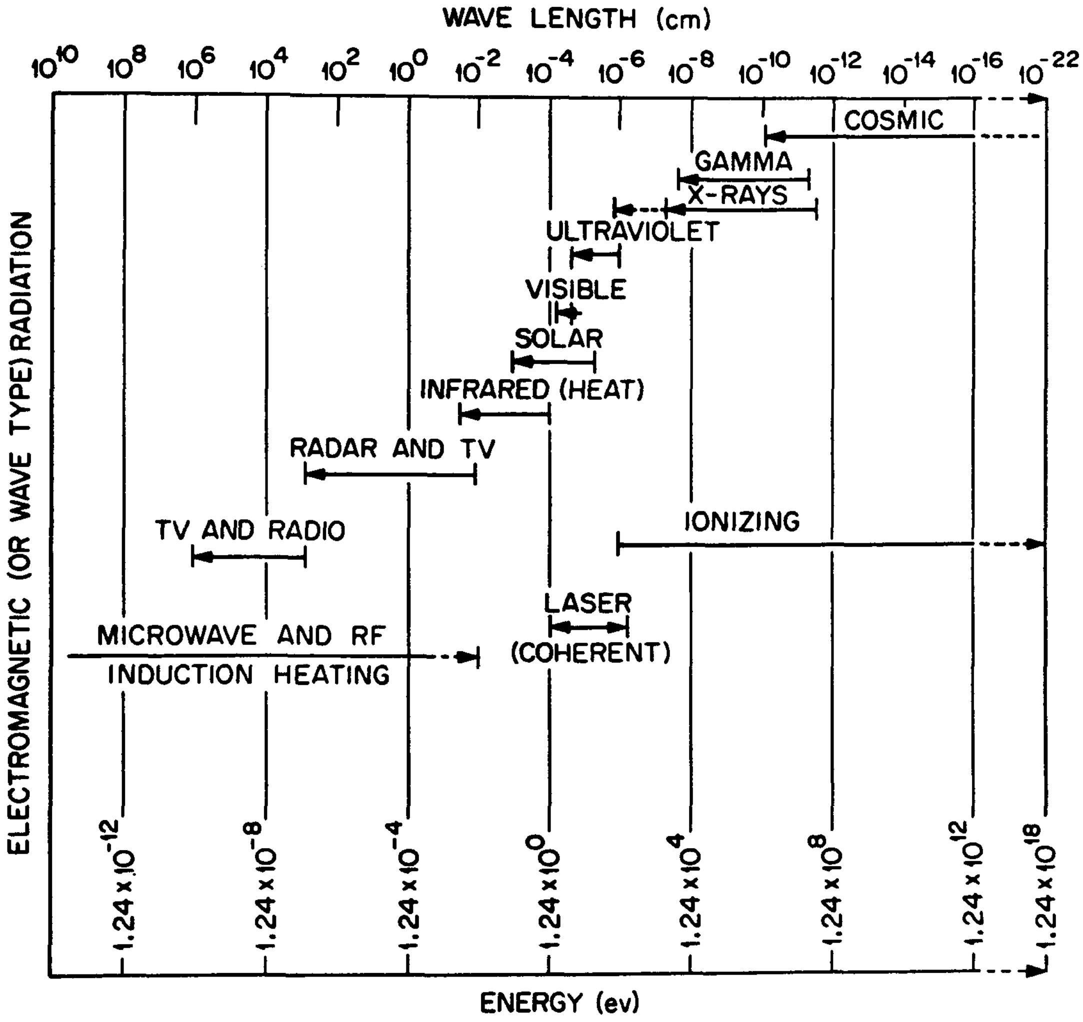


Figure 4. Electromagnetic energy spectrum.

must measure the dose these particles and their daughter products deliver and try to evaluate the biological consequences of such exposure. Also, the induced activities in the targets, equipment, and gases must be followed carefully in space and time, and the isotopes produced provide a constant need for health physics expertise. The radionuclides produced both by accelerators and nuclear reactors must be monitored all the way from their primary use in the hospital, university or industry to the final disposition in the radioactive waste disposal facility and often to the city sewage or garbage dump where pollution control becomes very difficult.

The health physics problems associated with primary radiations (neutrons, alpha, beta, gamma and x radiations) of nuclear reactors and with nuclear fuel reprocessing plants for the most part have been under effective control of the health physicist. The hundreds of various radionuclides produced by reactors and high voltage accelerators present more difficult problems of energy pollution than the machines that produce them because these radioactive materials are shipped to all parts of the world; their radiations are used in medical applications, static eliminators, thickness gauges, radio tubes, light sources, radiographic sources, tracer experiments, and in power generating plants. These generators are operating in polar regions and on the ocean floors, and some are circling our earth in satellites or supplying electrical energy to power equipment on the moon--perhaps inhabitants of the moon someday will condemn their earth ancestors for energy pollution of their living space. The most important mobile reactors are those used in nuclear submarines and ships. At present, there are seven reactors used for surface-ship propulsion and 118 for submarine propulsion. These nuclear-powered ships ply the seven seas and many of the rivers and lakes. In spite of fears expressed by some prophets of doom and the sinking of a few nuclear submarines, these vessels have demonstrated a remarkably good safety record in terms of maintaining their environment relatively free of radioactive contamination. The idea of nuclear airplanes has never been entirely abandoned, and some day these massive birds may wing their way into the crowded skies.

While speaking of nuclear power plants and their rather minimal pollution problem, it is perhaps appropriate to emphasize that we are in no case concerned about the possibility of a nuclear weapons type explosion occurring with one of these reactors--such an explosion would be impossible. For the most part, we are concerned with low levels of radioactive waste discharged from these plants; while with the larger units such as nuclear power plants, I am apprehensive concerning thermal pollution and the fact that the secondary containment of these plants is not designed at the present time to guarantee against rupture of the secondary containment in case of the so-called incredible accident (one beyond the design limitations). It is for such reasons I have indicated that I believe(10) the AEC should not yield to pressures of the electrical power industry to move the very large nuclear power plants into densely populated areas. I would be quick to add an even stronger admonition that power plants burning fossil fuels must be located in remote areas because I believe the risks from SO_2, nitrogen oxides and hydrocarbons are far greater than any of those associated with nuclear power plants. However, until we can be assured of the integrity of the secondary containment of nuclear power reactor plants for all eventualities, I think they should be located underground or in underwater caissons in remote areas, preferably along our coasts. In the meantime, efforts should be stepped up to improve methods of energy transmission, using d. c. as well as a. c. at voltages in excess of 1 Mev, and making use of cryogenic coaxial cables, a few of which would be sufficient to transmit all of the electrical energy now used in a big city such as New York. These conductors undoubtedly would have to be built underground, and I consider this an additional asset in terms of pollution of the aesthetic qualities of our environment. I think, also, further investigation should be made into improved methods of energy conversion such as magneto-hydrodynamic, electro-gas dynamic and thermionic conversion, and we should step up our efforts to replace as soon as possible the present water boiler and pressurized water reactors with the fast breeder and fused salt thermal breeder reactors. The advantage of these breeders is not only that they produce more fissile material than they consume (and thus conserve the earth's energy resources), but they can operate at as high or higher temperatures than fossil fuel power plants, thus reducing the thermal pollution into the rivers and atmosphere. In many respects, I believe the present nuclear power plants as well as fossil fuel power plants are very crude, antiquated and wasteful in that they are burning and destroying irreplaceable raw material (uranium, coal, oil and gas) which in centuries hence will be in short supply and used only for purposes other than fuel. The thermal breeder reactor has the additional advantage that it would use thorium rather than natural uranium as a primary source of fuel, and it has, I believe, a number of inherent safety features not easily duplicated with the fast breeder reactor. One interesting safety feature which would reduce tremendously the energy pollution potential of a reactor is that with the fused salt thermal breeder the fuel could be circulated continuously to remove the inventory of fission products. As has been widely publicized, the owners of nuclear power plants are expected to take out with private insurance companies $60 million in liability insurance against a major catastrophe, and the Price-Anderson Act provides at a relatively low cost additional, federally sponsored coverage up to $500 million and relieves the reactor owners of financial responsibility for claims in excess of $560 million. Perhaps this Act itself has done a great deal to call attention to what I refer to as the incredible accident involving widespread pollution by some fraction of the reactor inventory of fission products. It is partly for this reason that I have been enthusiastic about the development of the fused salt thermal breeder reactor which, if properly designed and operated, could make such a major catastrophe from environmental pollution by radioactive fallout well nigh impossible.

The fears expressed by some scientists(11-13) of environmental energy pollution from nuclear power plant operations has resulted in a most serious questioning of the safety and acceptability of these AEC-supported programs which many of us believe are essential in supplying the energy needs of the world in the centuries ahead. I do not believe there need be any serious radiation risks associated with these operations. Because of the special importance to health physicists of the burning issues that have been raised and because of the relation of this problem to energy pollution, I will devote much of the time I have remaining in attempting to answer what I consider the most important questions that have been presented as a challenge to the AEC.

Contrary to the expressed concern of a number of scientists that these nuclear power plants may become a menace to our environment and to exposed populations, I believe they will become a menace only if a literal interpretation is made by the AEC of the present Rules and Regulations (Title 10, Part 20). I am confident these nuclear power plants can and must become one of the most important contributors of our time toward reducing energy pollution of the atmosphere. I believe the AEC should be grateful for the recent criticisms and friendly reproofs it has been receiving which call attention to sharp contradictions and inconsistencies between (1) a literal and reasonable interpretation of statements set forth in its Rules and Regulations and (2) the interpretation and implementat of these Rules and Regulations as witnessed by the actual past practices of the AEC and its contractors. Certainly these Rules and Regulations for reactor siting need to be updated and rewritten as soon as possible. As I see it, the AEC could have--but has not as yet--supplied the public with very positive and what I believe would be satisfactory answers to the criticisms that have been raised regarding this energy pollution problem as follows:

(1) Some persons apparently have interpreted Title 10, Part 20, pages 63-76 (August 9, 1966), of the USAEC Rules and Regulations(14) and ICRP Publication 1, page 16, paragraph 68 (September 9, 1958),(15) to mean that it would be appropriate and that it meets adequately the ICRP recommendations and AEC legal requirements for a nuclear power plant simply to limit the discharge of its radioactive waste to the boundaries of its restricted areas such that the radioactive concentrations not exceed 1/10 or possibly 1/30 of the ICRP values of $(MPC)^{168}_{occ}$, i.e., 1/10 or 1/30 of the MPC values for occupational exposure continuously for 168 hr/wk. Nothing could be further from the truth so far as ICRP is concerned, and the many years of operating practice of the AEC and its contractors have demonstrated that simply a restriction to 1/10 or 1/30 $(MPC)^{168}_{occ}$ is not considered by the AEC to be sufficient to assure the environmental safety of its operations. I am still waiting to hear this stated clearly and convincingly by the AEC! The ICRP, however, has stated unmistakably its position in this matter in Publication 9 (September 17, 1965)(16) and Publication 7 (September 13, 1965),(17) namely, that dose to the individual or to the critical segment of the population is the important criterion and the various pathways and food chains must be evaluated carefully and followed sufficiently to assure no member of the population or critical segment of the population exceeds 10% of the annual dose permitted to the occupational worker.

(2) I gather that some persons interpret Title 10, Part 20, pages 63-70 (August 9, 1966) and FRC Report No. 1,(18) page 27 (May 13, 1960), to mean that the AEC and FRC might consider it permissible and acceptable for a single industry such as the nuclear power industry to use the entire permissible population dose of 5 rem/30 yr or the average of 170 mrem/yr. I do not believe such interpretation was intended. The ICRP in its Publication 1,(15) page 15, paragraph 65 (September 9, 1958), subdivided this 5 rem/30 yr among various components of population exposure but merely as a suggestion of how this might be accomplished by appropriate national bodies. In later publications (Publication 9,

page 15, paragraph 87 (September 17, 1965)),(16) the ICRP points out that it no longer suggests how this partitioning of the 5 rem/30 yr (or 170 mrem/yr) should be made since this should be done by an appropriate, responsible body for each country, taking into account national, economical and social considerations. Perhaps much of the recent misunderstandings would have been avoided had the FRC taken the initiative several years ago in making appropriate partitioning of this 170 mrem/yr. Table 2 shows for illustration how this partitioning might be done, for example, by the FRC. I believe the 67 mrem/yr I have suggested for nuclear power operations out of the 170 mrem/yr would be completely adequate and that this industry could limit its use of this population dose to no more than 7 mrem/yr without in any wise hampering its future operations. In this table, I have included medical exposure because it is delivering over 90% of the population exposure in the United States from man-made sources of ionizing radiation.

(3) Some persons are suggesting that the MPC's for radionuclides in the environment as the result of nuclear power operations should be as low as possible. I consider this unreasonable, and I believe the levels set last year by the Minnesota Pollution Control Agency, which in some cases are a factor of 10^9 below the $(MPC)^{168}_{occ}$, are unreasonable and do not permit sufficient flexibility for nuclear power plant operation. My solution in this case would be simply to change the word "possible" in the above to "practicable." The levels set in Minnesota for effluents from the Monticello nuclear power plant are orders of magnitude below the levels of contamination that would be found in the effluents of power plants using fossil fuels. I feel this is an unreasonable and unnecessary limitation that under certain conditions could become very costly or prohibitive and is a restriction that would provide very little protection to the population from energy pollution.

(4) There are those who have inferred that the radiation protection standards and maximum permissible doses of the ICRP and the AEC are based on the assumption that there is a threshold dose (such as the dose from the maximum permissible body burden of 0.1 μc of radium-226) below which the exposed individual is safe from all risk from serious radiation damage such as radiation-induced leukemia or bone tumors. I cannot state the AEC's views in this matter, but I would certainly hope it has never subscribed to this hypothesis. I believe R. D. Evans is almost alone among the scientists and specialists in the field of internal dose in his adherence to and belief in the threshold hypothesis. The ICRP states its views very clearly in ICRP Publication 9,(16) page 6, paragraph 29, September 17, 1965, "A basis of the Commission's recommendations is the cautious assumption that any exposure to radiation may carry some risk for the development of somatic effects, including leukemia and other malignancies, and of hereditary effects." This is why we should keep all exposures as low as practicable.

Table 2

SUGGESTED LEVELS OF PERMISSIBLE GENETIC AND/OR TOTAL BODY EXPOSURE OF THE UNITED STATES POPULATION TO ALL MAN-MADE SOURCES* OF IONIZING RADIATION THAT MIGHT BE ADOPTED BY THE FEDERAL RADIATION COUNCIL FOR APPLICATION IN THE UNITED STATES

500 mrem/yr to any critical segment of the population

5000 mrem/ 30 yr as the maximum

170 mrem/yr as an average as follows:

	mrem/yr
Internal dose from nuclear power operations	50 (5)**
Internal dose from other industrial operations	30 (3)
External dose from nuclear power operations	17 (2)
External dose from other industrial operations	15 (2)
Medical (diagnostic)	40 (5)
Medical (therapeutic)	10 (5)
Occupational† contribution to population dose	4 (0. 1)
Weapons Fallout	2
Miscellaneous(watches, television, high voltage switches, etc.)	2 (0. 1)
Total	~ 170 (22)

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*This includes medical exposure but excludes natural background. It includes also exposure from natural radioactive sources such as uranium, thorium, ^{226}Ra, ^{228}Ra, ^{210}Pb, etc. that have been concentrated by man and includes exposure in uranium or thorium mining operations.

**The values in parentheses are those I believe we can attain. Since this is a long range extrapolation some of those values are larger and others are smaller than the present estimates of population doses from the source.

†Exclusive of the nuclear power operations.

(5) Several persons have pointed out that there are many unanswered questions which cast some doubt on the environmental levels of radiation exposure or energy pollution allowed by the AEC. To this, I can only agree, but I would be quick to add that we probably know far more about ionizing radiation and the risks from it as an energy pollutant than any other vector such as SO_2, oxides of nitrogen, hydrocarbons, etc., associated with the exhaust fumes from automobiles and from power plants burning fossil fuels instead of uranium or plutonium. We could list many problems that will continue to haunt the health physicist until he has developed a coherent theory of radiation damage. Some which we might list are the particle problem associated with microcurie quantities of plutonium-238 and -239 deposited in the lungs, the effects of low levels of radiation on animals exposed over a lifetime (20 years or more), the exact locations in the pulmonary tree in which the lung carcinomas of the uranium miners have their origin, and continued efforts to inquire whether there are unusual or unique risks from exposure to certain chemical forms of hydrogen-3.

It is estimated by W. E. Johnson(19) that by 1990, more than half of all river run-off water in the United States will be required for power plant cooling purposes if the heat is rejected to the rivers. I would consider this an unacceptable use of our rivers but doubt if cooling lakes or cooling towers are the answer. I believe the best solution will be to build a few, extremely large nuclear power plants and locate them on or just off our coasts so that the heat can be dumped into the sea. J. C. Frye(20) has suggested that an investigation be made of the feasibility of using waste water from secondary sewage effluent as a coolant for nuclear power reactors. A. P. Fraas(21) suggested that the cheap heat of these power reactors be used to distill the sewage to solid wastes. Certainly, we must find some useful application for this tremendous loss of energy to power plant cooling water. I consider myself a conservationist as well as a health physicist and believe the only way the conservationist can be satisfied is to find some useful application of this waste heat such as the processing of sewage, space heating of homes and greenhouses, etc. Figure 5, taken from the paper by H. T. Peterson et al,(22) shows one of the many projected estimates of electrical energy requirements in the United States and forecasts that half of the U. S. requirements will be from nuclear energy by about 1990.

One of the concerns about this nuclear power program is the hydrogen-3 that may be released to the environment. Figure 6, also from Peterson et al, indicates the buildup of hydrogen-3 in comparison with that present naturally in the environment and that produced by weapons tests. It is estimated that by about 1990 the reactor-produced hydrogen-3 will about equal that present naturally in the environment. K. E. Cowser et al(23) estimated this hydrogen-3 in the environment may deliver doses by 2000 of 7×10^{-4} mrem/yr from inhalation and 1.4×10^{-3} mrem/yr from drinking water. Figure 7 from J. R. Coleman and R. Liberace(24) shows estimates of the dose rate from krypton-85 to the year 2060. Cowser et al(23) estimates the dose by the year 2000 from krypton-85 to be 1.8 mrem/yr.

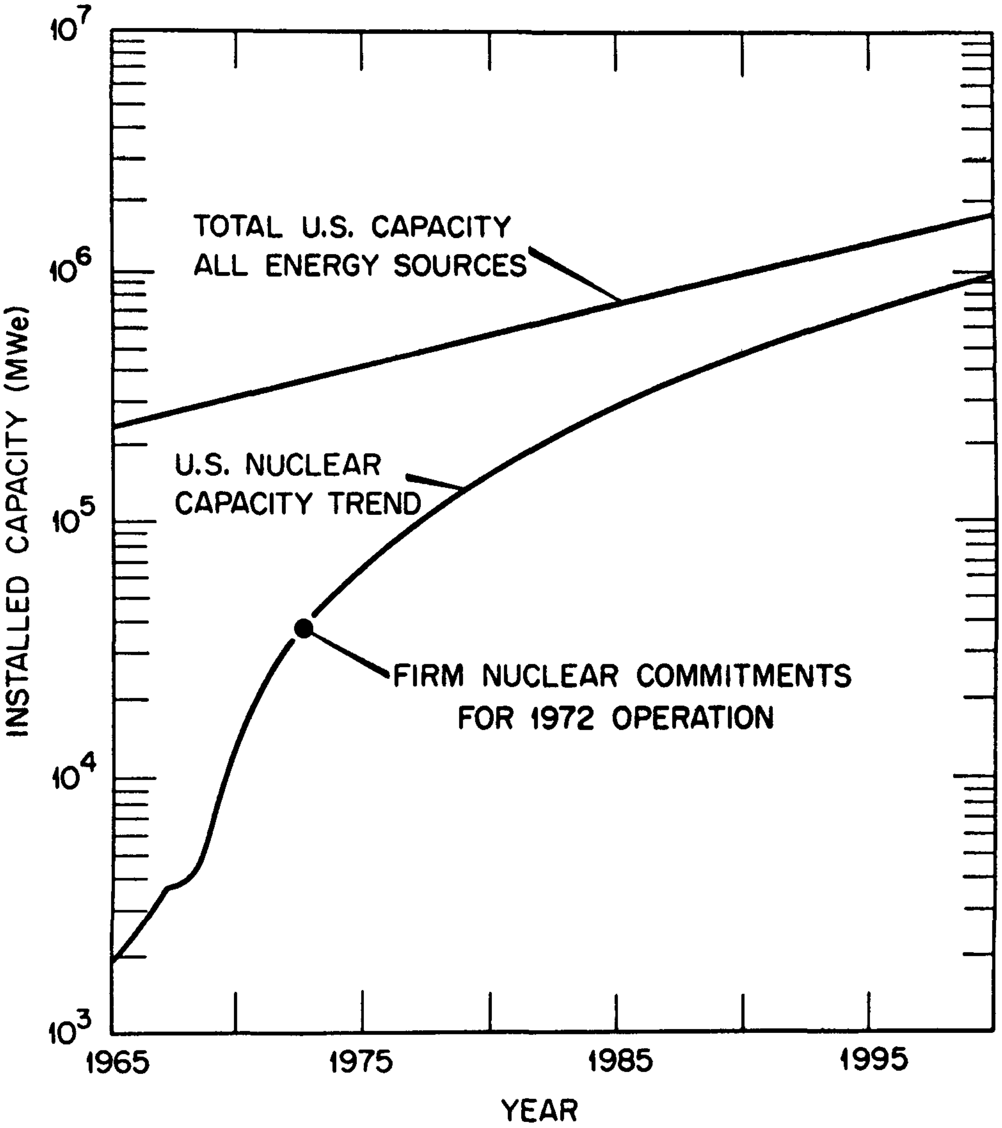

Figure 5. Projected power generating capacity from nuclear reactor discharges.

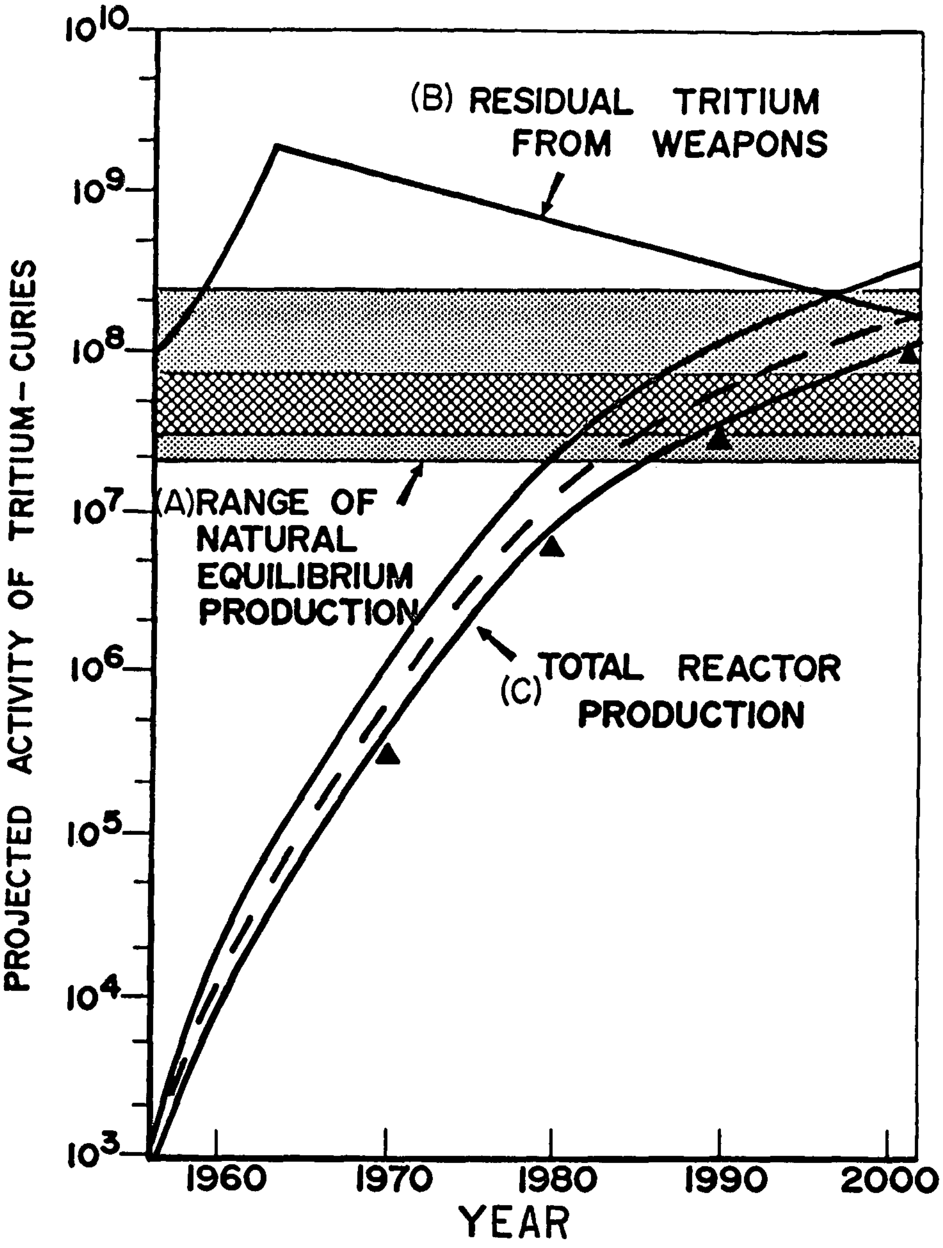

Figure 6. Comparison of tritium activity from: (A) natural production (wide range = all estimates; narrow range = most probable estimate), (B) residual weapons fallout, (C) U.S. reactor production and (D) worldwide reactor production (▲) estimated by Cowser et al.(23).

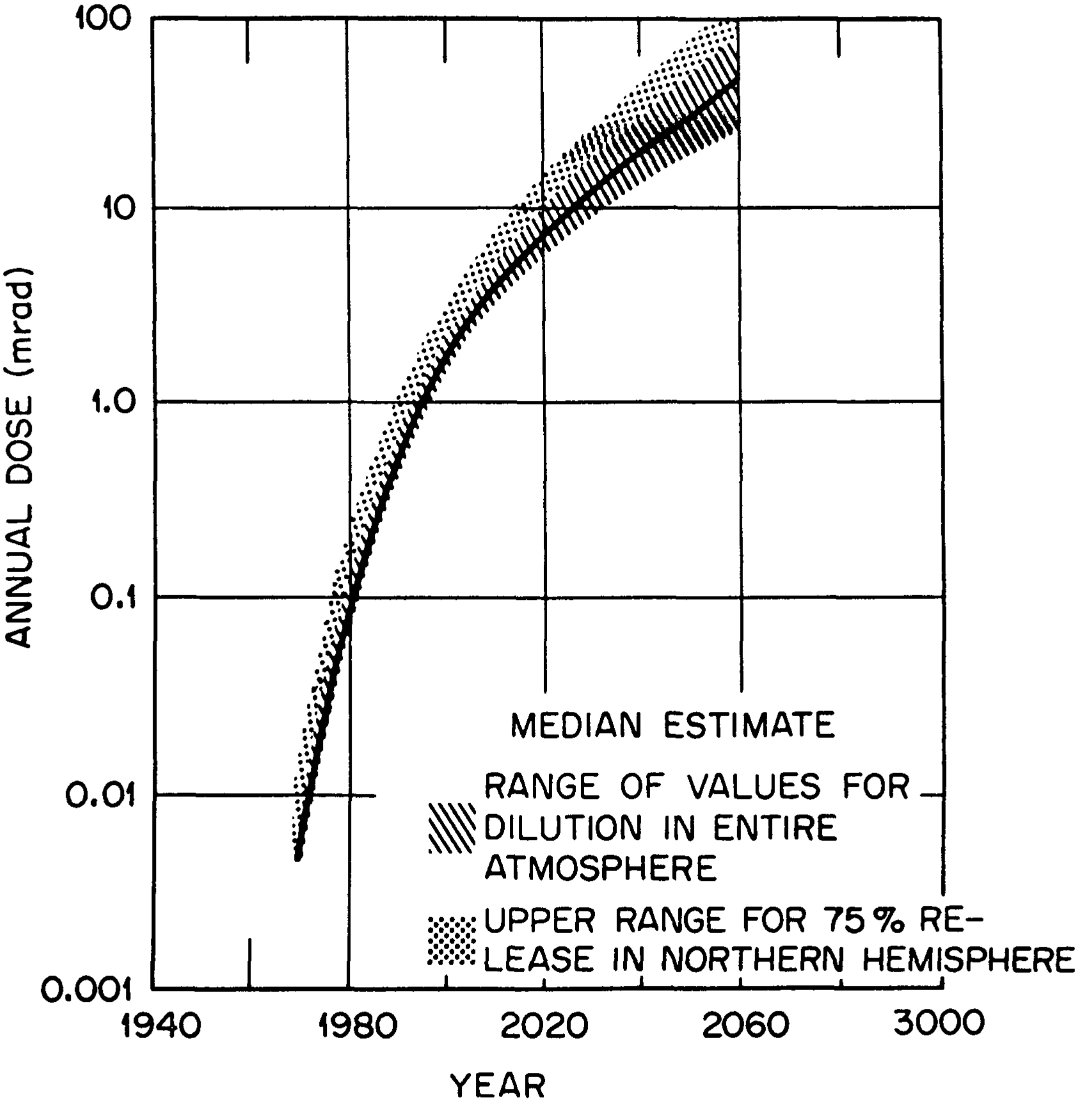

Figure 7. Estimated annual dose from krypton-85. 1970-2060

Although this is less than 2% of the average natural background radiation, I consider it a very significant contribution to the population dose or energy pollution. On the linear hypothesis, we would expect this to introduce from 3,000 to 12,000 deaths/yr from genetic mutations and malignancies in a population of 3 x 10^9. Methods of krypton-85 removal are now rather well worked out, and I believe it is likely that they will be implemented before the krypton-85 becomes a problem. It should be pointed out that the estimate of dose depends very much on the assumptions made in the calculations. For example, Coleman and Liberace(24) estimated the krypton-85 dose to be on the order of 50 to 100 mrad/yr by the year 2060. It is obvious from the above that if these calculations of dose are correct, the urgency of removing the krypton-85 will be very great by 2060. After the year 2050, I predict fusion reactors will have come into their own and will slowly replace fission reactors for power plant operation. These reactors would have the advantage that there is essentially an infinite power supply because the oceans could now be the source of fuel. One of the finest features of these reactors from the standpoint of energy pollution is the fact that they would not produce fission products and that the only radionuclide of significance would probably be hydrogen-3. D. J. Rose(25) has made what is probably the most conservative possible assumption, namely, that if all the world's power of every kind were produced by nuclear fusion and the power were the maximum permissible without warming unduly the world (10^{22} j/yr or 0.25% of the earth's incident solar energy), the steady state inventory of hydrogen-3 would be 4.3 x 10^{16} curies worldwide or 430 rem/yr. He suggests, therefore, that the operation should be such that less than 10^{-4} of the tritium is released or a world dose of less than 40 mrem/yr/person. I would suggest this reduction factor should be no more than 10^{-6} or a world dose of 0.4 mrem/yr/person from this source of hydrogen-3. Rose goes on to point out that A. P. Fraas(26) has worked out a promising method for the removal of hydrogen-3 from a fusion reactor blanket, and, therefore, long before the year 2500 when we might approach this upper limit of such a calculation, the release of hydrogen-3 to the environment could probably be reduced essentially to negligible quantities. In any case, during the next 400-500 years our descendants will have plenty of time to work on this problem.

Probably the most widely publicized worldwide energy pollution problem associated with radioactive contamination has been the fallout from nuclear weapons testing. Some of us were gratified with the passage of the weapons atmospheric tests moratorium. Fallout, with the exception of a few slight rises due to the French and Chinese weapons tests, has been decreasing during the past few years. For example, it is estimated by W. D. Cottrell(27) that the gonad and total body dose from cesium-137 was 1.2 mrem in 1966, 0.68 mrem in 1967 and 0.54 mrem in 1968, and the average dose to bone marrow from strontium-90 was 3.6 mrem in 1966, 2.8 mrem in 1967 and 2.3 mrem in 1968.

There has been some apprehension expressed, also, regarding the atmospheric energy pollution if certain plans for the Plowshare program are carried out. I believe nuclear devices offer the promise of saving billions of dollars in excavation for minerals, in releasing gas in certain natural formations, and for harbor and canal excavations. I am convinced that we must weigh very carefully the risks against the benefits we expect to derive from such applications. Before we permit any unwarranted radiation phobia to frighten us away from such explorations into peacetime applications of the nuclear bomb, we must have a good assessment of these risks and an appropriate body must decide on their acceptability. It is estimated that a canal across the isthmus of Central America could be dug for $1 billion less if nuclear explosives were used rather than chemical explosives. I would favor such a program if relatively "clean" weapons were used and if detailed studies indicate this use of nuclear devices can be carried out with sufficient safety to local population groups and if those governments most closely concerned approve.

Another possible source of energy pollution from radioactive material is aborted satellites carrying nuclear power plants, such as, for example, the plutonium-238 device which was incinerated over the Indian Ocean in 1964. Another similar problem is the destruction of nuclear weapons in fires and chemical explosions such as were experienced in 1966 on the coast of Spain and in 1968 in Greenland. I think it must be assumed that until man learns to live in peace, trust and harmony in all parts of the world, we will have to continue expecting accidents with satellites, planes and submarines carrying nuclear weapons. Let us hope and pray the world will never be led into the worst conceivable situation of energy pollution, namely, a nuclear war.

Microwave, radiofrequency, ultraviolet and laser radiations are an important part of the energy polluters we have classed as electromagnetic and elementary particles, but, as I have indicated above, we will avoid extended discussion of them since immediately following this lecture we begin a three-day discussion of them. Radiofrequency is used, for example, in communications, diathermy units, cauterizers, etc., and microwave is used in ovens, dryers, heaters, spectroscopy, alarm systems, diathermy units, radar, TV transmission, communications and navigation devices. One of the problems of greatest immediate concern in this area has been the rapid expansion in the use of microwave ovens in restaurants and in homes (40,000 of 100,000 in use are in homes). R. H. Finch(28) recently reported that a random survey of microwave ovens indicated one in three is leaking enough to be a potential problem. There have been a number of reports(29) indicating the possibility of damage to the gonads, eye and other body organs, especially of the repairman who sometimes is exposed in excess of 10 mw/cm^2. Although microwave, as indicated in Figure 4, extends from about 300,000 MHz to 300 MHz (1 mm to 1 m), rf from 300 MHz to 30 MHz (1 m to 10 m) and other industrial frequencies from 30 MHz to 30 Hz (10 m to 10^4 km), the classifications are quite arbitrary so that lower frequencies (longer wavelengths) can and have been extended below the limits shown in Figure 4, and the higher frequencies (lower wavelengths) overlap into what we call infrared. For this reason, I am including infrared in this discussion with microwave or the SHF band of radiation. At these higher frequencies, however, it is unlikely that biological effects are distinguishable from those caused by deeply penetrating heat radiation. Shortly, we will hear from the experts who think in terms of frequency bands and will define for us some of the characteristics of the SHF, UHF, VHF and HF bands. Also, they will tell us of some of the health physics problems associated with and characteristic of each of these frequency ranges. Some of the problems we will hear about will be the relative biological significance of the electrostatic field, E, and the magnetic field, H, and perhaps conclude that most of the biological risk occurs by way of the E component. Also, I anticipate we will hear about factors that affect the amount of biological damage such as frequency, harmonics, nature of modulation, rise time of pulse, standing waves, power, peak power, relative strength of E and H components of field, near and far fields, exposure pattern, methods of measurement, power output, power density, fluence, absorbed energy, ambient temperature and humidity, kind and size of animal or organism exposed, kind of damage investigated, etc. There are many types of damage reported as a result of excessive exposure to these radiations. There are many who believe that the damage to man from exposure to these radiations is due entirely to the heat produced in the body, but we will find that there is a growing mass of evidence that other exchanges in the body are responsible for many types of damage. At high doses, this radiation can cause cataracts, sterility, stunting of growth, burns, etc. At lesser doses, the Soviet scientists report microwave radiation can result in headaches, fatigue, aches, changes in the EKG pattern, drowsiness, depression of mental functions, involuntary motor functions, etc. Presumably, the Soviets have recommended a maximum permissible power level of 10 $\mu w/cm^2$, a factor of 10^3 below that commonly used in the United States. I await enthusiastically the opportunity to hear the last word from the experts working in this field. Likewise, we would welcome an evaluation of the few studies that seem to indicate various forms of biological damage from stationary or static E and H fields. With the very high voltages produced by some of the electrostatic machines and extremely high currents possible using superconducting magnets, these static E and H fields may extend over fairly large areas in which parts of the body may enter, and the question of whether biological damage can result from static fields may become more important to the health physicist than simply academic interest. Many types of lasers will be discussed on the program that follows, and, here, as with rf and microwave, I predict we will find there is room for considerable improvement in instruments, measurement techniques and hazards evaluation on the part of the health physicist. I believe we will find the principal risk with lasers is from superficial burns and cataracts. Unlike the case with x-rays, microwaves and rf, we need not be concerned about internal damage except where we burn a hole in the body or the radiation is focused on the retina by the lens of the eye. Microwave lasers will bring problems of both coherent and microwave radiation.

With laser radiation as with uv, we must be careful in providing protection from radiation reflected by almost any smooth surface. Similarly, when monitoring microwave and rf radiation, the health physicist must be cautious to prevent reflected radiation from conducting surfaces and from dipoles; for example, a wire reinforced pipe cleaner stuck through a "Faraday's cage" door of a microwave oven by the child may lead to excessive exposure. In making microwave and rf surveys, care must be taken to locate standing waves. Similar problems of reflected waves from smooth surfaces and standing waves must be evaluated in the case of mechanical radiations such as sound and ultrasonics. Ultraviolet radiation (3970 to 163 Å), as seen in Figure 4, is on the high energy or low wave length side of the visible spectrum. At wave lengths shorter than 136 Å, there is a spectral region that has not been extensively explored until we reach the so-called grenz rays at about 2 to 5 Å. The common bands of ultraviolet radiation are (beginning with the visible spectrum) 3970 to 3000 Å called the near ultraviolet, 3000 to 1850 Å called short ultraviolet radiation, 1850 to 1200 Å called the Schuman region, and 1200 to 136 Å called extreme ultraviolet. Ultraviolet radiation is finding increasing uses in research (uv microscope), medicine (air sterilizer in hospital rooms) and industry (photographic and reproduction facilities) and thus must be considered as an energy pollutant at least by those who receive skin burns or eye damage from sources that are not under proper health physics supervision.

I will conclude this review of energy pollutants with a brief discussion of the most important source of population exposure to ionizing radiation, namely, x-rays. Over 90% of all man-made exposure to ionizing radiation in the United States is from medical diagnosis. I(30) and others(31, 32) have shown that this exposure can be reduced to less than 10% of its present value with very little effort simply through education and training of all those who use this radiation in medical diagnosis and by the employment of better equipment and techniques; for example, the U. S. Public Health Service(33) made the shocking disclosure, "It is estimated that restriction of the x-ray beam to an area no larger than the film size would result in a reduction of the genetically significant dose from 55 to 19 mrad/person/yr." In other words, energy pollution from ionizing radiation to the gonads could be reduced almost by a factor of 3 simply by confining the area of the beam to that of the film. This is just one of the 63 improvements I(30) suggested in the Congressional hearings which could be implemented with very little effort to bring about this reduction in exposure by a factor of 10. Of great importance, also, is the fact that almost all of these improvements in education, techniques and equipment would result in a vast improvement in the quality and quantity of information provided from medical radiograms. I would like to emphasize here that I am not advocating any reduction in the beneficial uses of medical diagnostic x-rays which I believe are probably saving over 100,000 lives each year and is one of the most important of medical tools. If one assumes a linear relationship between dose and effect, this medical diagnostic exposure in the United States is introducing into the population from 3,000 to 30,000 deaths/yr from genetic mutations and malignancies. Most of this damage derives from unnecessary exposure due to carelessness, ignorance, and lack of proper motivation on the part of the medical and paramedical personnel who use this equipment. It is this unnecessary or wasted exposure from medical x-ray sources that I believe we health physicists should do all we can to eliminate. Unnecessary diagnostic exposure is not only the cause of unnecessary deaths in the population but is introducing suffering, severe handicaps and malformations into future generations. I know of no area in energy pollution where the health physicist can accomplish more for his efforts than here. Sometimes I am led to wonder why so much concern by members of the public about the less than 1 mrem/yr of population dose from operations of the AEC and its contractors and yet so little concern about this unnecessary diagnostic exposure of 55 mrem/yr genetically significant dose and greater than 100 mrem/yr somatic dose. I must confess I become rather impatient at times with the American Medical Association, the American College of Radiology and HEW for the slowness at which they have faced seriously this problem. It is difficult, also, to understand why such worthy organizations as the American Cancer Society and the March of Dimes have not done more to concern themselves with this radiation pollution problem which causes so much unnecessary suffering and death.

Although of far less importance in terms of contribution to population exposure, there are many other x-ray sources that lead to energy pollution; a few of these are television (including the voltage regulator, rectifier and picture tube), industrial x-rays, electron microscope, x-ray diffraction equipment, shoe-fitting machines, high voltage vacuum switches and condensers. Although it has been shown by H. J. Rechen et al(34) that under what are probably the worst possible circumstances some color television sets could be made to deliver doses as high as 800 R/hr at the bottom of the set, it is very unlikely that any sets in home use have ever approached this level. The surveys in Clearwater(35) and Washington(36) revealed no sets approaching this extreme. However, Rechen's studies do emphasize the urgency that was developing for some agency such as the Public Health Service to bring about the necessary corrections. The Washington survey, moreover, did indicate that 6% of the sets examined exceeded the National Council on Radiation Protection permissible limit (0.5 mrem/hr at 5 cm). Equipment such as the high voltage vacuum switch is particularly dangerous because it has been marketed and placed in use in industry, hospitals, universities, etc., without any indication or warning that it becomes under certain circumstances an intense x-ray source. Haywood and Auxier(37) measured several of these devices, finding doses as high as 1 R/hr at a distance of 10 feet. I would say the chance of someone showing injury a short while after exposure to a high voltage vacuum switch is many orders of magnitude greater than with color television. However, since there are over 15 million color television sets in use in homes in the United States, this presents a far greater long-range problem.

In conclusion, I have covered very briefly a few of the problems of energy pollution from mechanical, chemical, electromagnetic and elementary particle energies. Although I have discussed them separately, it should be kept in mind that they usually interact with each other, sometimes displaying a synergistic relationship. All these energy forms are essential to our modern way of life, and, if kept under proper control and used intelligently, they will make this world a much happier place in which we and our children may live.

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~~THE~~ IMPACT OF THE ELECTRONIC PRODUCT RADIATION CONTROL PROGRAM
(P.L. 90-602)

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In this presentation it is intended that you be made aware of the impact of the electronic product radiation control program generated by Public Law 90-602. I will tell you who this program influences, and what the impact is. There is an indication that the public health philosophy regarding control of radiation and how the Radiation Control for Health and Safety Act of 1968 is structured to achieve the objectives of this philosophy. Further, I will describe in part the evolution of two performance standards: one for television receivers which is now in effect, and the second for microwave ovens which is still in the process of development.

The Act has a direct influence on most all of us. This includes you as members of a professional society chiefly dedicated to dealing with radiation. It includes the staff of the Bureau of Radiological Health as a part of the Executive Branch of the government which must discharge responsibilities under the Act; it includes investigators and researchers in universities and private foundations concerned with bioeffects, instrumentation, and basic phenomena; it includes manufacturers, distributors, and dealers of electronic products; and it includes all of us as the purchasers of such electronic products.

In each instance the impact has a different result. To you as members of a professional society which has as its objectives the development of knowledge of radiation and the practical means of dealing with radiation in man's environment, the Act must be seen as an incentive in accelerating the achievement of your objectives. Individually as employees of a public agency each of you may have another reaction, and there may be a somewhat different reaction if you are employed by industry. To us in the Bureau of Radiological Health, Public Law 90-602 required some reorientation of effort.

The impact of the Act on manufacturers, distributors, and dealers of electronic products likely has the greatest range. The impact may be a workload concerned with records and reports, with certification and labeling, with repair and replacements, with defects and noncompliance, and with imports. And, as always, such requirements cost money and effort.

The impact of the Act on researchers and investigators is that it opens and exchanges exploration and testing in the non-ionizing radiation area as well as continued research in the ionizing radiation field.

To all of us as the purchasers of electronic products, the impact should produce sighs of relief. We would hope that, eventually, we will be able, with a degree of confidence, to purchase electronic products knowing they will be where necessary certified as conforming to applicable performance standards. These standards have been prepared, after consulting with Federal and State departments and agencies having related responsibilities or interests and with appropriate professional organizations and interested persons, including representatives of industry, and labor organizations which have given consideration to the latest scientific and medical data in the field of electronic product radiation. Further, even if there is no standard for a particular electronic product and a defect related to its safety of use by reason of the emission of electronic product radiation is identified, we as purchasers also derive protection under the Act.

Most important ionizing radiation sources are under strict governmental regulation, such as that exercised by the Atomic Energy Commission over fissionable materials and the byproducts of nuclear fission. Other electronic product sources are neither adequately studied nor controlled. For some of these sources, there is now sufficient evidence that exposure should be reduced. For others, we do not know enough about the radiation they may be emitting, or the number of people being exposed. To a public health official, this is exceedingly undesirable.

There is renewed attention to the control of environmental radiation exposure to keep it at the lowest levels possible.

Manmade radiation is one of the many environmental hazards that have resulted from technological advance, industrialization, population growth, and affluence. One of the main difficulties in coping with such hazards as air pollution, pesticides, water pollution, and radiation, is that often the health effects are delayed for many years. Another difficulty is one which health officials did not have to worry about when our main problems were the infectious diseases and our objective was simply to eradicate the disease. The simple truth is that we often cannot completely eradicate an agent which, in itself, may be closely associated with benefits as well as hazards to man. Since we cannot eradicate completely sources of radiation because they may also confer social and health benefits, we must control them to the point where the benefits clearly outweigh the hazards. And since we cannot always offer positive proof of the hazards associated with long-term exposure to low levels of a particular environmental agent, we often must act upon circumstantial evidence. But action based on association rather than cause-effect proof is not new to medicine and public health.

Dr. Donald Chadwick, of the Public Health Service, cogently summarized scientific and official philosophy on this matter at the Congress of Environmental Health held in Chicago in 1964 when he said:

> "Our knowledge of the biological effects of radiation has many gaps, but enough is known that practitioners of medicine, dentistry and public health should make every feasible effort to prevent or reduce all unnecessary radiation exposure. The size of the population at risk, and the possible consequences of failure to take appropriate action are too great".

This same principle was applied to other environmental health problems by former Surgeon General Leroy Burney in an address before the 1958 National Air Pollution Conference:

> "In law the suspect is innocent until his guilt is proven beyond reasonable doubt. In the protection of human health such absolute proof often comes late. To wait for it is to invite disaster, or to suffer unnecessarily through long periods of time".

The principal objective of the Public Health Service and other public as well as private organizations interested in radiation protection is to prevent exposure of the population to unnecessary radiation and to reduce to a minimum commensurate with need the exposures that may be necessary for medical and other beneficial applications. The extent of injury or biological hazard to humans which has resulted from or can be caused by the general operation of most types of electronic products is receiving greater attention.

Therefore, it becomes apparent that in order to provide adequate protection to the public, there is a need for a mechanism for setting standards for the manufacture of such products, particularly those which will expose members of the general public. As a result of extensive hearings during 1967-1968, the Congress passed the Radiation Control for Health and Safety Act, Public Law 90-602. The purpose of this Act is to protect the public from unnecessary exposure to harmful radiation emitted from electronic products. To accomplish that purpose, the Secretary of the Department of Health, Education, and Welfare is authorized to establish an electronic product radiation control program to include (1) the development and administration of performance standards to control emission of electronic product radiation, and (2) among other things, the undertaking by public and private organizations of research and investigation into the effects and control of such radiation emissions. Except for certain administrative aspects of the Act, the authority has been delegated to the Bureau of Radiological Health in the Environmental Control Administration of the Consumer Protection and Environmental Health Service. This was effective June 4, 1969.

The objects of the radiation control program prescribed by the Act are electronic products capable of emitting ionizing, non-ionizing electromagnetic radiation, particulate radiation, or sonic, infrasonic, and ultrasonic waves which result from the operation of an electronic circuit in a product. Electronic products such as microwave ovens, color televisions, X-ray machines, and particle accelerators and lasers are examples of products included by the above definition of the control program.

The heart of the Act is the requirement for performance standards for new equipment. The performance standard could include the definition of the maximum level of radiation emission permissible from an electronic product. Such standards may include provisions for the testing of products and the measurement of their electronic product radiation emission or it may require the attachment of warning signs and labels, or it may require the provision of instructions for installation, operation, and use of such products. In the evaluation of such a standard, the Act advises that the latest available scientific and medical data in the fields of electronic products should be considered as well as standards currently recommended by other Federal agencies having responsibilities relating to the control and measurement of electronic product radiation and public or private groups having an expertise in the field. Consideration must also be given to the reasonableness and technical feasibility of such standards as applied to a particular electronic product.

The Act required that the first standard be prescribed on or before January 1, 1970. The rulemaking for television receivers was published in the Federal Register on December 25, 1969. The development of this standard commenced after studies by the States and the Bureau of Radiological Health revealed that television receivers could emit excessive radiation and that a performance standard was necessary for the protection of the public health and safety. In the course of consulting with persons and organizations, it was determined that virtually all television receivers were designed with the intent that the exposure rate at any readily accessible point five centimeters from the surface of the receiver did not exceed 0.5 milliroentgens per hour under normal operating conditions. This 0.5 mR per hour level was the exposure limit recommended by the National Council on Radiation Protection and Measurements in November 1959. Further available information indicated that actual exposure rates from receivers designed to meet this level were generally well within this limit. However, consultations with appropriate agencies and with the Technical Electronic Product Radiation Safety Standards Committee, a committee of 15 experts established under the Act, concluded that an 0.5 mR per hour limit was a legally enforceable standard with the added requirement that the tests on receivers be made under the most adverse conditions: that is, operated at maximum rated voltage with adjustment of user and service controls to produce maximum X-radiation from the receiver together with conditions identical to those which result from component or circuit failure which maximizes X-radiation emissions. Careful consideration of all factors, including those specified in the Act, lead to the rule which was published in the Federal Register December 25, 1969 which is reasonably attainable and technically feasible. The rule will reduce electronic product radiation from television receivers to the lowest level practicable at this time and will protect the public health and safety. The standard will be reviewed as technology improves and the radiation limits will be reduced accordingly. It should be pointed out that the articles that appeared in the newspaper following the publication of the notice of proposed rule-making on October 16, 1969 did not reflect the stringent conditions of testing that are included in the standard which became effective January 15, 1970 with additional test conditions effective in June of 1970, and June 1971. This method of testing will achieve better protection of the public than the establishment of a lower emission rate initially without regard to a testing program.

In addition to the performance standard for color television just mentioned, the Bureau has consulted with the Technical Electronic Product Radiation Safety Standards Committee on several other proposed standards. These are performance standards for demonstration-type cold cathode gas discharge tubes and microwave ovens. The proposed performance standard for demonstration-type cold cathode gas discharge tubes was published as a proposed rule on January 30, 1970. It is anticipated that the performance standard on microwave ovens will appear in the Federal Register in the next several months. In addition, the Bureau has under draft a performance standard for medical and dental radiographic equipment but because of the more complex nature of this standard, it is not expected that it will appear in the Federal Register until later this year. Although the establishing of performance standards is strictly a Federal responsibility under the Act, it must be emphasized that the Act requires the Department to consult with Federal and State departments and agencies having related responsibilities or interest and with professional organizations such as the National Council on Radiation Protection and interested persons including representatives of industry and labor organizations which would be affected by such standards. Therefore, in discharging this responsibility the Department normally seeks the advice of experts. Your advice as members of the Health Physics Society can be valuable.

The proposal for a performance standard for the microwave oven was referred to above. Consider this as a case study and let us examine our actions in the development of the standard. We made an assessment of the exposure including the lack of a microwave oven standard; gave consideration to the bioeffects and existing microwave radiation standards; reviewed surveys; analyzed our instrumentation problems, determined our needs; and proposed a standard.

Some estimate and evaluation of the magnitude of radiation exposure received by the population or its critically sensitive segments normally precedes the development of a standard.

The microwave oven is a source of potential microwave radiation exposure. It consists of a microwave-generating magnetron tube, a waveguide to direct the radiation to the cooking chamber and a mixer to distribute the radiation throughout the chamber. Microwave ovens in use are estimated to exceed 100,000 units. Microwave ovens are currently available from fewer than 20 domestic and foreign manufacturers, but additional industrial firms have indicated their probable entry into this market. The increasing use of this source of energy for applications other than those of the military and industry, particularly in consumer products, warrants the study of the potential hazard to the population. It is anticipated that the population that would be affected by the increased availability of microwave ovens would be the individual owners of home ovens, patrons of commercial facilities, and employees of food service establishments.

The microwave radiation exposure received by individuals from commercial, public, and private utilization of microwave ovens is not yet clearly defined, particularly with respect to type of risk and exposure times for members of the public. The only current indications of the degree and extent of possible exposure are the results of limited field surveys of microwave oven units, almost all of which were located in commercial or food service establishments. In many cases, these same ovens with only slight modifications could be used in the home. Investigation of these units to determine the leakage of microwave radiation, during both normal and improper operation, in terms of power density (milliwatts per square centimeter, mW/cm^2), has indicated that the potential for human exposures from these devices does exist.

Factors other than power density levels that contribute to an estimate of exposure are the location of the units in relation to the individuals at risk and the duration of exposure. Most ovens are installed on counters or built as console units at comparable heights and would tend to expose the upper part of the body. The operation of these ovens is usually intermittent, and the use of the ovens by patrons of self-service food facilities would generally result in short periods of exposure. However, these latter factors of individual risk and exposure times have not been sufficiently explored. Based on survey information emission levels measured at approximately 5 cm from the surface were 10 mW/cm^2 or less for ovens under normal conditions of use where the oven had no obvious physical defects; under the same conditions, when there was leakage around the door seals, the levels ranged from 10 to 200 mW/cm^2 and under the worst conditions, done experimentally, in which the door was open and the interlocks defeated, there was a level of 700 mW/cm^2.

At present, we do not have a performance standard specifically applicable to microwave ovens. However, in order to intercompare survey results, a radiation emission of 10 mW/cm^2 will be used here as a reference value because of its relationship to existing guidance for sources and situations of microwave radiation other than microwave ovens.

The results of a number of surveys completed as of July 1969 and not including recently reported surveys by the Bureau of Radiological Health and States reported in the literature noted 494 units of which 109 units or 22 percent emitted levels of radiation greater than 10 mW/cm^2 under normal operating conditions. These results represent measurements made with either water or food placed in the oven to simulate actual operating conditions. The microwave emissions occurred at the periphery of the oven door due either to leakage through the door seal or conditions which prevented the doors from closing completely.

In addition to the potential leakage of electronic product radiation from microwave ovens resulting under normal operating conditions, a second potentially serious exposure hazard exists if safety features are either circumvented or fail.

In a recent investigation, the Public Health Service examined the types of safety interlock switches on four models of home microwave ovens and one commercial model, the manner in which they could be purposely bypassed, and the potential exposures that would result from such actions. Also studied was the radiation leakage that could be expected if microwave energy seals on the doors of the ovens failed or were worn. All measurements were made with a load of 250 milliliters of water in the oven. These measurements demonstrated that power densities exceeding 700 mW/cm^2 could be produced in front of the oven if the door safety interlocks failed or were defeated and the door was wide open. A separation distance of 120 cm between the detecting instrument and the open door was often insufficient to lower the power density level to 10 mW/cm^2. In the tests that simulated failure of the door seals, levels of 10 mW/cm^2 or greater were observed for some of the ovens at 5 cm from the door; this was similar to the observations made in field surveys when door seals were worn. The investigators noted that there were no warning mechanisms in the ovens to alert an operator of an interlock failure.

Biological research and military and occupational experience with microwave radiation have indicated that microwave exposure can cause serious bioeffects when conditions of use are not controlled.

Laboratory, field, industrial and military experience has shown that certain bioeffects in humans result from microwave exposure from sources other than microwave ovens, such as radar. Depending on the frequency of the radiation and the time of exposure, bioeffects reported in humans from microwave exposure at power density levels on the order of several mW/cm^2 to several hundred mW/cm^2 include temporary sterility in males, eye cataracts, and blood changes.

Certain effects of microwave exposure on humans reported by Soviet and other Eastern European investigators have not been corroborated by Western scientists. Although these were the result of radar exposure or special laboratory studies, similar effects might occur after exposure to microwaves emanating from microwave ovens. These effects include periodic headaches, neural disorders, and abnormal slowing of the heartbeat, and were noted at very low radiation intensities. Adequate reporting is needed in this area in order to evaluate and delineate the validity and impact of these effects. Research is needed to evaluate the possible cumulative bioeffects from microwave exposure. Experimental evidence is lacking to accurately establish the nature of cumulative effects or the existence of a threshold.

Another area of concern is the theoretical definition of "exposure" and "dose", if such a distinction can be made. This would include bioeffects comparisons, possibly analogous to studies in radiobiology, in which the relative biological effectiveness (RBE) concept is employed. Research which helps correlate microwave frequency with the degree and type of bioeffects in humans and experimental animals should be performed. If necessary, this knowledge can then be applied to setting varying exposure standards depending on frequency.

Standards have been developed by various organizations for limiting exposures from microwave equipment used in scientific, medical, and industrial, and military applications. These standards generally relate to occupationally exposed personnel. To date, a standard specifically for exposure from microwave ovens has not been promulgated.

Microwave radiation emitted at the periphery of the doors and the spaces where the door grill meets the door frame is considered a directional narrow beam. Leakage levels noted in surveys referred to above were generally limited to the periphery of the door seal. However, comments of the investigators indicated that additional important potential causes of high leakage power densities were worn door spacers, failure of interlocks, ovens operating with partially open doors, and ovens operating with completely open doors in which the interlocks were purposely disconnected. Emissions from an open door would have broad-beam characteristics and could result in whole-body exposure. The limitation of the instrumentation must be considered when evaluating such survey data. Horn antennas designed and calibrated for far field measurements have serious limitations when measurement of the near field is attempted. These fields are defined as:

Near Field - The area relatively close to a microwave source where the average power density remains relatively constant with distance and the wave front is characterized by extreme field curvature and power density variation.

Far Field - the area beyond the near field where the wave front is planar and the average power density decreases with the inverse square of the distance. The distance from the source at which the far field begins depends on the shape and size of the source and hence cannot be defined for microwave ovens.

Power density variation is extreme in the near field since the source antenna does not approximate a point source and wave fronts approach the antenna from different angles, resulting in interaction in either an additive or subtractive manner, as a function of their relative phase. In addition, an individual wave front appears to a large aperture horn to be a curved, rather than plane wave, causing phase substraction. These effects made interpretation of near field measurements made with these instruments very uncertain. Although not necessarily stated in the reports, much of the data reviewed was taken under near field conditions.

The environment in which a microwave oven is located can have a significant effect upon the power density pattern surrounding the oven. Reflected waves, primarily from metal surfaces, can interact with the direct radiation to cause an irregular power density pattern in what would normally be the far field. This interaction may result in addition of the direct and reflected beams, creating power densities in certain locations that are several times greater than would be present if the oven were in an anechoic environment. The magnitude of the increase is a function of the number and proximity of reflective surfaces present around the oven.

In summation as you can see from the very brief outline of the functioning of the Act and its impact we are dealing with a most complex situation. For one thing it covers the entire electromagnetic spectrum. The newest factor that is involved is the oldest - the consumer in the home. For another element the development of a standard is not just a matter of numbers. There are problems of instrument measurements, survey and methodology techniques, and always in the background the need for providing the ultimate in public health protection and consumer relation.

I would be remiss if I did not make a special point of our efforts to develop a Radiation Incident Registry, especially in the non-ionizing field. The development of a Radiation Incident Registry is an important aspect of the Bureau of Radiological Health research activity. The Registry concept envisions the receipt, storage, and dissemination of information on radiation incidents reported to the Public Health Service.

Although this is a Federal Act with a specific charge placed on the Secretary and subsequently on the Bureau of Radiological Health, there is no doubt that the complexity of the electronic products radiation program is such that the assistance of all health agencies will be needed to implement the Act. There are provisions for agreements to obtain the assistance of State personnel. There appears to be no reason why the agreements cannot be implemented such that the State personnel may be involved in the compliance aspects of certain industry inspection programs, and certainly we will continue to need the input from the States in the identification of problems and their concepts for performance standards.

I would also wish to reemphasize that the Act applies to electronic products manufactured after the date of the enactment, October 18, 1968. Therefore, there are still many sources of electronic product radiation manufactured prior to that date that are being used today which fall outside of the Act as it presently exists. The responsibility for these sources must be at the State or local level and we encourage the States and interested groups to continue their efforts in these areas as well as working with us on the Federal level in the implementation of the Act.

EDUCATIONAL NEEDS TO IMPLEMENT NEW RESPONSIBILITIES IN RADIATION SAFETY

ABSTRACT

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Since health physics as a professional entity is still quite new, the ways in which current health physicists were trained must be looked at first before the educational needs to implement new responsibilities can be set down. Our origins are diverse and the field especially broad in some respects. There is not yet a "core" which any health physicist can be expected to have been through, unlike the situation in the preparation of chemists, physicists, physicians, etc.

Since we are already diverse it might be argued that adding new responsibilities would be an easy matter. In a sense it may well be, particularly since the new responsibilities are in areas where the amount of directly applicable current knowledge is relatively small. Yet I believe there will be some necessary changes in education and training. Among these are the addition of much more classical physics, since much of the needed information here is, at least in part, derived from the pre-quantum aspects of physics. Likewise the biological effects are widely different over relatively short spans of wavelengths. The need to understand quite thoroughly the biological processes being affected may be greater than in the field of ionizing radiation. We should be prepared for this.

Therefore the new responsibilities may well add the need to become adept in not only classical physics but in classical physiology and other areas of biology not currently in the usual training program for either health physicists or radiological health specialists. On this basis new curricula can be developed and an example will be given.

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EDUCATIONAL NEEDS TO IMPLEMENT NEW RESPONSIBILITIES IN RADIATION SAFETY*

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When we consider the demands which the broadened base of activities of the health physicist place on his education and training we must first look at how he is educated currently. Unlike the old established professions of medicine, law, engineering, and the like, professional training for health physics is extraordinarily diverse (this is not to imply that the others are not broad but they are now reasonably unified). This results partly from the newness of the field as a professional entity, partly from the diversity of disciplines required for the solution of problems of the protection of man and his environment from the adverse effects of radiation while realizing, to the fullest, the potential benefits. Chemistry, physics, biology, mathematics, sociology,psychology, oceanography, meteorology, geology, to name a few, are all disciplines with a bearing on our field. Conversely persons with training in any one of several professions may find themselves regarded as health physicists, and indeed _be_ health physicists - and good ones.

No one can expect to be equally good at all of these things in the depth expected of specialists in one of the older disciplines. Many of us were something else before we became health physicists and got our so-called "depth" this way. But many of the younger ones among you came more or less directly into the field from training aimed in part at least in this direction specifically. Your "depth" may be of a different sort, i.e. depth in _this_ field.

So our origins are diverse - or they have been. Our Society's Committee on Education and Training once began the task of setting down what might be regarded as a "core" curriculum. We found diversity here too especially in the _types_ of institutions in which the subject matter was found. But some common denominators were discernible even though they had different titles in different environments. Neither the committee nor the Society has finished this task for a number of reasons - more immediate problems need attention, the growth is so different in different

*Presented at mid-year Topical Symposium of the Health Physics Society, January 28, 1970.

places that the pattern is hard to define. We are still far from the sort of accreditation function which has devolved upon organizations like the American Chemical Society, the Engineering Societies, and the medical groups. It is good we are not at this point. We are too young and we need elbow room to grow and mature in. Yet in many respects we are asked to encompass just as many areas of knowledge as, for example, is the physician. In a sense even more is expected of us because most of the physician's problems are at least in biological science or the underlying chemistry and physics without introducing geology, meteorology, oceanography, et al!

Let us turn now to the present question; Does the simple addition of a few new wavelengths of radiation really make much difference in what is required from our education and training? We are already "jacks of all trades". Addition of one more should be easy.

In my view it will not be easy. Despite the impingement of many disciplines (or parts of them) on our needed expertise, we have had the central theme of ionizing radiation and "nuclear science"; nuclear this or nuclear that including nuclear education and training as a Division of the Atomic Energy Commission. We have in a sense been fortunate that there were enough problems in the ionizing radiation field to keep us occupied full time. (There still are, probably, but this is not the point). Addition of the new areas will make a difference. I am sure some of you who have general safety or industrial hygiene duties will testify that these add greatly to the diversification of your problem-solving requirements. Does our new base in health physics add a similar dimension?

I believe that to a degree, our new base requires both greater breadth and greater depth than the simple facts would predict. Let us look at the kind of physics and physical chemistry needed in the microwave field as an example. Here I will use mostly material very kindly supplied me by Dr. Howard Andrews whom I tried to convince to give this talk in my place.

'An understanding of microwaves and their interactions with living tissues will require an added emphasis on the classical, or pre-quantum aspects of physics. At the high energies, where every incident quantum is capable of producing one or many ionizations, detailed spectral information is seldom needed. Only over extremes of energy need one take into account differences in biological action. In the microwave region resonances can be expected to play important roles. Maxwell's equations must be invoked to account for radiated field patterns. Antenna theory, involving a wide variety of radiation types, will be needed to describe the transmission of energy from the generators. Classical wave theory will be required to explain the wave reflections and the standing waves that are to be expected, since, in this frequency region wavelengths are of the order of the sizes of macroscopic objects rather than the "atom sizes" of wavelengths in the X-ray region.

Classical circuit theory, supplemented by Maxwell's field equation will be needed to understand the production of the frequencies involved and their transmission to the radiators. Similar considerations will enter into an understanding of the measuring instruments needed to characterize the fields.

The microwave frequency band includes the region of molecular rotations and vibrations. When absorbing material is in a gaseous state these motions will be relatively unhindered, and there will be many sharp absorption bands comparable to those seen with electronic energy levels in the ultraviolet. When the absorption takes place in a liquid or a solid, as is the case for almost all components of living systems, most of the mechanical motions will be bonded to adjoining structures, and free rotations, at least, will be hindered. Unlike the electronic transitions, the sharp absorption frequencies in the microwave region will be coupled or "smeared out" into broad absorption regions. Any motion derived from energy absorption from an external field will be heavily damped, and will be quickly degraded to very low-energy quanta or to photons which in turn will end up as thermal energy.

According to the above considerations almost all energy absorbed from a microwave field should be rapidly degraded to heat. Resonance or specific reaction effects analagous to the skin tanning by specific UV wavelengths should be absent. Although this argument is plausible, its conclusions are by no means certain. A tremendous amount of detailed investigation will be needed to establish the true situation. Much of this work will be difficult and definitive results may be slow to appear. We still have almost no information on the energy gap between that needed to produce ionization and that needed to create an ion pair. Most or all of the "lost" energy is degraded into the microwave region, but its biological effect, if any, is completely unknown.

Molecular spectroscopy can then be expected to be an important field in the future of microwave effects. Microwave chemistry will become an important research field. It is not sufficient to say that the quantum energies are too low to produce either ionization or molecular dissociation. It is not sufficient to say that the frequencies are too high to have any physiological effects on cells or large molecules. In strong microwave fields electric currents may play an important role in biological effects. Any rectifier can serve to convert the alternating fields into D.C. currents. Any circuit asymetry is a potential rectifier, and the numbers of molecular asymetries in living tissue is legion. So one mustteach and investigate electrochemistry to the point where there is an awareness of potential electrolytic effects. ' **

Many or all of these leads will prove false but eventually those parts of physics pertinent to the microwave field will emerge. Until the pertinent physics and chemistry are known one must train students to cope with the unknown, help to separate the essentials from the inapplicable, to eventually arrive at a rational, practical health physics for microwaves.

Now let us turn to lasers and masers. Is there a different physics and chemistry involved in the laser and maser field? Yes, indeed. They are different from microwaves and different from ionizing radiation. Again wavelength changes of no significance in the ionizing radiation field may make large differences in this area. Consider for example the changes in visual sensitivity of the eye as a function of wavelength, as compared with the variation in the biological effects of ionizing radiation over an equivalent span of wavelength change. It is negligible in the latter case; quite large in the former. There are many subtleties. Consider that the change in visual sensitivity of the eye over the range from blue to red is several orders of magnitude while the factors controlling potential retinal damage from a laser beam are not so related to wavelength. The result is that the beam becomes more or less visible or invisible so that the optical system of the eye plays a critical role in bringing the image to the retina in terms of damage but not in terms of seeing it.

Dosimetry in this field as for microwaves is where the ionizing radiation field was thirty years ago. It is done mostly by calculation; very little by measurement. Regulation and standards are much more on an individual basis than is now the case in the ionizing radiation field. There is no ICRP or NCRP to look to although the American Conference of Governmental

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** The section indicated by '....' was prepared in consultation with Dr. Howard Andrews.

Industrial Hygienists, the American Industrial Hygiene Association and individual laboratories are actively trying to bring standards to a stable state. This means considerably more lattitude for individual judgement in setting standards or procedures and the need for more breadth of knowledge and depth in those working in the new area than might be expected now in the ionizing radiation field where much more has been standardized and routinized.

I do not view this as necessarily inherently good or inherently bad. It is different from the situation in nuclear energy and involves coping with the unknown to an extent requiring both broad and specific training.

What of the biomedical aspects? In many respects I believe the individual dealing with the biological hazards of the radiations from electronic products may need to know more of the biology underlying these effects than in the ionizing radiation field. Small differences in the physical setup can make much more difference in energy absorption and thus the biological result than with the relatively non-specific, sometimes highly penetrating ionizing radiation. The enhancement factor in the eye for focusing a laser beam on the retina for example, may be of the order of 10^6. The difference between a direct view and a sidelong lance can be critical. Thus physiological as well as physical optics have a bearing on understanding the processes and evaluating the risk. One can be a reasonably good health physicist without knowledge in depth about the biological effects of ionizing radiation, even though it helps to know a reasonable amount. I believe this is going to be less true in the new fields and the specifics of the biological risk will have to be understood to a greater extent.

The same conclusion applies to the ultraviolet region. Specific absorption by nucleic acids, cellular proteins, etc. makes for very great dependence of effects on the wavelength of the incident light. Also there are photo-recovery processes which have a different wavelength dependence than the processes of cell damage. This all familiar to most of you and is going to be heard in detail from persons better qualified than myself as this Symposium progresses. But to me it says that the new wavelengths have added a need for the professional health physicist to be a different kind of a generalist than when he dealt primarily with ionizing radiation and radioactive materials. Whereas in the ionizing radiation field he is a generalist by bringing a number of fields together around an effect that is relatively non-specific, now he must deal with several, perhaps many specific biological effects which are critically dependent on the physical conditions of exposure. Also he cannot be sure that the biology is well understood or is a general phenomenon and that all he has to do is make measurements of the dose to predict effect.

Translated into education and training requirements I feel the expansion of our field requires, besides the return to classical physics and physical chemistry, a detailed knowledge of the important biological processes involved. The individual needs to be partly a physiologist and have some training in classical physiology as well as in classical physics. To the extent that this is important I believe a program in this area will prosper best where there is a proper mixture of physical science (perhaps in an engineering school or wherever classical physics may be found) and biomedical science perhaps in a medical school, a school of public health or a similar institution. Alternatively the instruction might occur in a center with faculty drawn together from these several areas.

Lest I be misinterpreted, let me state that I am not advocating a new subspecialty in health physics or radiological health. Indeed becoming acquainted with the new area is not an overwhelming chore. There is hardly enough real knowledge in it yet for this to be the case. But it is tricky. It is subject to more individual error and needs more individual judgement now than does the ionizing radiation field. For this reason I feel an almost disproportionate effort will be required for the present at least in the training field to do the job right. In a few years it too will have some traditions even a"core" and by then much of what I have said will probably have been proven wrong, but I will take that chance!

The above concerns formal academic education. Time does not permit a consideration of informal training courses, on-the-job training and the like. However, I believe the same basic concepts would apply to these as well, and the development of expertise will come only with the same type of effort, albeit less extensive.

To take an even further chance of being proven wrong I have asked a man who is busy developing a new curriculum in the electronic product radiation field to describe his plans. He is Dr. Emmett Bolch, Assistant Professor of Environmental Engineering at the University of Florida, Gainesville. He will conclude this talk by giving a concrete example of how one of several institutions making plans in this field will modify its offerings to bring trained manpower into the field of electronic radiation and the evaluation of possible hazards thereto attendant.

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ELECTRONIC PRODUCT RADIATION AND THE ENVIRONMENTAL ENGINEERING CURRICULA

by

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Introduction

One of the most recent definitions of environmental engineering comes from the Second National Conference on Environmental and Sanitary Engineering Graduate Education:[1]

> "Environmental engineering is that branch of engineering that involves the application of scientific principles to the prevention, control and management of environmental factors that may influence the physical and emotional health of man and his well-being."

It is generally agreed that specialty areas such as sanitary engineering, water resources management, air pollution control, industrial hygiene and radiological health can be brought under this umbrella term, environmental engineering. "Environmental Sciences" may even be the more descriptive name, since many of these specialty areas are more applied science than classical engineering.

For almost two decades, radiological health could be defined as the art and science of protecting human beings from injury by ionizing radiation as well as improving the health and welfare of mankind through the beneficial application of radiological techniques. In the last several years, however, a new definition began to take form. The health and safety problems of non-ionizing electromagnetic radiation were known to the many personnel working with particular electronic devices, but these problem areas were not generally associated with the specialty area of radiological health. On the other hand, problems associated with the X-ray emissions from color televisions were definitely within the purview of radiological health specialists. This potential hazard was widely publicized both within and without the technical community. The awareness and concern of the general public probably precipitated a broader spectrum of discussions than may have otherwise developed. The color television receivers thus served as a stepping stone to consideration of electronic products in general. Furthermore, the rapidly developing laser industry required appraisal by the Federal government during this time. The evolution of the definition of "radiation" to include the entire electromagnetic spectrum was thus inevitable.

This evolution is recorded in the Congressional hearings; preliminary bills and accessory documents, papers and records that culminated with the passage of the Radiation Control for Health and Safety Act of 1968 on October 18, 1968. This Act, either by direct definition or by implication, groups into "radiation" the ionizing electromagnetic radiations such as X-rays and gamma rays; all particulate radiation; non-ionizing radiations such as microwaves; laser beams and sources of infrared and ultraviolet light; sonic, infrasonic and ultrasonic waves and intense magnetic fields. There is a great need for qualified personnel to work on the many facets outlined in the Act. The radiological health specialist programs appear to be the most logical source of these people. Conferences, short courses and various self-help measures will provide limited, but immediate capability within the pertinent agencies, organizations and industries. It is imperative, then, that the burden for manpower be placed, as soon as possible, on formal graduate education. The aforementioned definition of environmental engineering can, and should, embrace environmental factors wuch as microwaves, laser beams, intense magnetic fields and ultrasonic waves.

Supportive Courses

The radiological health training programs within, or closely associated with, schools of engineering have a great deal of potential for developing a strong curricula emphasizing electronic product radiation control. One can make a strong case for curricula leading to a laser safety technologist, a microwave hazards engineer or other similar narrow specialties; however, the positions and opportunities available to such individuals would be likewise limited. The combination of certain fundamental environmental engineering courses and a basic radiation science core, with sufficient latitude for emphasis in a particular aspect of radiological health, has been a successful formula. Electronic product radiation control should be planned as an "emphasis area" just as radiobiology, environmental radiation, radioactive waste, medical applications, etc. have been in the past.

At least three ingredients should be available to the radiological health student wishing to place an emphasis on electronic product radiation control: (1) engineering courses, mostly dealing with the theory, design and application of microwave devices or lasers;

(2) a course in the radiological health sequence specifically dealing with the evaluation of hazards and control of electronic product radiation; (3) existing courses in the radiological health program should be critically reviewed and updated where it is necessary to provide an orderly transition to this new definition of radiation; and (4) research facilities for those students pursuing a thesis degree.

The first ingredient can often be furnished by the Department of Electrical Engineering. In the microwave area the following series may be typical:

EE 555 - MICROWAVE LABORATORY 1 credit*
The laboratory for the corequisite course EE 556, Microwave Techniques.

EE 556 - MICROWAVE TECHNIQUES 4 credits*
Prerequisite: Undergraduate required sequence in electronics. Waveguides and resonant cavities. Methods of generating, transmitting and receiving microwaves.

EE 651 - ELECTROMAGNETIC FIELDS AND WAVES 3 credits**
Prerequisite: Undergraduate course in fields and waves. Electromagnetic theory applied to engineering including static field problems and propagation, reflection and guiding of electromagnetic waves.

EE 655 - ACTIVE MICROWAVE DEVICES 3 credits**
Prerequisite: EE 651. Generation and amplification of microwaves, with emphasis on devices still in the research stage. Solid-state devices utilizing the Gunn effect (domain, quenched and LSA modes), avalanche transit-time semiconductor diodes (IMPATT devices), acoustic wave amplification in solids, traveling-wave interaction in solids.

EE 656 - WAVEGUIDES AND MICROWAVE NETWORKS 3 credits**
Prerequisite: EE 651. Theory of rectangular and cylindrical waveguides; resonant cavities. Microwave network theory; one-ports, two-ports, n-ports; scattering matrix. Directional couplers, magic tees, circulators.

The number of these courses taken for graduate credit would depend greatly upon the background of the student and upon the subject of the

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*Advanced undergraduate courses available for graduate credit
**Graduate courses

proposed research for those working on a thesis degree. A liberal audit policy for regularly enrolled full-time graduate students is most helpful to students. In this manner they can accumulate sufficient background to take graduate level courses outside of their department.

Courses dealing with the fundamentals and principles of laser systems are often located in Electrical Engineering. For radiological health graduate students, one can assume that a course in modern physics is included or prerequisite to the program. With this background then, a student may enter the sequence:

PS 530 - CLASSICAL AND MODERN OPTICS 3 credits*
An advanced course in physical optics that includes such modern topics as coherence, lasers, holography and nonlinear optics.

EE 611 - PHYSICAL OPTICS FOR ENGINEERS 3 credits**
Electromagnetic theory of light waves; Fresnel laws of reflection and refraction; eight polarization and interference phenomena.

EE 613 - LASER TECHNOLOGY 3 credits**
Theory of stimulated emission processes and the design of laser systems.

EGC 677 - GAS LASERS AND THEIR ENGINEERING APPLICATION 4 credits**
Introduction into theory of gas lasers. Discussion of laser design; extensive coverage of application of gas lasers.

Radiological health trainees who wish to place a strong emphasis on electronic product radiation may vary their supportive courses within the Department of Environmental Engineering. For example, in the past some trainees have taken as many as three air pollution courses. This could be held to the one-course minimum and courses like OCCUPATIONAL HEALTH would probably be more in line with his career objectives.

Radiological Health Curriculum

The second ingredient listed in the above section is that of a specific course on the electronic product radiation. Radiological

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*Advanced undergraduate courses available for graduate credit
**Graduate courses

health training curricula normally have courses containing radiation biology, radiological health, radiological techniques, radiation dosimetry, instrumentation, radioactive waste, environmental radiation, statistics, epidemiology, public health, etc. One alternative to specific training in electronic product radiation control would be to incorporate various aspects into these existing courses; as examples, biological effects into radiation biology, evaluation and standards into radiation dosimetry and survey techniques into instrumentation. This does not appear to be an acceptable solution because most existing courses in radiological health curricula are already bulging with material. Secondly, the continuity of "theory, evaluation and control" would be fragmented.

A second solution would be to design courses with limited credit (2 credits, quarter system, for example) on specific areas such as Laser Hazards, Evaluation and Control; Microwave Hazards, Evaluation and Control; etc. The Laser Safety Conference and Workshops, Cincinnati, Ohio, January 29-31, 1968[2] recommended a course outline for instruction in laser safety:

Evaluation of Laser Hazards
Laser Safety

I. Electromagnetic spectrum (lasers)
II. Theory of lasers
III. Characterization of lasers
    A. Types and operation
IV. Hazards (recognition and evaluation)
    A. Eye
        1. Anatomy and physiology of the eye
        2. Review of optics
        3. Injury mechanisms
        4. Injury evaluation
    B. Skin
    C. Environmental
    D. Electrical
    E. Survey techniques and instrumentation
        1. Laser output
        2. Beam characterization
    F. Threshold values
V. Control of hazards
    A. Engineering measures
    B. Personal protective devices
    C. Medical monitoring
VI. Guides and regulations

The word "microwave" could be substituted for the word "laser" in the above outline and it would approximately describe a course in the Evaluation of Microwave Hazards. With this approach, a third low-credit course may be necessary as a catch-all for the other areas such as "by-product" X-radiation, sonics, intense magnetic fields, etc. This approach is necessary for industrial training or agency short courses because one must assume very limited foundations and almost all the material must be formally presented. However, in the academic situation, certain basic knowledge can be prerequisite and a considerable volume of outside material can be expected to be read and digested by the student. In addition, the trend in graduate education is to minimize the number of one-, two- or three-hour courses and provide compatible material in four- and five-hour course offerings. The advantages in the limited scope courses do not appear to be particularly remunerative.

The four-hour course on the broad title ELECTRONIC PRODUCT RADIATION may be the most practical solution. A proposed outline follows:

ELECTRONIC PRODUCT RADIATION

1. Historical Aspects
    - Color Televisions
    - Congressional Hearings
2. Public Law 90 - 602
    - Scope
    - Implications
    - Enforcement
3. Color Television
    - Nature of Radiations
    - Monitoring
    - Standards
    - Solutions
4. X-radiation Sources
    - Tubes, Rectifiers, Demonstration Units
    - Industrial Radiographic
    - Analytical Instrumentation
    - Accelerators
    - Standards and Control
5. Microwave Production
    - Fundamentals
    - Magnetrons, Klystrons, Traveling Wave Tubes
    - Accessories
6. Microwave Devices
    - Industrial
    - Commercial
    - Military

7. Biological Effects of Microwaves
    - Thermal
    - Non-thermal
    - Critical Organs
8. Field Measurements of Microwaves
    - Operating Parameters
    - Instrumentation
        - Calibration
        - Field Use
    - Calculations
9. Control of Microwave Hazards
    - Standards
    - Source
    - Antenna
    - Environmental
    - Associated Ionizing Radiation
10. Laser Theory
    - Light and Controlled Emissions
    - Cavities and Excitation
    - Accessories
11. Laser Types
    - Solid State (Ruby, Neodynium)
    - Semiconductor (Gallium Arsenide)
    - Gaseous
        - CO_2
        - He-Neon
12. Laser Applications
    - Industrial
    - Military
    - Research
    - Medical
13. Biological Effects, Lasers
    - Thermal
    - Non-linear
    - Critical Organs
14. Evaluation of Laser Hazards
    - Primary Beams
    - Reflected Beams
    - Other Factors and Calculations
15. Control of Laser Hazards
    - Standards
    - Personnel
        - Eye Protection
        - Exposed Skin
        - General

- Area Control
    - Laboratory Design
    - Electrical Hazards

16. Additional Subjects
    - Ultra Violet
    - Infra-Red
    - Intense Magnetic Fields
    - Sonics, Infrasonics and Ultrasonics
    - Standards and Control
17. Demonstration and Field Trips

Many of the areas mentioned in the outline are rapidly developing. The course will have to be constantly reviewed and up-dated. Recent publications and conference proceedings will provide major input of material into the course. No formal laboratory exercises are included; however, demonstrations and field trips are necessary for complete understanding of several aspects of the course. The laser cannot be fully appreciated until many of its unique characteristics are shown with a laser and an optics kit. It would be extremely helpful if a powerful pulsed laser were also available on campus. Some "in-house" demonstrations can be performed with microwave apparatus; however, field trips to governmental, military or industrial installations would be most valuable experiences. Microwave survey meters of various types should be available.

Research

The final aforementioned ingredient was the availability of research facilities. Students in environmental engineering are most likely to pursue research topics along the lines of quantifying hazards, development of instrumentation, investigation of dosimetry, design of control procedures and epidemiological approaches to limits rather than biological, biochemical or behavioral studies.

Equipment and facilities are extremely dependent upon the specific project, and listing of items here would serve no useful purpose. The research developed in a particular graduate program tends to become narrow in scope and usually reflects the interest of the faculty investigators. Few radiological health specialist programs have formalized their research activities in the electronic product radiation areas. Not all programs will want to expand into the field, but there is a well-documented[3,4,5] need for fresh and imaginative approaches to many problems. Each school should survey its own and various other departments to inventory the capabilities available. It is likely that cooperation between two or three departments would provide an excellent basis from which to attack a particular problem area in electronic product radiation.

Students

The graduate programs available in environmental engineering should be open to a wide spectrum of baccalaureates including sanitary engineers, biologists, public health engineers, physicists, electrical engineers, etc. This concept is somewhat contradictory to quality education. An inflexible graduate program having a very specific undergraduate degree as a prerequisite should produce high quality specialists, but the market seems to demand the broader-based individuals. Programs can accept many types of undergraduate degrees and still produce high quality graduates by (1) demanding proven ability as may be reflected in high GRE scores, in undergraduate grade point averages and/or in non-academic experience; (2) requiring a few, high-quality foundation courses as a means of placing incoming students at a common level, and finally (3) expecting students to fill in certain "gaps" in their background on their own initiative.

Conclusions

The radiological health specialist programs appear to be one of the most logical sources of manpower for electronic product radiation control. Those programs within, or closely associated with, schools of engineering have special potential and therefore a special responsibility to provide opportunities for graduate education in this important field. Electronic product radiation control should be an "emphasis area" within radiological health. The curriculum may best consist of one comprehensive course, ELECTRONIC PRODUCT RADIATION, supported by courses from other departments and an updated radiological health sequence. The program should accept a wide spectrum of baccalaureates.

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SESSION II: MICROWAVE AND X RAY, CONTRIBUTED PAPERS

Chairman: E. Dale Trout

National Inventory of Electronic Products
J. V. Harris

A Review of International Microwave Exposure Guides
J. R. Swanson, V. E. Rose, C. H. Powell

Microwave Cataracts—A Case Report Reevaluated
F. G. Hirsch

The Dipole/Slot Radiation Pattern and its use in Understanding Microwave Leakage and Survey Techniques
G. I. Coats, C. B. Nelson, R. G. Underwood

Microwave Oven Repair: Hazard Evaluation
W. M. Eden

RF Response of Radiation Survey Instruments
F. J. Bradley and Alan H. Jones

X-ray Measurements Around High Power Klystrons
R. L. Lehman

Radiation Emissions from Demonstration Type Cold-Cathode Gas Discharge Tubes
W. S. Properzio

U.L. X-radiation Requirements for Color TV Receivers
L. Horn

Radiation Hazard Assessment of Privately Owned Colour Television Receivers in Canada
A. K. DasGupta and K. R. Fujimoto

NATIONAL INVENTORY OF ELECTRONIC PRODUCTS

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INTRODUCTION

The Bureau of Radiological Health conducted ten special studies in 1969 in response to the report requirements of P.L. 90-602. One of these special studies, the subject of this report, was the Inventory of Electronic Products.[1/] The inventory study was initiated for overall program planning purposes although it is obvious that the public health significance of any source of radiation would be dependent on several factors such as:

1. The number of devices in use (inventory);
2. Anticipated inventory growth rate;
3. Population at risk;
4. Toxicity of radiation;
5. Level of exposure;
6. Length of exposure.

This study was initiated to obtain information on the first two factors mentioned.

SOURCES OF INFORMATION

Information used in this study was obtained from various governmental and trade association publications as well as from personal communications with individuals and associations active in production, sales, or use of radiation-producing electronic products. Estimates were based on available data and no attempt was made to conduct original industrial surveys during this initial study.

RESULTS - IONIZING RADIATION SOURCES

Various electronic products produce ionizing radiation. Estimated numbers of some of the devices in use are shown in

Table 1. Although this list is not all inclusive, it is evident that ionizing radiation producing products are used in medical, industrial, and consumer products.

Color TV households have risen dramatically in the past five years as indicated in Figure 1. Surveys by the National Broadcasting Company indicate that the number of households with color TV sets rose from 2.8 million (4.9% of all households) in January of 1965 to 20.6 million (33.6% of all households) in april of 1969.[2] At the present rate of increase it is estimated that approximately 70 percent of all homes may have color TV sets by 1975. Although the number of TV sets and the exposure times exceed by far any of the other electronic product ionizing sources, it is known from past experience that medical and dental X-rays contribute over 90 percent of the genetically significant dose to the U.S. population. Similarly the mere numbers alone of the various non-ionizing radiation-producing products can not be taken as indicators of their relative public health significance, but the numbers are required for the overall evaluation of the problem.

Based on trends observed in licensed and registered X-ray apparatus, it is estimated that the annual inventory growth for these devices is less than 5 percent.

There has been a tremendous growth of the accelerator industry during the past 10 years. The number of accelerators in the U.S. has risen from about five hundred in 1960 to twelve to fifteen hundred at the present time.

The inventory of electron microscopes in the U.S. is estimated to be increasing by approximately 200 units per year at the present time. Department of Commerce statistics indicate that about 80 percent of the total U.S. sales are imports.

RESULTS - NON-IONIZING RADIATION SOURCES

In the area of non-ionizing radiation P.L. 90-602 covers devices emitting electromagnetic radiation of various wavelengths as well as those devices producing vibrations at various frequencies. These include:

Ultraviolet Light
Visible Light
Infrared Light
Microwave
Radio Frequency EMR
Coherent EMR
Ultrasonic
Sonic
Infrasonic
Magnetic Fields

TABLE 1

Sources of Ionizing Radiation

Product	Estimated Inventory Jan. 70
Color TV (households)	24,000,000
Medical X-ray	115,000
Dental X-ray	100,000
Industrial X-ray	15,000
Accelerators	1,200
Electron Microscopes	500

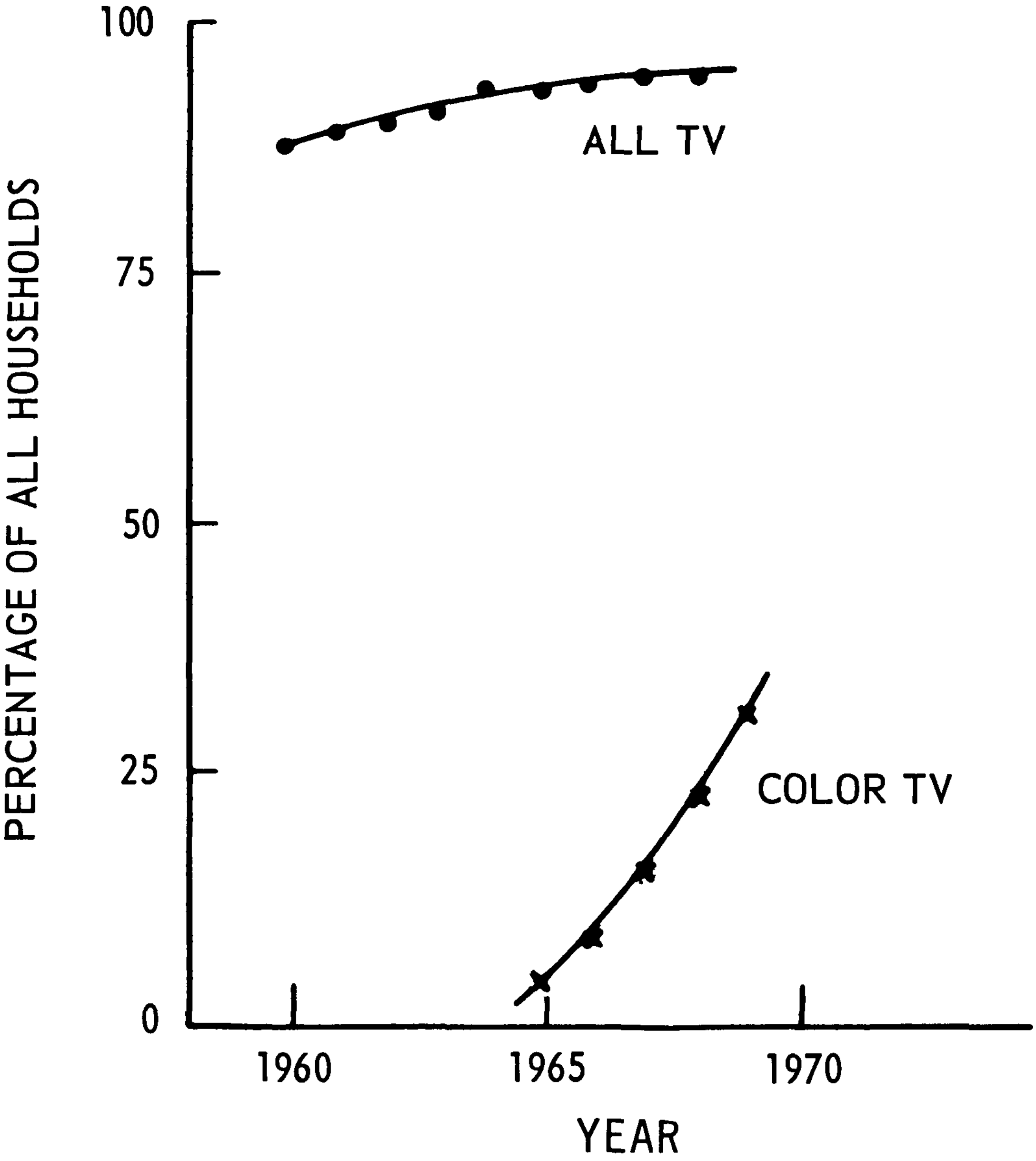

Figure 1. Percentage of U.S. households with TV receivers (1960—1969).

Ultraviolet Light

No statistics were obtained on the national inventory of ultraviolet devices. It seems plausible, however, that these devices number in the tens or even hundreds of thousands and are increasing. Some typical uses of ultraviolet light include cosmetic and therapeutic sun lamps, disinfection, sterilization, and analytical instruments.

Visible Light

There are numerous visible light sources, most of which are relatively innocuous. Certain high intensity light sources (producing absorbed energy levels greater than 50 calories/cm^2/Min) may cause eye injury. No statistics were obtained on the number of devices capable of delivering this amount of energy to the eye at reasonable distances. However, types of items which would possibly fall in this category include high intensity reading lamps, movie and slide projector bulbs, spot lights, flood lights, etc. These items probably run into the hundreds of thousands or even millions.

Infrared Light

Infrared exposures may occur in a variety of industrial and non-industrial settings, not only from sources designed to emit infrared but also from other heat sources. The more common industrial exposures are found in hot metal operations, glass making, photoengraving, paint and enamel drying, and welding. Infrared is also used for heating and cooking in both homes and commercial establishments. A 1966 survey by the U.S. Department of Agriculture indicated that 3.3 percent of the 370 thousand food service establishments in the U.S. had operational infrared ovens.[3/] The national inventory of commercial infrared ovens was estimated to be 13,400 in 1966.

Microwave

Microwave radiation is emitted by a variety of devices including diathermy units, ovens, industrial heating devices, communications devices, and radar units. Some inventory estimates are indicated in Table 2.

The microwave communications transmitters are reported to have an average of about five frequencies per transmitter making a total of almost 400 thousand broadcast frequencies.

TABLE 2

Sources of Microwave Radiation

Product	Estimated Inventory Jan. 70
Communications Transmitters	66,000
Domestic Ovens	50,000
Commercial Ovens	45,000
Diathermy Units	15,000
Radar, Pleasure Boats	7,500
Radar, Stationary	5,500
Industrial Heating	300

Microwave ovens were first introduced in the late 40's and originally sales campaigns were directed toward food service establishments. The 1966 USDA survey referred to earlier indicated that there were approximately 7,700 microwave ovens (1-2 kw) in food service establishments.[3] Approximately 2 percent of the food service establishments had microwave ovens in 1966. The statistics are divided into two categories (1) public eating places, and (2) institutions. The distribution of these ovens in 1966 is shown in Tables 3 and 4.

It has been estimated that since 1965 monthly sales of commercial microwave ovens have approached 1,000 with the majority of these going to the vending trade. On this basis, the present inventory of commercial microwave ovens should be close to 45,000 units and a linear extrapolation would produce an inventory estimate of approximately 100,000 units by 1975.

The inventory of home microwave ovens is estimated to be similar to that of commercial ovens at the present time. However, various trade groups predict an exponential type growth with a total inventory in homes of about a half million by 1975 at which time sales are anticipated to be in the neighborhood of 200 thousand units per year (see Table 5). There are expected to be substantial Japanese imports included in these sales.

The Executive Director of the American Physical Therapy Association has roughly estimated that one out of every six hospitals in the U.S. may have microwave diathermy units.[4] From data supplied by the Executive Director of the American Academy of Physical Medicine and Rehabilitation, it is estimated that the national inventory of microwave diathermy units is about 10-15 thousand and increasing by about 300 units per year.[5]

"Electronics" magazine predicts that the shortwave and microwave diathermy market will increase by 80 percent between 1968 and 1972, whereas, Department of Commerce statistics indicate a decreasing trend in shipments of diathermy equipment as shown in Figure 2. The lack of specificity of the data precludes the determination of possible contradictions in these statistics. A similar problem exists with the current classification of products by the Department of Commerce which should include microwave ovens. The sales of "Industrial Dielectric Heating Equipment

Table 3. Microwave Ovens in Public Eating Places, 1966

Establishment	Number of establishments	Percent with MV ovens
Separate eating places	201,734	1.6
Separate drinking places	51,644	0.8
Drug or proprietary stores	12,013	0.3
Retail stores	22,820	0.8
Hotels, motels, or tourtist courts	16,558	4.3
Recreation and amusement places	19,411	0.7
Civic, social, or fraternal associations	4,355	1.1
Factories, plants, or mills	6,784	5.3
Other public eating establishments (including vending)	8,429	5.2
Total establishments	343,749	
Total number of ovens	6,900	

Table 4. Microwave Ovens in Institutions with Food Service, 1966

Institution	Number of institutions	Percent with microwave ovens
Hospitals	5,931	5.9
Sanatoria, convalescent, or rest homes	5,118	1.6
Homes for children, the aged, handicapped or mentally ill	4,092	0.0
Colleges, universities, professional or normal schools	2,766	4.0
Other institutions	9,738	0.0
Total institutions	27,645	
Total number of ovens	900	

TABLE 5

Estimated Annual Sales of Home Microwave Ovens (1965-1975) Based on an Exponential Model

Year	Home Microwave Oven Sales
1965	4,000
1966	5,908
1967	8,720
1968	12,880
1969	19,040
1970	28,400
1971	41,520
1972	61,320
1973	92,000
1974	132,800
1975	200,000

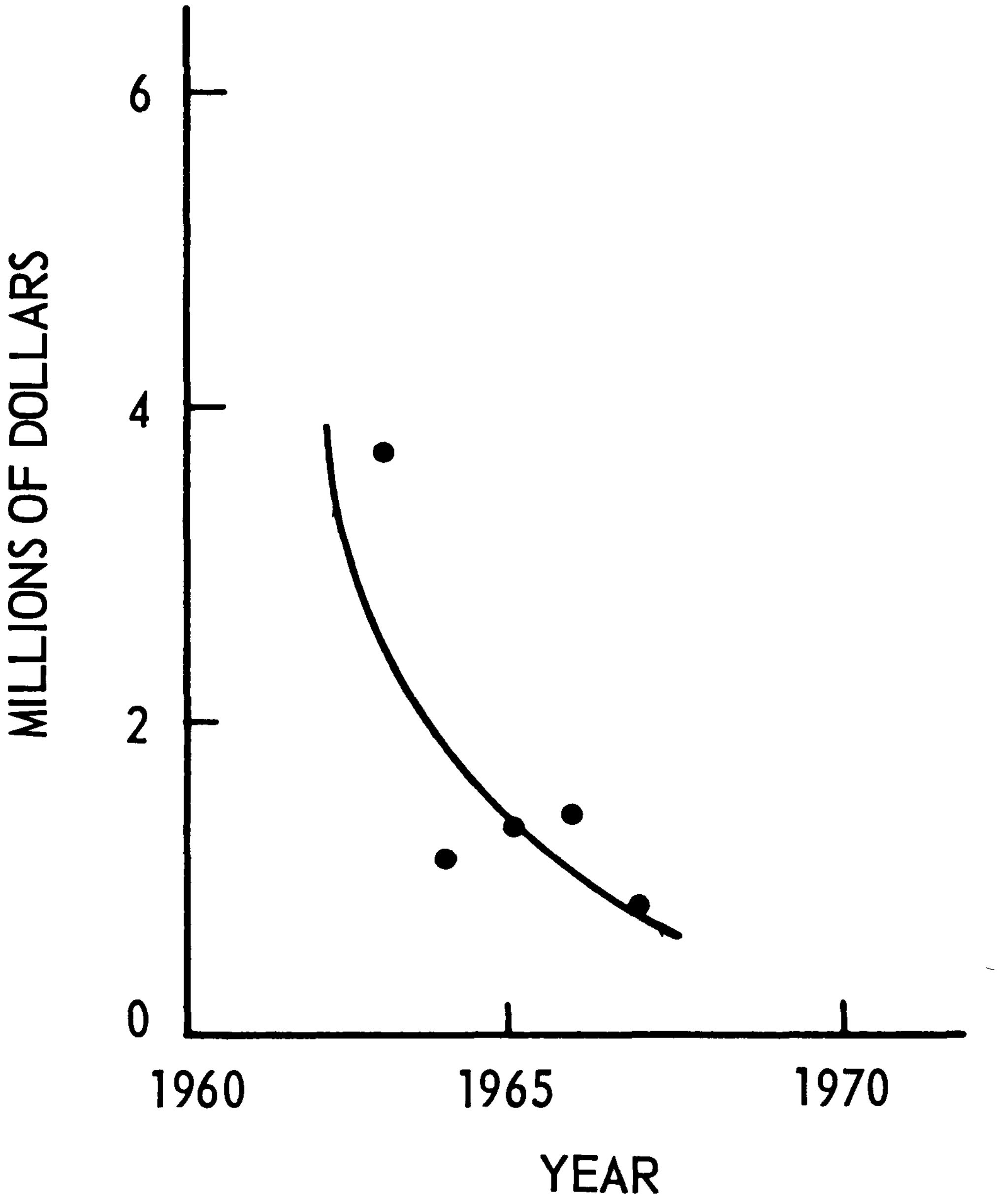

Figure 2. Shipments of diathermy equipment 1963–1967.[a]

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[a] Information from the Department of Commerce Current Industrial Reports, MA-36N.

and Commercial Electronic Stoves and Ovens" decreased during the period from 1963-1966 (Figure 3) whereas the sales of industrial and commercial microwave equipment has been increasing.

Radar units are used in a variety of settings including mobile units on ships and planes, and stationary units at airports. Probably one of the most interesting observations is the estimate of close to 8,000 units on pleasure boats. Table 6 gives U.S. Coast Guard estimates of the inventory of radar units on recreational boats in 1967.[6] It was estimated that 18.3 percent of the boats in the 40-65 foot class were equipped with radar units.

Industrial heating by microwaves has been widely publicized recently; however, it is estimated that there are only about 300 units in use at the present time and that the current installation rate is approximately 5 units per month. It is further estimated that there will be in the neighborhood of one thousand units in use by 1975.

Radio Frequency

Radio and low frequency radiation emitters are mainly transmitting devices. However, certain industrial, scientific, and medical devices do utilize these frequencies. Table 7 contains inventory estimates of various radio and low frequency devices as of January 1970.

Again it should be noted that the number of devices is only one of the factors determining the public health significance. In this regard it should be pointed out that a rough appraisal based on data on biological effects of various radio frequencies, and transmitter power output, as well as number of transmitters indicates that the UHF television transmitters (channels 14-83) could possibly be the most significant public health problem in this area of the spectrum. These transmitters are permitted to operate at a maximum power level of 5 megawatts and tower heights are limited to 1,000 feet in zone I and 2,000 feet in zone II.[7] Statistics as of December 31, 1968, indicated that 109 (approximately 22 percent) of the 496 UHF TV broadcast stations on the air, authorized, or applied for as of that date, employed or proposed effective radiated powers greater than 1 megawatt.[8]

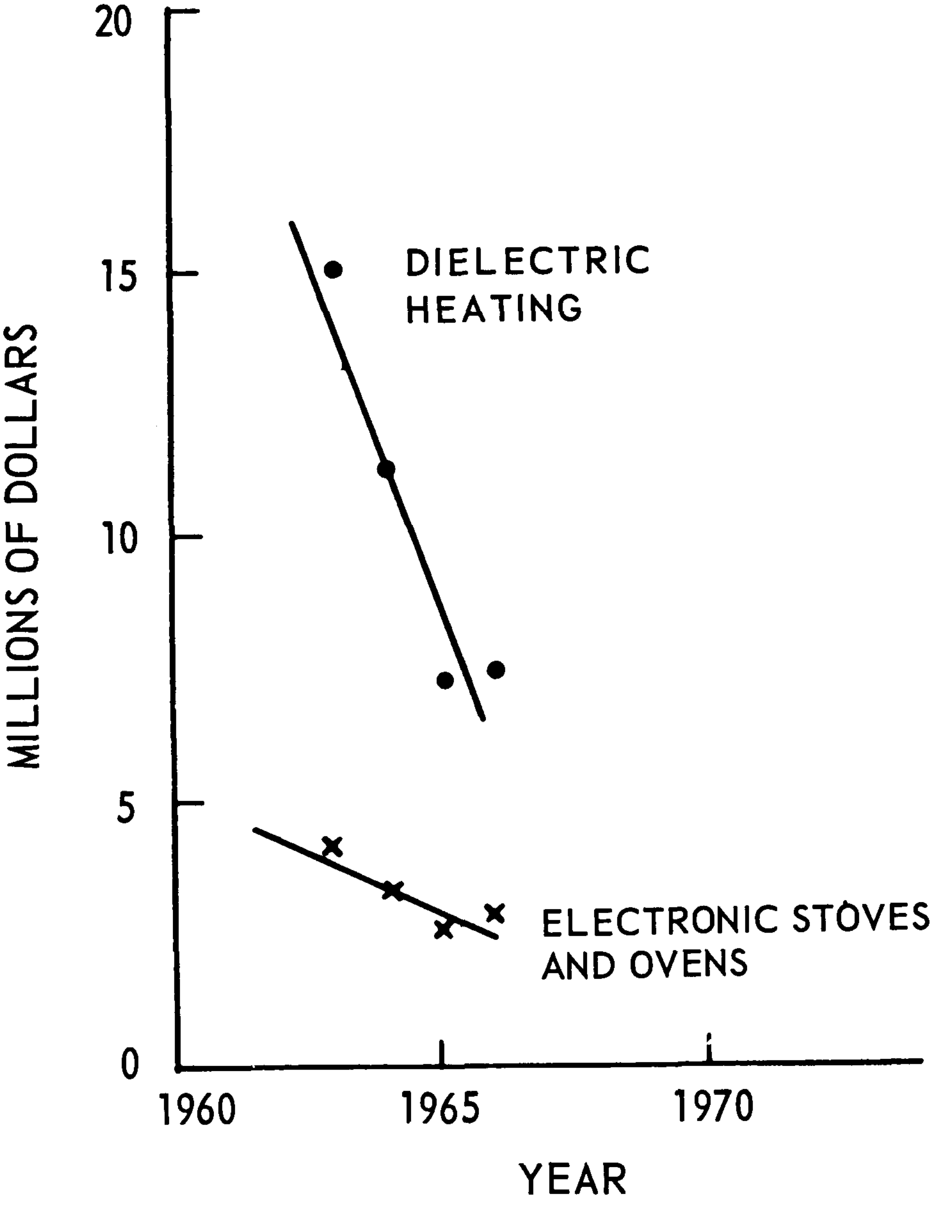

Figure 3. Shipments of industrial dielectric heating equipment and commercial electronic stoves and ovens, 1963–1966.[a]

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[a] Information from the Department of Commerce Current Industrial Reports, MA36N.

TABLE 6

Inventory of Radar on Recreational Boats, 1967

Class of Boat	Total Number in Class (1967)	Total in Sample	Total Radars in Sample		Extrapolated Total Radars
			No.	%	
1(16-26')	1,200,000	2,405	5	.2	2,400
2(26-40')	149,000	2,444	35	1.4	2,140
3(40-65')	14,000	398	73	18.3	2,560

TABLE 7

Estimates of Inventory of Radio and Low Frequency Devices, Jan. 1970

Device	Estimated No.
Transmitters	
Commercial AM	4,300
Commercial FM	2,200
Educational FM	400
Commercial TV	700
Educational TV	200
Amateur	300,000
Citizens	3,000,000
Aviation Services	200,000
Industrial Services	1,700,000
Transportation Services	500,000
Marine Services	200,000
Public Safety Services	700,000
TV Translators and Boosters	2,200
Diathermy Units	Several Thousand

Coherent Electromagnetic Radiation

Coherent EMR includes both lasers and masers, the microwave counterpart. The use of masers, however, presently appears to be limited to a highly specialized developmental phase. Figure 4 depicts the growth of the U.S. laser market from 1963 through 1968. Estimates of the cumulative sales of individual types of lasers in the U.S. from 1963 through 1968 are given in Table 8.

One published estimate of the inventory of commercial laser units in the U.S. in 1968 was 9,400.[9] This is about 50 percent of the estimated cumulative sales indicated in Table 8. The cumulative sales of commercial lasers could be in the neighborhood of 50 thousand units by the end of 1970. In addition a significant number of laser units are built by students from kits and are not included in the available statistics.

Ultrasonics

Although ultrasonics is a relatively new energy source, its versatility has led to its widespread employment in a variety of industrial, medical, scientific, and consumer products. Table 9 gives estimates of the inventory of some ultrasonic devices as of January 1970.

"Electronics" magazine has predicted that the ultrasonics market will almost double in the period from 1968 to 1973.[10] During that same period they predict that the consumer products will increase from about two-tenths of a percent to about six percent of the total ultrasonic market. The increasing trend in sales of industrial ultrasonic equipment is shown in Figure 5.

Sonic and Infrasonic

Sonic and infrasonic vibrations emanate from a variety of sources, both natural and man made. No pertinent statistics were obtained on electronic products producing these vibrations.

Magnetic Fields

Magnetic fields, likewise, emanate from a variety of natural and man-made sources, possibly numbering in the billions. However, probably only a few sources such as accelerators, high capacity electric power generators, and

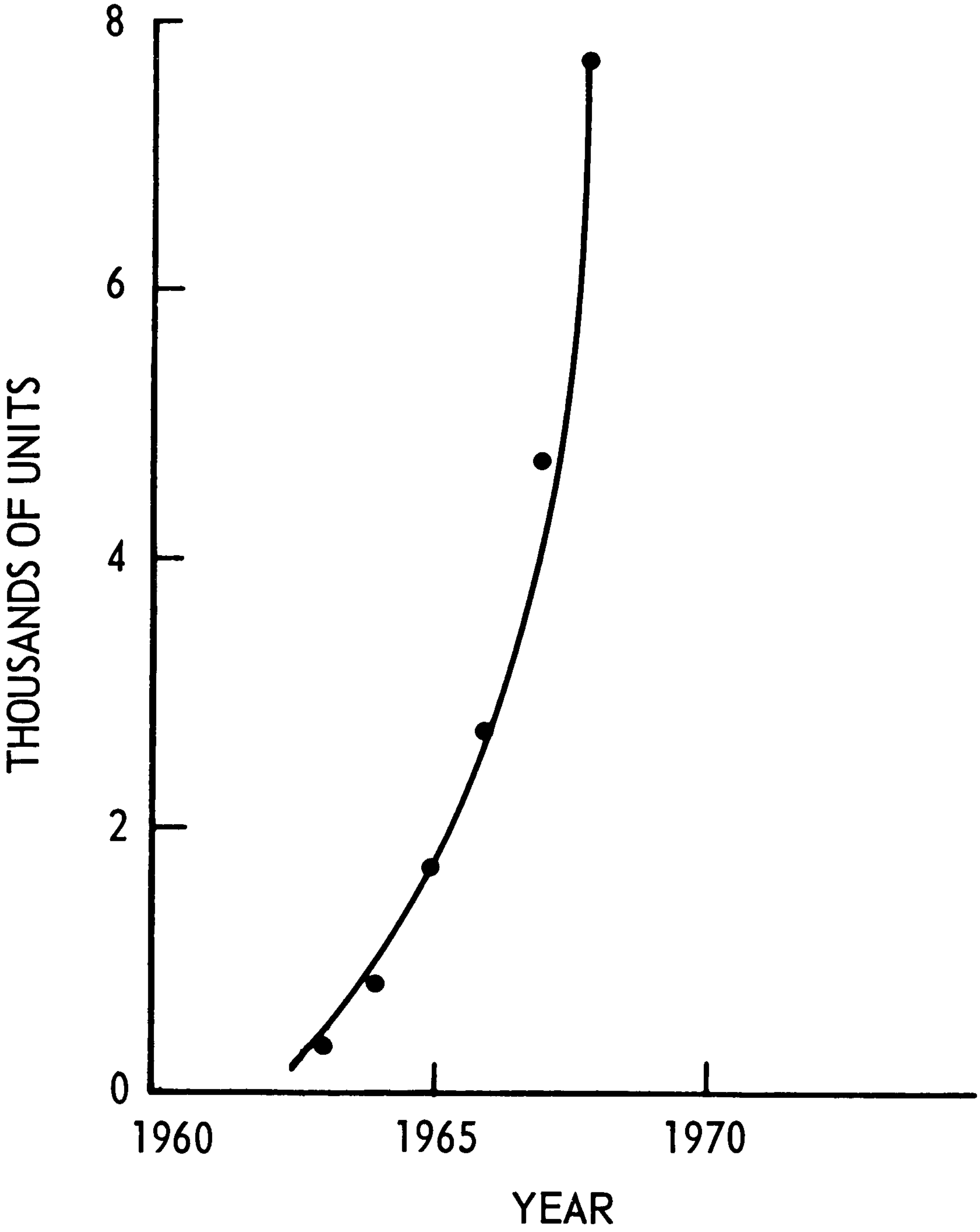

Figure 4. Total U.S. sales of lasers 1963—1968.

TABLE 8

Cumulative U.S. Sales of Lasers, 1963-1968

Type	Cumulative Number	Percent of Total
HeNe	11,150	62
Ruby	2,075	12
Nd Glass	1,155	6
CO_2	1,500	8
Argon	1,335	7
YAG	785	5
Total	18,000	100%

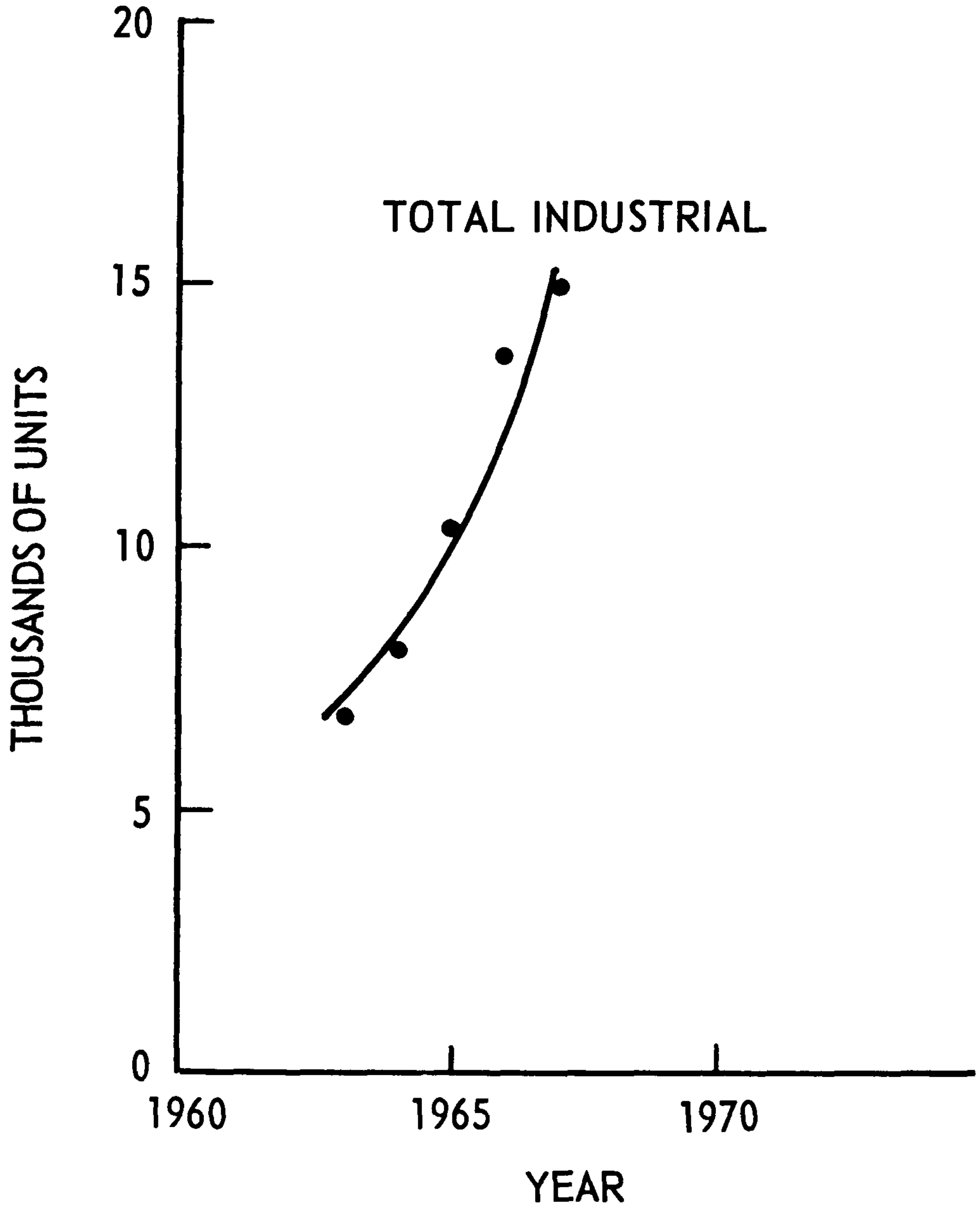

Figure 5. Shipments of industrial ultrasonic equipment 1963–1967[a]

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[a] Information from the Department of Commerce Current Industrial Reports, MA-36N.

TABLE 9

Estimates of Inventory of Ultrasonic Devices, Jan. 1970

Device	Estimated Number
Medical Diagnostic Units	3,000
Medical Therapeutic Units	3,000
Cleaners	Tens of Thousands
Welders	Few Thousand

plasma physics apparatus, are capable of generating fields of sufficient strength to be of public health concern.

Electronic Components

Although the electronic components are an integral part of the products which may have been inventoried separately (e.g. color TV picture tubes and color TV sets), the component production information is generally more readily available and in some cases can give an advance indication of production activity for certain products. An outstanding example of this would be that magnetron sales should reflect to some degree the production of microwave heating devices. For these reasons production rate data on specific components capable of emitting harmful radiation were obtained to supplement the electronic product inventory. Figure 6 shows the total and non-defense shipments of magnetrons for the years 1960-1967. Figure 7 shows the same for klystron shipments.

SUMMARY

An initial attempt has been made to determine the national inventory of electronic products capable of emitting harmful radiation. The main resources utilized were Department of Commerce statistical reports and information supplied by various industry associations. Some of the highlights of the study include the following inventory estimates for January 1970: dental X-ray (100,000); medical X-ray (115,000); industrial X-ray (15,000); accelerators (1,200); color TV households (24,000,000); domestic microrave ovens (50,000); commercial microwave ovens (45,000); radar units on pleasure boats (7,500); laser devices (17,000); and ultrasonic devices (tens of thousands).

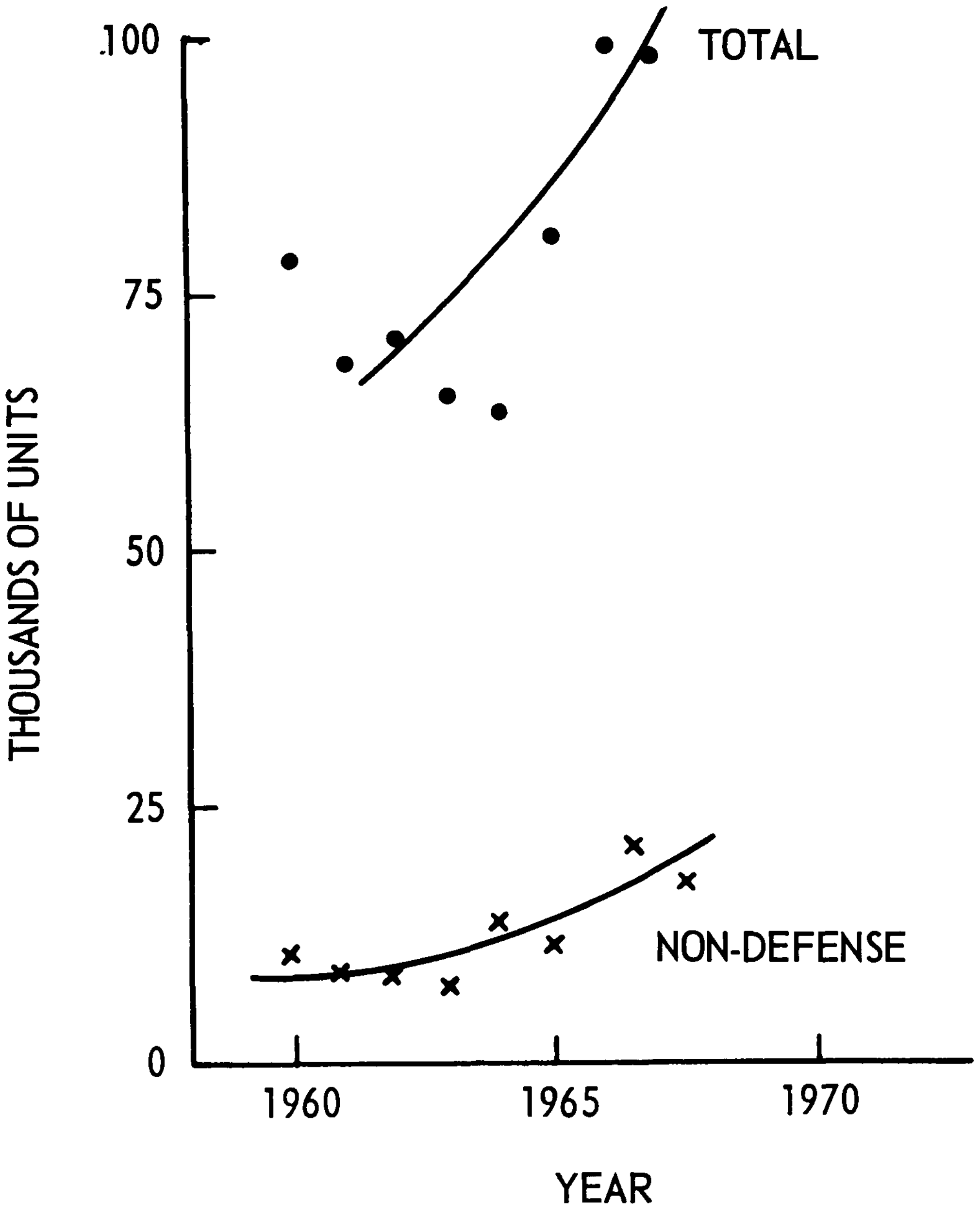

Figure 6. Shipments of magnetrons 1960–1967.[a]

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[a] Source: Consolidated Tabulation Shipments of Electronic Components for Calendar Years 1960–1967, U.S. Department of Commerce.

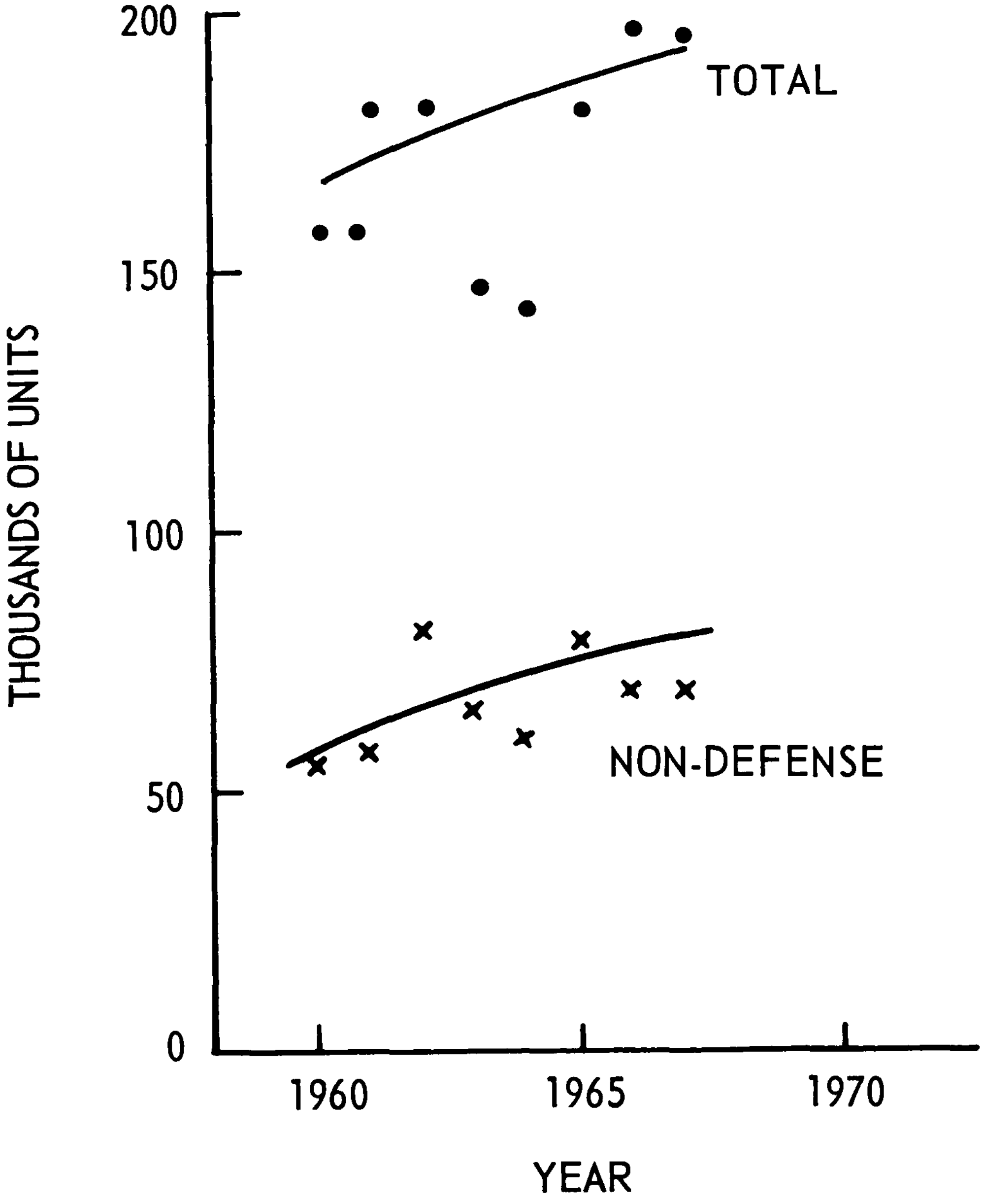

Figure 7. Shipments of klystrons 1960—1967.[a]

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[a] Source: Consolidated Tabulation of Shipments of Electronic Components for Calendar Years 1960—1967, U.S. Department of Commerce.

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ACKNOWLEDGEMENTS: The author is grateful for the assistance of several staff members (particularly Mr. Louis H. Niemann) of the Business and Defense Services Administration of the U.S. Department of Commerce in providing available statistical reports.

A REVIEW OF INTERNATIONAL MICROWAVE EXPOSURE GUIDES

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INTRODUCTION

Since the early 1940's the development and use of higher powered electronic equipment emitting electromagnetic energy in the microwave region has increased considerably. Although definitive boundaries for the microwave region have not been established, the United States of America Standards Institute defines this region as that portion of the electromagnetic spectrum encompassed by frequencies of 10 to 10,000 megahertz (MH_z)[1] while most European countries[2] consider the frequencies of 300 to 300,000 MH_z in the microwave region. This wide range of frequencies serves television, radio, and commercial and military radar. Microwave energy is also used to dry thermosetting glues, to dry chemical and biological samples, to cook or heat foods in microwave ovens, and as a medical application in diathermy and microthermy. Practically no country can be found today without some form of microwave generating apparatus.

Biological effects resulting from microwave exposures are primarily a thermal response produced by the absorption of the energy and its conversion to heat. Areas of the body which cannot dissipate heat rapidly are more susceptible to thermal injury from microwave energy. Of special interest are the lens of the eye where exposure may result in the production of cataracts[3], and the reproductive organs, in that temporary sterility or degenerative changes have been reported in exposures involving research animals and man.[4,5,6]

The amount of heat generated in the tissues is primarily a function of the strength of the microwave field expressed as the average power flow per unit area measured in milliwatts per square centimeter (mw/cm^2), the length of time exposed, and the type of tissue exposed. The type of tissue exposed is, in part, determined by the depth of penetration of the microwave energy which is a function of the frequency of the energy. The lower the frequency, the greater the depth of tissue penetration. Thus, the range of frequencies from 150 to 10,000 MH_z is of primary concern in evaluating potential hazards to microwave exposures.

MICROWAVE CRITERIA

UNITED STATES OF AMERICA

Although many different organizations have promulgated or adopted microwave exposure criteria in the United States,[7,8,9] the following four standards are representative of the various exposure control limits employed in the United States in the past 10 years. The remaining standards represent a majority of the existing criteria used throughout the world.

Tri-Service Conference - 1957

The first microwave exposure standard to gain widespread usage, and to be considered by segments of the U.S. Government, was presented in July, 1957, at a Tri-Service (U.S. Army, Navy, and Air Force) Conference on the Biological Hazards of Microwave Radiation.[10]

Information presented at this Conference was based on observations and tests at random frequencies and at differing power density levels performed by various investigators. It was the opinion of those participating in the Conference that there were not sufficient data to determine safe exposure levels for each frequency, or ranges of frequencies, within the microwave region; therefore, a level of $10mw/cm^2$ was selected for all frequencies.

The U.S. Air Force in adopting this exposure level in May, 1958, applied it to the frequency range of from 300 to 30,000 MH_z,[11] and established it as a maximum permissible exposure level, which could not be exceeded. The only factor considered in this criterion is the power density level. Such factors as time of exposure, ambient environmental temperatures that could have an increased or decreased effect on the body's thermal response, the frequency of the microwave energy, effects of multi-frequency exposures, differing sensitivity of various body organs, and effect of air currents on cooling the body are not considered, although they are all recognized as factors that might affect biological response.

Bell Telephone Laboratories - 1960

The Bell Telephone Laboratories reviewed the data concerning the biological effects of microwaves and qualified the military's maximum exposure level of 10 mw/cm^2 to establish in 1960 the following criteria:[12]

> "1) Power levels in excess of 10 mw/cm^2 are potentially hazardous and personnel must not be permitted to enter areas where major parts of the body may be exposed to such levels.
>
> 2) Power levels between 1 and 10 mw/cm^2 are to be considered safe only for incidental, occasional or casual exposure, but are not permissible for extended exposure.
>
> 3) Power levels under 1 mw/cm^2 are safe for indefinitely prolonged exposure."

These criteria were based on data that indicated the formation of cataracts at power density levels of 100 mw/cm^2 and on the lethal effect of 50 mw/cm^2 on dogs, rabbits, and rats with only a 40% absorption of incident energy.

U.S. Army/Air Force Standard - 1964 and 1965

In 1964, the U.S. Air Force established additional microwave exposure criteria which began moving away from the concept of a maximum permissible exposure limit to that of a time-weighted average.[13] In the case of pulsed radar systems, the time on, time off, could be averaged if the power density did not exceed 100 mw/cm^2.

In 1965, the U.S. Army and Air Force developed an exposure standard[14] which permitted, under certain conditions, personnel exposures to microwave energy in excess of 10 mw/cm^2. This standard was the first to relate completely the individuals exposure time to the incident power density. The two parameters are related by the formula:

$$Tp = \frac{6000}{W^2}$$

where Tp is permissible exposure time in minutes during any 1-hour period and W is power density that the worker is exposed to in mw/cm^2. This standard is applicable between exposure levels of 10 and 100 mw/cm^2. At an exposure level of 10 mw/cm^2 the allowable exposure time is 60 minutes per hour, or continuously, but at 100 mw/cm^2 the allowable exposure time is 0.6 minutes per hour. In actual applications, the standard states "It is not feasible to control limited exposures of less than 2 minutes, and consequently this formula should not be applied to intensities over 55 mw/cm^2."

If workers are exposed to power densities greater than 10 mw/cm^2, this criterion requires that they receive a specific preplacement and periodic medical examinations. The medical surveillance program should include a routine physical examination and a comprehensive opthalmological examination that includes an evaluation of ocular motility media and fundus, and corrected visual acuity for near and far vision and a slit-lamp examination of the lens with the pupil widely dilated.

United States of America Standard - C-95.1, 1966

The United States of America Standards Institute (USASI) in November, 1966, developed a standard entitled "Safety Level of Electromagnetic Radiation with Respect to Personnel.[1]" This standard sets the protection guide at 10 mw/cm^2, as averaged over any possible 0.1 hour period. This standard is based on a power density of 10 mw/cm^2 for exposure times greater than 0.1 hour, and on an energy density of 1 milliwatt hour per square centimeter (mwh/cm^2) for periods less than 0.1 hour. The energy-density concept is a time weighted exposure criterion by which the allowable exposure time in hours per 0.1 hour can be determined by dividing 1 mwh/cm^2 by the incident power density, expressed in mw/cm^2. Thus, for a power density of 60 mw/cm^2, the allowable exposure time (ET) is:

$$ET = \frac{1 \text{ mwh/cm}^2}{60 \text{ mw/cm}^2} = \frac{1}{60}\text{ hr, or}$$

1 minute per 0.1 hour.

In addition to considering exposure time, the USASI standard attempts to consider environmental factors that may affect biological response. The USASI standard guide numbers are applicable for moderate environments; however, "Under conditions of moderate to severe heat stress the guide number given should be appropriately reduced. Under conditions of intense cold, higher guide numbers may also be appropriate after careful consideration is given to the individual situation." The standard also indicates that exposures to microwave energies characterized by a power level tenfold smaller will not result in any noticeable effect on mankind.

UNITED KINGDOM

Standards recommended by British officials are found in the booklet "Safety Precautions Relating to Intense Radio-Frequency Radiation.[15]" These recommendations cover radio-frequency equipment operating in the frequency range of 30 to 30,000 MH_z. This document limits continuous daily exposure to an upper permissible limit of 10 mw/cm^2 with no reference to a time-weighted average. Where the radiation is pulsed, the level should be averaged over the pulses including any intervals between the pulses. Further, if it can be shown, beyond a doubt, that no radiation intensity of 1 mw/cm^2 can be attained at any point where anyone may reasonably and normally have access then radiation measurements do not have to be made. Subsequent sections cite precautions for: the public prohibiting access to an area of radiation intensity exceeding 10 mw/cm^2; and research, experimental and testing personnel providing the same limitations, but pointing out special precautions which might not be necessary.

In the event of an overexposure exceeding 10 mw/cm^2, a medical examination is required along with measurements of the radiation intensity to which the individual was exposed.

FRANCE

Military guidelines have been the subject of a recent decision[16] by the Ministry of Armies fixing microwave exposure criteria similar to the U.S. Army-Air Force standard of 1965. Thus, French military norms fix a safety limit of 10 mw/cm^2 for exposure of one hour or longer. The formula $Tp = 6000/W^2$ is used for periods of exposure less than one hour where power levels are between 10 and 100 mw/cm^2, but, in fact, a 55 mw/cm^2 limit is recognized due to the difficulties in controlling exposures of less than two minutes duration. For rest areas and public areas, a limit of 1 mw/cm^2 is considered desirable.

POLAND

A large amount of research on the health effects of microwave radiation has been conducted in Poland especially at the Institute of Occupational Medicine in Lodź.[6] Based on clinical and experimental research, Polish officials set levels of permissible intensity for microwave radiation with frequencies between 300 and 300,000 MH$_z$. These levels were officially published in an Order of the Council of Ministries[17] in 1961 and contain many prescriptions for work with microwaves. The principle articles state:

> "The following maximum allowable mean values of the power intensity of the electromagnetic field of microwaves are laid down for areas where people are present:
>
> 1) intensity 10 μw/cm^2 - no limitation for time of work or sojourn in this field
> 2) intensity between 10 and 100 μw/cm^2 - cumulative time of work or sojourn not to exceed 2 hours in every 24 hours.
> 3) intensity between 100 and 1000 μw/cm^2 - cumulative time of work or sojourn not to exceed 20 minutes in 24 hours.
>
> No person shall remain in an electromagnetic field of an intensity exceeding 1000 μw/cm^2 unless in cases of emergency and on the condition that special protective measures, as decided for each case by the person in charge of the undertaking, are taken."

Other articles of this order include items requiring an annual medical examination for exposed workers, safe placement of microwave generating installations, protective screening, personnel protection, site surveillance, and safety education.

The medical standards which must be fulfilled prior to work with microwaves are listed in a 1963 regulation of the Minister of Health and Social Welfare.[18] This regulation forbids work with microwave radiation for young people (age not provided), pregnant women, and other people suffering from certain diseases which are listed in the regulation. Preplacement medical examinations are required for all workers who will be exposed to microwaves and include neurological and ophthalmological examinations.

UNION OF SOVIET SOCIALIST REPUBLICS

The vast amount of research and experiences with microwaves in the Soviet Union was recently reported on by Professor Z.V. Gordon of the U.S.S.R. Institute of Occupational Health and Hygiene.[19] Microwave radiation is now used on a wider scale approaching the experiences of other industrialized countries. This fact has promoted the need for regulations specifying maximum permissible intensities and preventive measures consistent with Soviet research and philosophy of worker health protection. Frequencies between 300 and 300,000 MH_z are considered as microwave, and the following values are listed as maximum permissible intensities for frequencies greater than 300 MH_z.

10 $\mu w/cm^2$	for a working day
100 $\mu w/cm^2$	for 2 hours daily
1000 $\mu w/cm^2$	for 15 minutes daily

The U.S.S.R. is also one of the first to propose exposure standards for low-frequency electromagnetic radiation, which heretofore had been considered as having no effect on the human body. These levels are:

Medium-Wave (100 KH_z - 3 MH_z) - 20 volts/meter
Short-Wave (3 MH_z - 30 MH_z) - 5 volts/meter
Ultra-Short Wave (30 MH_z - 300 MH_z) - 5 volts/meter

Medical examinations also are regulated in the Soviet Union for persons exposed to electromagnetic radiation. Medical counterindications are enforced so that workers are not allowed to be exposed to microwave radiation if specified diseases exist. Heavy emphasis is placed on blood disorders, neurological disturbances, and chronic eye diseases.

Preventive measures of an engineering nature are utilized by Soviet health and epidemiological centers to insure compliance with their health regulations. Decreasing the amount of radiated energy, reflective and absorptive screening, and personnel protection measures are all reported to be widely used for personnel operating microwave equipment. Where equipment is used for thermo-machining, drying dielectric material, and for other industrial processes, the Soviet regulations specify area requirements for installing the generating equipment. For example, new generators require a separate room with an area greater than 25 square meters where the power of the generator is greater than 40 kilowatts.[6]

CZECHOSLOVAKIA

Human exposure criteria in Czechoslovakia was officially cited in a 1965 regulation[20] which set the following exposure levels for microwave radiation in frequencies greater than 300 MH_z:

25 $\mu w/cm^2$ (continuous generation)
10 $\mu w/cm^2$ (pulsed generation)

However, an extensive review of the literature and the results of Czechoslovakian experiences were published in 1968 by Marha, Musil, and Tuha.[2] This book has stimulated a review of the existing standard resulting in a new proposal[20] which was placed in the legislative process during 1968. This new proposal covers both high frequencies and microwaves with the latter being defined as the range from 300 to 300,000 MH_z. In this range, the new proposal uses values which are a multiple of energy flow per unit area and time. The proposal states:

> "1) The following values are considered for workers with vf (high frequency) and vvf (microwave) as tolerable doses of radiation not to be exceeded in the working place during one calendar day:
>
> ...c) <u>for continuous generation in the vvf (microwave) frequencies</u>-value = 200
>
> where the energy is expressed in microwatts per square centimeter and the time in hours $[N(\mu w/cm^2) \times t(\text{hours}) < 200$, therefore eight hours working time corresponds to an average energy flow of 25 $\mu w/cm^2]$.
>
> d) <u>for pulsed generation in the vvf (microwave) frequencies</u>- value = 80
>
> where the energy is expressed in microwatts per square centimeter and the time in hours $[N(\mu w/cm^2) \times t(\text{hours}) < 80$, therefore eight hours working time corresponds to an average pulse energy flow of 10 $\mu w/cm^2]$
>
> 2) The following values are considered for the general population and other workers not employed in generation of electromagnetic

energy as tolerable doses of radiation not to be exceeded at the person's location during one calendar day:

...c) for continuous generation in the vvf (microwave) frequencies-value = 60

where the energy is expressed in microwatts per square centimeter and the time in hours [N(mw/cm^2) X t(hours) $<$ 60, therefore twenty-four hours exposure time corresponds to an average energy flow of 2.5 μw/cm^2]

d) for pulsed generation in the vvf (microwave) frequencies-value = 24

where the energy is expressed in microwatts per square centimeter and the time in hours [N(mw/cm^2) X t(hours) $<$ 24, therefore twenty-four hours exposure corresponds to an average pulsed energy flow of 1 μw/cm^2]"

Further articles of this proposal define continuous and pulsed generation where continuous generation is defined as operation with the ratio of on to off time as 0.1 or greater. Another section of the proposal outlines a standard method for measurement of electromagnetic radiation with Czechoslovakian measuring equipment.

WEST GERMANY

The German Association for Radar (Direction Finding) and Navigation has published a guide[21] which is considered authoratative in the Federal Republic of Germany. This guide entitled "Health Damages by Radar and Similar Appliances and their Prevention" sets the critical limit of microwave radiation intensity at 10 mw/cm^2 for human exposure. No allowance is made for time of exposure.

N.V. PHILIPS- EINDHOVEN, NETHERLANDS

Private industry was requested to supply information for this survey.

Philips appears to be the only European industry with extensive criteria outlined for the protection of their employees. Their Labour Protection Department issued a safety regulation[22] for work with microwave radiation (30-300,000 MH_z) in 1967 which must be complied with in the Netherlands by Philips' employees. This regulation states:

> " Radiation intensities higher than 10 mw/cm^2 should be considered dangerous. Safety precautions should; however, be based on a permissible level of 1 mwh/cm^2 (average values)."

Further clarification of these values by the Philip's Industrial Medical Department places the limit for human exposure at 1 mwh/cm^2 for radiation lasting less than six minutes and 10 mw/cm^2 for all radiation longer than six minutes duration.[23] Medical examinations, protective clothing, warning signs, and other measures are included in their protection program. Using these guidelines the medical department has not detected any harmful effects to the eyes or body of Philips' workers who are engaged in the production of radar sets and microwave ovens.

SUMMARY

A review of microwave exposure criteria used in the United States and other western countries in the past ten years indicates a general acceptance of a power density exposure level of 10 mw/cm^2. The U.S.S.R. and Poland specify permissible levels one thousand times lower at 10/$\mu w/cm^2$ while Czechslovakia has proposed a sliding scale allowing 25 $\mu w/cm^2$ for an average working day exposure. The basis for these differences was not discussed in this paper, but in general they arise by the acceptance of data showing non-thermal functional changes from microwave radiation exposure of animals and humans.

The first standards developed in the United States considered the 10 mw/cm^2 value to be a maximum permissible level which should not be exceeded. These standards considered only the power density level of microwave energy and did not consider other factors affecting biological response such as multi-frequency exposures, time of exposure, frequency used, and environmental factors such as the heat load or cooling capacity of the workplace. Several countries have maintained this concept of a permissible value while others have incorporated exposure time. The two latest exposure criteria which have been developed in the United States since 1965 permit exposures to power densities in excess of 10 mw/cm^2; however, the duration of such exposure is limited. This concept has been accepted by France for military guidelines. Czechoslovakia has also accepted this newer concept incorporating exposure time by proposing a sliding scale of allowable radiation intensity but retaining their much lower allowable daily exposure level as the starting point.

In applying the concept of a time-weighted exposure the health specialist must consider how far the dose-time relationship can be extrapolated. The biological response to extremely high microwave power densities, even though such exposure may be for a very short time period, must be considered. The effects of severe heat stress or intense cold on the body's cooling capacity are noted in the latest United States standard, although definitive recommendations for applying the concepts are not provided. Future standards should reflect environmental stress as well as other factors found to affect the biological response to microwave energy.

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MICROWAVE CATARACTS - A CASE REPORT REEVALUATED

Frederic G. Hirsch, M. D.[*]

I. INTRODUCTION

In 1952 Dr. John T. Parker and I reported on a case of bilateral cataracts which occurred in a technician who operated a radio frequency power source whose output was in the microwave portion of the electromagnetic spectrum.[1] At the time, for a number of reasons, it was not possible to publish a meaningful estimate of the magnitude of his exposure, so that the indictment of microwave radiation as etiologic in the case perforce rested on circumstantial evidence. In the first place, much of the data on which an estimate of dose rested was at that time subject to security restrictions. A second, and more important reason was our inability (at that time) to determine dosage due to the rudimentary state of the body of knowledge of the impact of microwave energy on biologic systems. Now, after seventeen years have gone by, the first impediment has been removed, and the second has profited by the research of many workers in the United States, the United Kingdom, and the USSR. Indeed the bibliographic reference file which I have maintained since I first became interested in the subject now contains hundreds of entries.

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I am continually amazed at the continued interest in this case over the past seventeen years and into the present. It seemed useful, therefore, to take advantage of this forum, provided by the Blue Grass Chapter of the Health Physics Society, for a reevaluation of the case utilizing the freedoms resulting from the lifting of security restrictions and taking advantage of the present state of the art. In doing so my purpose is threefold. First, I would like to present my own evaluation and some unpublished studies which make that evaluation possible. Second, by presenting the data on which dosage calculations can be made, others can make their own estimations and decide for themselves whether or not my conclusions can stand critical scrutiny. Third, I think it will be of interest to present the ophthalmic findings as of the present time and to equate the changes with the passage of seventeen years.

II. HIGHLIGHTS OF THE CASE HISTORY

The patient was a 32-year-old white male electronics technician who operated a microwave RF power source for a year prior to the onset of his visual disturbance. For the immediate three days prior to the onset of symptoms he had worked the apparatus on a more or less continuous basis during most of each working day with the antenna horn arranged in a peculiar geometry with respect to his head. This period of increased risk amounts to something approximating 24 hours with intervals of 16 hours separating each 8 hour period at risk. Figure 1 diagrams his relationships to the output of the power source.

It will be apparent that the limited space available placed the patient's head in close proximity to the radiation coming out of the horn antenna for

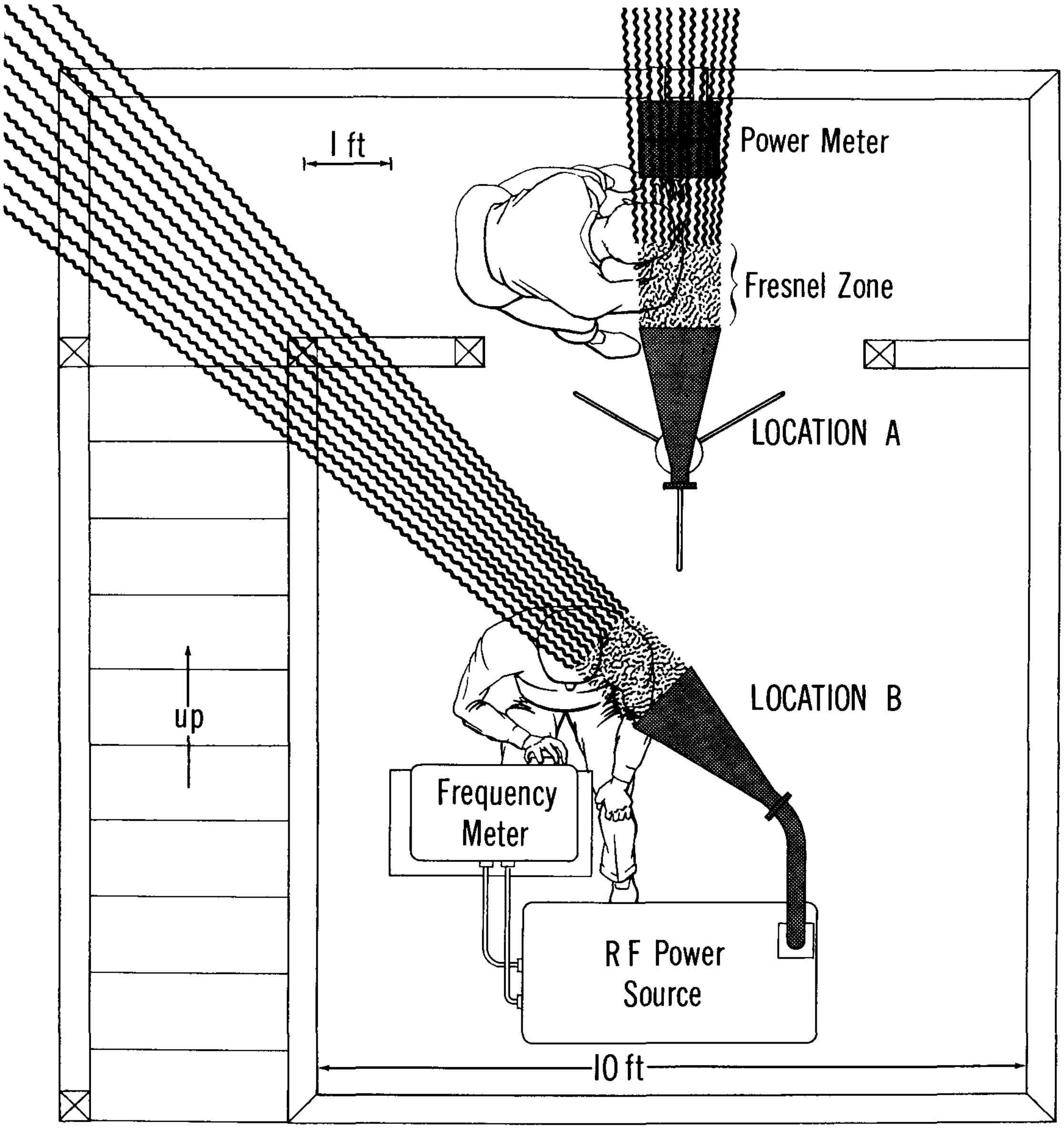

Figure 1. Plan view of test tower platform.

what must have been a good share of the time. When the antenna horn was in its usual configuration as shown in position A, he had to cross in front of the beam many times during the course of his activities; and, as was noted in the original report, he had the habit of sticking his hand into the open end of the antenna horn to gauge from the heating effect on his hand whether or not the source was radiating power. However, it was probably the exposure incurred in the three days when he worked in position B that caused his lesions to develop. He was aware of a sensation of heat on his head, but was not uncomfortable. He did notice that his eyes were somewhat "blood shot" at the end of each working day. His visual disturbances developed quite suddenly during the night two days after the last working day. Please note that the left side of his head is closest to the antenna horn. As will be pointed out the lesions in the left eye were substantially more severe than in the right.

In October of 1951 he was first seen complaining of blurred vision which had developed between retiring on Sunday night and awakening on Monday morning. He was found on examination to have moderately advanced bilateral cataracts, chorioretinitis in the left eye, and numerous opacities in the vitreous humor of the left eye. The nature and extent of the left retinal lesions found are shown in Figure 2.

Figures 3 and 4 are histologic sections which show changes in the lenses at a time later than the original examination. These are quite identical to those reported by others in cases of cataracts resulting from radiant energy, notably Duke-Elder.[2] The large swollen "foam cells" are characteristic. The left lens was completely cataractous at the time of

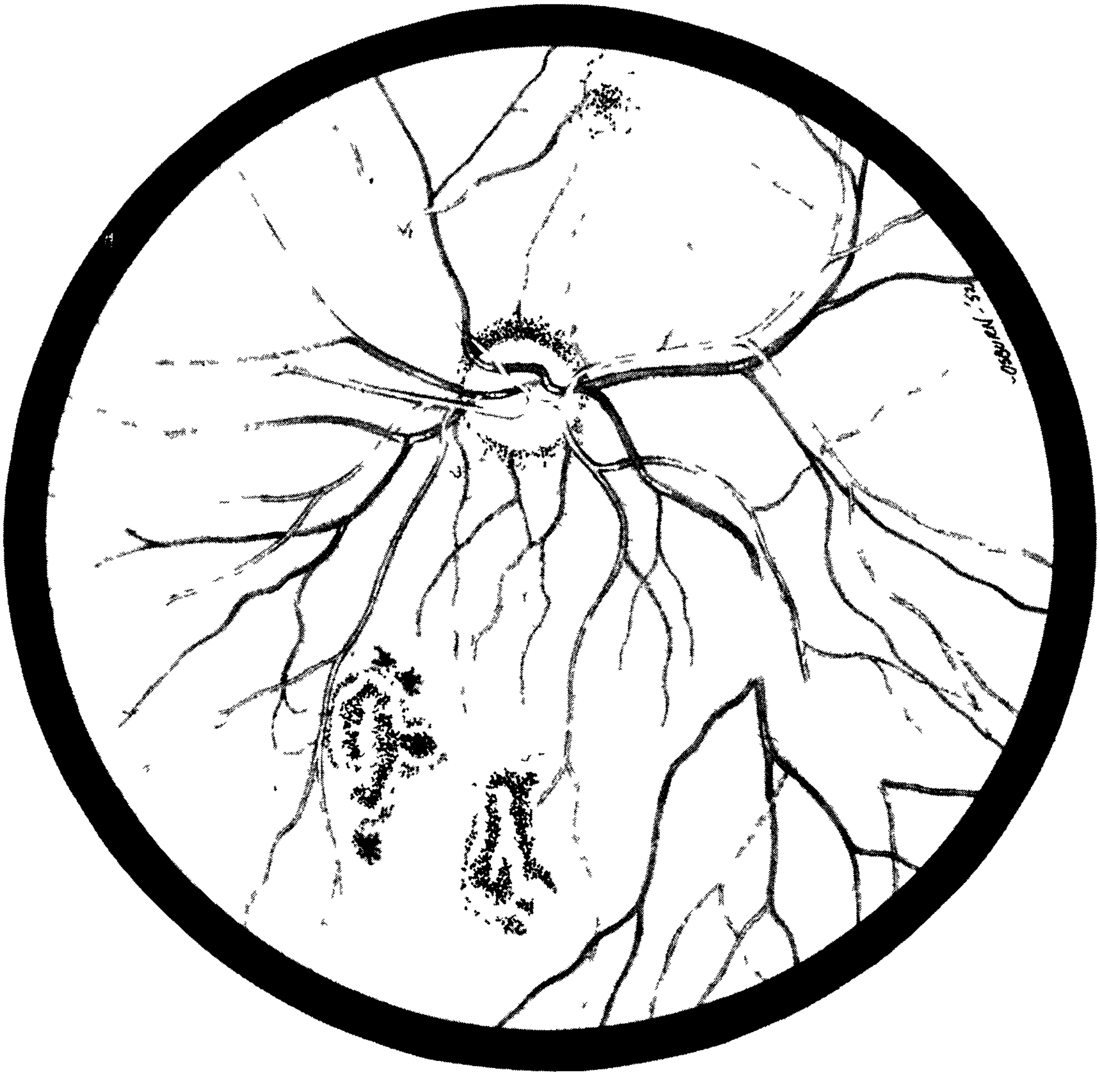

Figure 2. Artist's rendition of left fundus showing pigmented lesions of retina and choroid which are surrounded by pigmentation, and oedematous areas in retina.

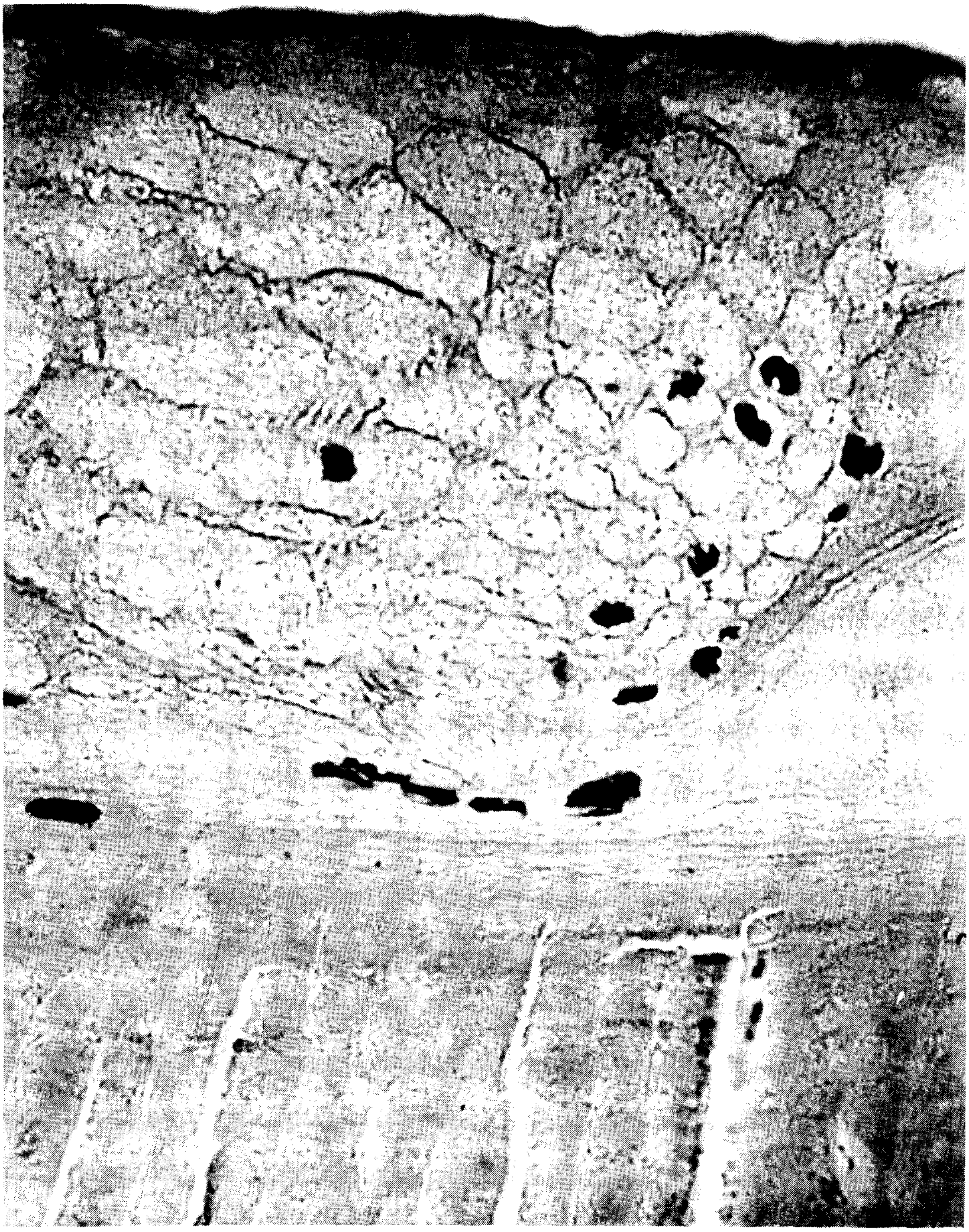

Figure 3. Histologic section through the left lens. Posterior capsule is at the bottom of the picture.

Figure 4. Histologic section through the left lens taken near attachment to ciliary body.

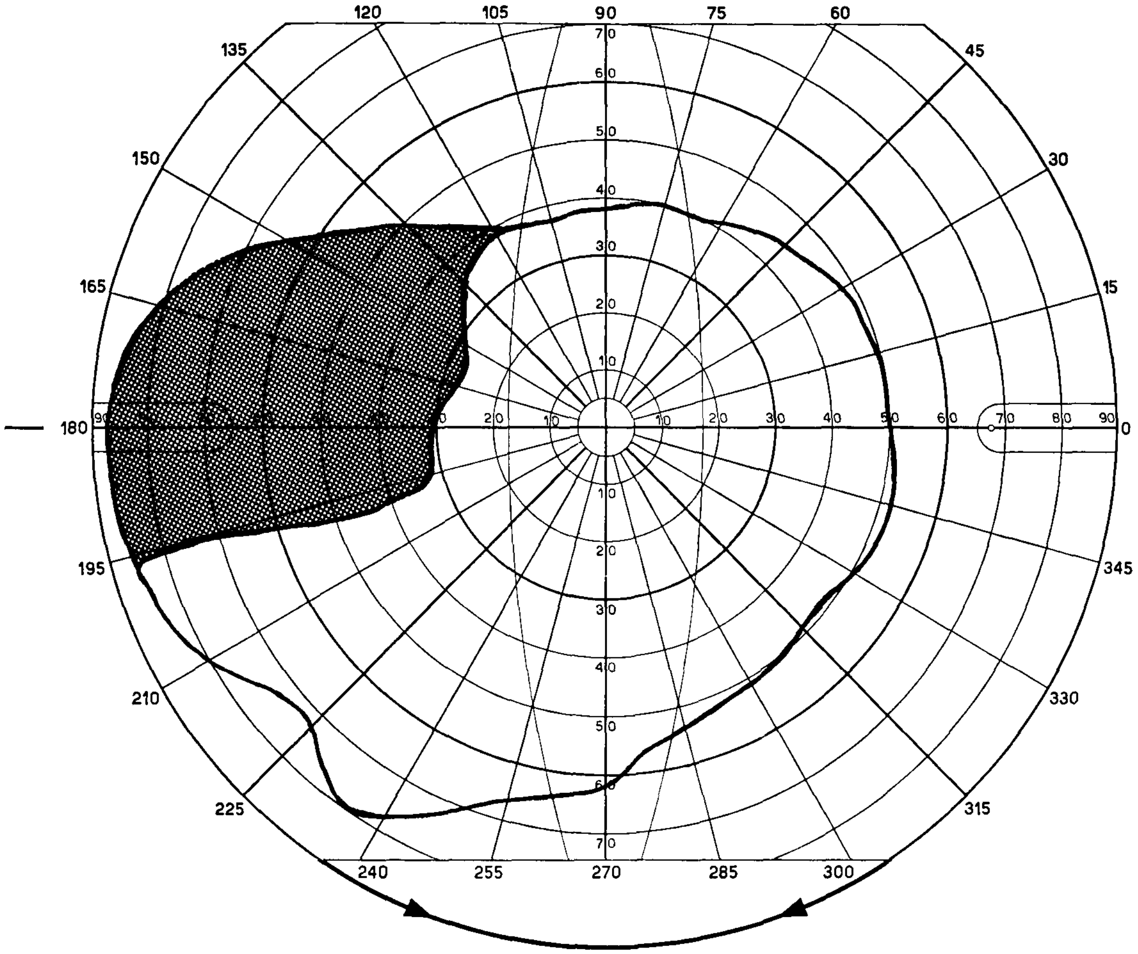

Figure 5. Scotoma produced by chorioretinal lesions in left eye.

its removal in March 1953. The retinal and vitreous lesions stabilized with the passage of time and treatment by cortico steroids. He was fitted with an appropriate contact lens and has functioned since without significant visual handicap, although he has a troublesome chronic uveitis, probably associated with a small amount of retained lens material. A recent followup examination established that the cataract in the right lens has remained stable over the past fifteen years. That is to say, it has neither progressed to complete opacification nor has it regressed to any apparent degree. At the present time the retinal lesions can still be seen,and they cause scotomata as can be seen by the visual field map which is shown in figure 5. Figure 6 is a recent photograph of the left fundus showing the present appearance of the old lesions. How much of the present activity of the chorioretinitis is due to the radiant energy he received many years ago versus that caused by his persistent uveitis is conjectural. My own feeling heavily indicates the latter.

III. ESTIMATE OF DOSAGE AND ITS RATIONALE

In order for radiant energy to produce a biological effect, mere exposure to it is not enough. The energy must be absorbed in sufficient quantity to produce functional or structural change in a tissue or organ, whether it be simply by producing damaging temperature elevations or whatever else. My purpose in that which follows is only to establish that in this instance sufficient energy was absorbed, and I shall not consider the possible pathophysiologic mechanisms. I will use the heat developed only as an index of absorption of energy, because whatever else happens, when an eye absorbs radiant energy heat is produced and to submit that the amount of temperature rise in a tissue is directly proportional to the energy absorbed seems to be altogether reasonable.

Figure 6. Fundus photographs of left retina showing chorioretinal lesions after 15 years.

The RF power source in this case was a "C" band magnetron which was connected by wave guides to a standard "S" band rectangular horn antenna. The output of the oscillator was at a frequency between 5000 and 4000 Megahertz corresponding to a wavelength between 6.0 and 7.5 cm. The apparatus was operated on a 50 percent duty cycle with a peak power output of 500 Watts, and an average power output of 250 Watts. The peak power density in a plane at the rim of the horn was 0.9 Watts/cm^2. The area of the aperture of the horn was 120 in.^{2} or 792.5 cm^2. The effective area of the antenna was 550 cm^2. The gain factor of the antenna was 123. These parameters are shown in Table I.

An RF power source such as this has certain characteristics which are germane to our present considerations and which are shown diagrammatically in Figure 7. There is a zone extending from the rim of the horn out into space which is commonly known as the "Fresnel" or "Near Field" Zone. The dimensions of this Fresnel Zone depend on the area of the antenna, the peak power, and the wave length of the radiation. The intensity of the radiation is not uniformly distributed, but is more intense in the center of the beam than at the edges. Further, there are finger-like concentrations of intensity distributed throughout, with those in the center being more intense than those at the edge as diagrammed in Figure 8. The radiation in the Fresnel Zone is roughly collimated to the dimensions of the horn and does not diminish in strength in this zone with increasing distance.[3, 4]

TABLE I. PARAMETERS AFFECTING DOSE CALCULATIONS

1. Magnetron (C Band). Wave guides to a standard "S" band horn. Duty cycle 50%.

2. Wave length -- 6.0 to 7.5 cm.
   Frequency – 5000 to 4000 megahertz/sec.

3. Maximum peak power -- 500 Watts.
   Average power -- 250 Watts.
   Power density at plane of rim of horn = 0.9 W/cm^2

$$\frac{\text{Power}}{\text{Effect area}} = \frac{500\text{W}}{550\text{ cm}^2} = 0.9\text{ W/cm}^2$$

4. Area of horn – 10" x 12" or
   25.4 cm x 31.2 cm (120 in^2 or 792.5 cm^2)
   Effective area of horn = 550 cm^2 (10" x 8.5")
   Gain of antenna – 123

$$G = \frac{4\pi}{\lambda^2} \times A\text{ effective} = \frac{12.6}{56.25} \times 550 = 123.02$$

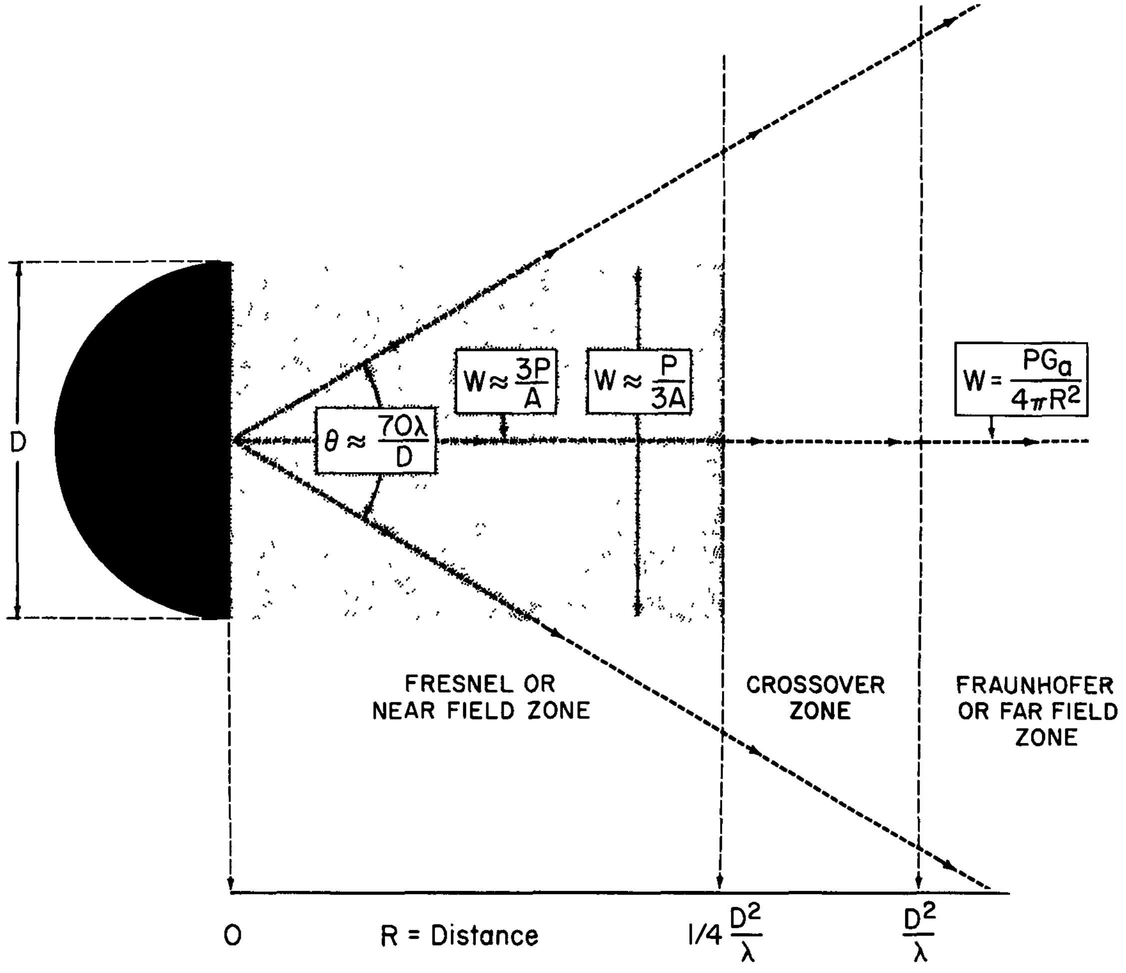

Figure 7. An output diagram of a typical antenna radiating into free space illustrating the various radiation zones. Not to scale.

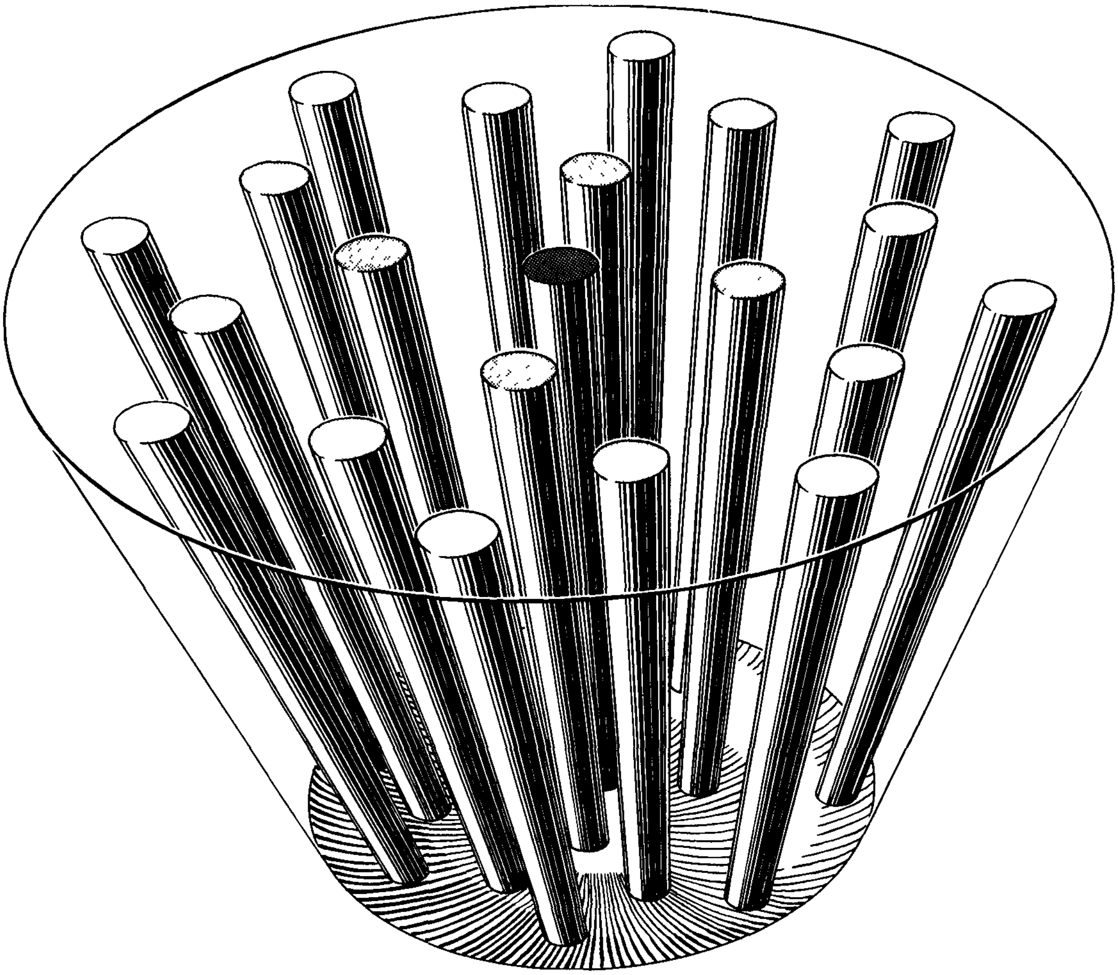

Figure 8. A diagrammatic representation of the finger-like projections of energy concentration in the Fresnel zone of a radiating antenna. The shading represents relative intensities, the blacker, the more intense.

The length of the Fresnel Zone can be estimated by the equation:

1. $R = \frac{1}{4}\left(\frac{A}{\lambda}\right)$

where:

R = Length of Fresnel Zone in feet.

A = Area of antenna horn in sq. ft.

λ = Wave length in feet.

In the case in point, the area was 0.83 ft.^2, and the wave length was 0.23 ft. so:

$$R = 0.25 \times \left(\frac{.833}{.23}\right) = 0.905 \text{ feet or about 30 cm.}$$

This means that the patient operated in the Fresnel Zone whenever he was within 1 foot or 30 cm of the front of his antenna.

As previously mentioned the power intensity in the Fresnel Zone is unevenly distributed. At the center axis the intensity is approximated by the equation:

2. $W_c = \frac{3P}{A}$

where:

W_c = Power density at center axis. ($\text{W}/\text{ft.}^2$)

P = Power in Watts.

A = Area of the antenna horn in square feet.

At the edges of the horn the power density is approximately given by the expression:

3. $W_e = \frac{P}{3A}$

where:

W_e = Power density at the edges of the Fresnel Zone.

In this instance we obtain values for the center axis and edge powers as follows:

$$W_c = \frac{3 \times 250}{.833} = 900 \text{ Watts/ft.}^2$$

$$W_e = \frac{250}{3 \times .833} = 100 \text{ Watts/ft.}^2$$

In summary, whenever the patient was a foot or less in front of the horn and six inches or less to one side of the center axis of the horn, he was in the Fresnel Zone where the field was between 100 and 900 Watts/sq. ft.

Extending from the far end of the Fresnel Zone out into space the radiated energy becomes more coherently organized. This is known as the "Fraunhofer Zone" or "Far Field." Between these two zones there is a "Crossover Zone" for which there is no satisfactory mathematical expression. The intensity of the radiation available for absorption in space in the Fraunhofer Zone can be calculated by several equations one of which is shown in Figure 7. Since the case in point involves an exposure which took place in the "Fresnel" and "Crossover" zones for the most part, no more consideration will be given to the "Fraunhofer" zone.

One is probably justified in assuming that one can use Fresnel Zone calculations for as much as a foot in front of the antenna horn in estimating this patient's exposure. Certainly it can be said that the field in front of the horn extending almost to the hand rail of the platform was well above the accepted 0.01 W/cm^2. This becomes apparent when one uses Bovill's equation[5] for calculating safe distances in the Fraunhofer zone:

4. $R = (P_w \times G_a / 4 \times L)^{\frac{1}{2}}$

where:

R = So-called "safe-distance" (cm).

P = Radiated power (Watts).

(continued)

G_a = Antenna gain

L = Maximum permissible exposure level (10m W/cm^2)

Substituting the appropriate numbers in Equation 4 we have:

$$R = (250 \times 123/1.2566 \times 10)^{\frac{1}{2}} = 49.47 \text{ cm.}$$

So we can add the length of the Fresnel Zone (30 centimeters) to the length of the unsafe distance in the Fraunhofer Zone (49.5 centimeters) and find that the length in front of the horn where the patient was exposed to hazard was about 80 cm or 2.6 feet. These calculations do not take into consideration the intensity or length of the Transition Zone. We know its intensity is somewhat less than in the Fresnel Zone and greater than in the Fraunhofer Zone, so something more must be added to this estimate of the hazard zone. I have arbitrarily elected to add 0.4 feet which makes the hazard zone extend one yard in front of the horn.

In order for radiant energy to have a traumatic or biologic effect, absorption must take place. According to Maskalenko,[6] the absorption of radiant energy by tissue can be calculated using the expression:

5. $P_{in} = P_{thru} \times e^{2\alpha z}$

where:

P_{in} = Incident power (W/cm^2)

P_{thru} = Unabsorbed power which passes through.

$e^{2\alpha z}$ = Factor of absorption. z in the exponent is the thickness of the irradiated object. α is a complex function which has in it the dielectric constant, conductivity, frequency, and other entities.

A simple set up was used to measure the power which passed through a freshly excised cow's eye. The eye was suspended by thread in a square of lucite in which a hole had been cut large enough for the eye to pass through. On the front surface of the lucite square a good thickness of lossy material was affixed which also had a hole in it so that the incident energy could strike the eye. In back of the eye a small receiving horn was placed which was connected through a calibrated attenuation network to a Hewlett-Packard Field Intensity Meter. The power passing through the eye was measured. A number of such measurements showed that the quantity e^{2az} had a numerical value of 1.64 in the case of the cow's eye.

Elsewhere I have reported on the use of spheres having the dimension of a cow's eye made of 35 percent gelatin as a simulant.[7] In order to establish the equivalency Figure 9 is presented. In all my work where temperatures in cow eyes were compared with gelatin spheres the maximum temperature in the eye was 12 percent higher than that in the sphere. Measurements of the numerical value of e^{2az} in gelatin spheres showed that it too was about 1.64.

Figure 10 shows the temperature reached as a function of the duration of irradiation. It will be noted that this curve shows the data when the power density was increased to 1.0 W/cm^2. This was done to compensate for the difference between the temperatures measured in cow eyes and those reached in gelatin spheres, and was accomplished by reducing the effective area of the antenna horn.

In experiments using gelatin spheres their absorption was measured at diminishing levels of incident power. This was done by increasing the distance between the antenna horn and the sphere over a range from 2.0 cm to 30 cm. It was found that the percentage absorption was surprisingly constant at 39 percent. Furthermore the agreement with calculated absortions using Maskalenko's equation was good. These data are shown in Table II.

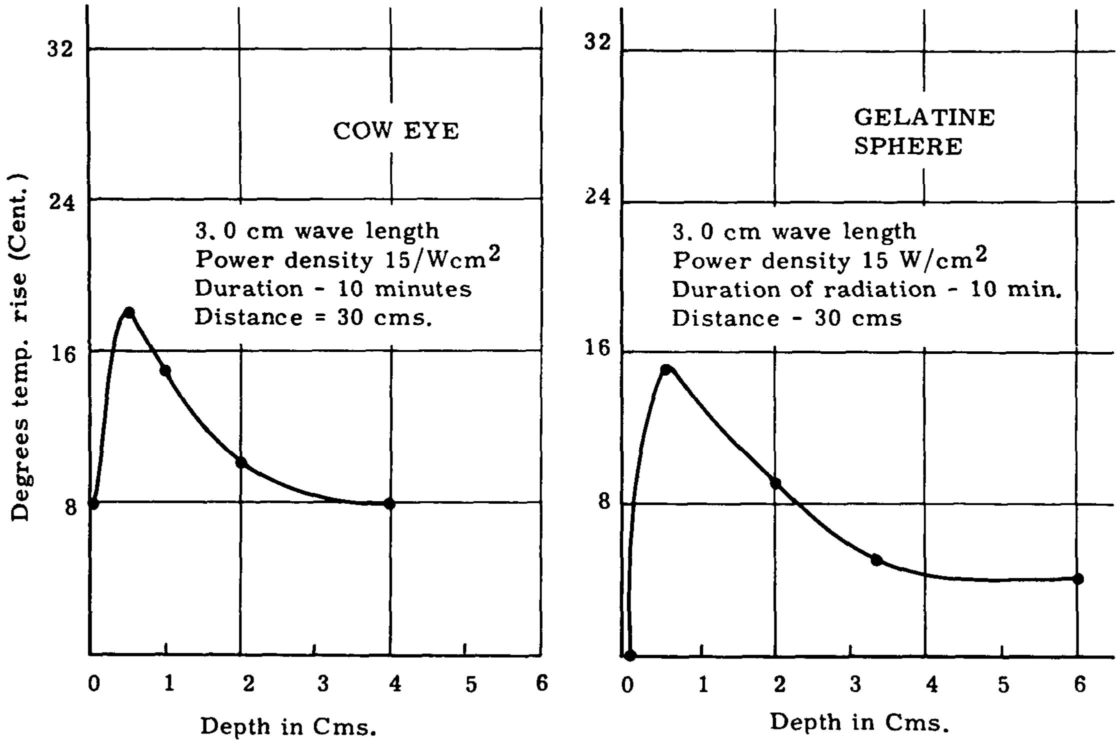

Figure 9. Comparative plots showing temperature rise versus depth in excised cow eyes and 35 percent gelatin spheres.

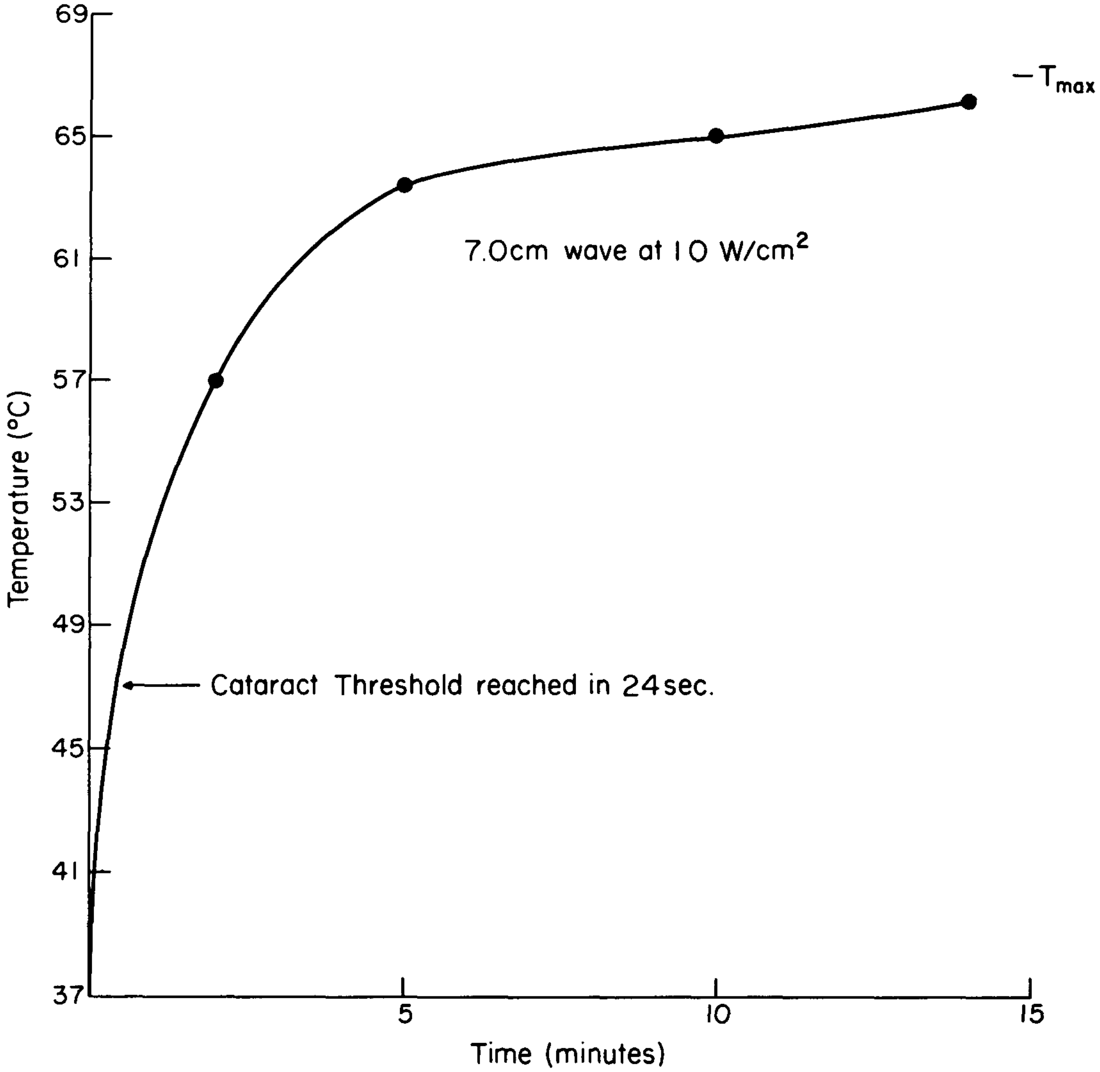

Figure 10. Temperature rise versus time in a 35 percent gelatin sphere of the same dimension as a cow eye.

TABLE II
POWER ABSORPTION BY 35% GELATIN SPHERES

Distance from Antenna (cm)	Incident Power (Watts)	Power Passed through (cm)	Percentage Absorbed
2	368	224	39
4	92	56	39
8	23	14	39
20	4	2	39
24	3	1.5	39
30	2	1	39

If one can accept the assumption that the human eye and the cow eye have essentially the same absorption characteristics, then one can say that the patient in this case absorbed about 39 percent of the incident energy on his eyes. During those times when his head was in the Fresnel Zone, and he was facing the horn, his eyes probably were receiving between 39 $W/ft.^2$ (0.04 $W/cm.^2$) and 351 $W/ft.^2$ (0.38 $W/cm.^2$) of RF energy. This does not take into consideration the parameter of time which is always of the essence in dosage calculations, and time per se is meaningless unless the rate of absorption is known.

In order to investigate the rate at which RF energy was absorbed, freshly enucleated cows' eyes were placed in a perfusion apparatus which caused a modified Ringer's solution to circulate through them at a temperature of 37° C. These preparations remained apparently viable for as long as twelve hours as evidenced by finding active mitosis in the corneal epithelium at the end of that period of time. A bead thermistor was placed at the back of the lens and temperature was measured versus time. A typical result is presented in Table III.

TABLE III

TEMPERATURE RISE IN LENS AS A FUNCTION OF TIME

Time	Temperature	Temperature Rise
Start	37°	0°
5 minutes	49°	12°
10 minutes	52°	3°
15 minutes	54°	2°

If one makes five assumptions then he can estimate the rate of absorption by a tissue mass. These assumptions are:

1. The rate at which the radiant energy is being delivered is constant.
2. The rate at which the lens temperature increases is directly proportional to the rate of radiant energy absorption.
3. The percentage of energy absorbed is constant.
4. The temperature reached in the lens is directly proportional to the amount of absorbed energy.
5. As tissue damage progresses, repair also commences, and that repair continues during hiatuses between exposures. The implication of this being that the amount of tissue damage is mitigated by repair processes to the end that the elapsed time of exposure probably does not truly reflect resultant effect. One should, therefore, use some function of time in dosage calculations. A common one in current use by radiobiologists is the square root of time.

Using these assumptions one can set up a relationship which states that the absorbed power is equal to the incident power times the percentage absorption multiplied by the square root of the duration of exposure. Such a relationship would have the form:

6. $$P_a = P_i \times A_{bs} \times \sqrt{t}$$

where:

P_a = Power absorbed. (W/cm^2, min).

P_i = Incident power. (W/cm^2).

A_{bs} = Percent of P_i absorbed. (%).

t = Time (minutes).

This data is presented graphically in Figure 11.

In the experiments previously described it was noted that opacification of the lens began at 47° C, so additional experiments were performed using several other methods of determining the critical temperature for coagulation, e.g. placing excised lenses in a water bath whose temperature was gradually increased. That 47° C was the threshold temperature for opacification of the bovine lens was confirmed.

In the Fresnel Zone of the antenna involved in the present case we have seen that the power density varied from 900 Watts/ft.^{2} in the vicinity of its center axis to 300 Watts/ft.^{2} at the edges. This amounts to 1.16 W/cm^2 and 0.39 W/cm^2 respectively. Integrating the energies over a plane coinciding with the rim of the horn can be practically accomplished by dividing the peak power by the effective area of the antenna horn, i.e.:

7. $$\frac{P_\circ}{A_{eff}} = P_a$$

where:

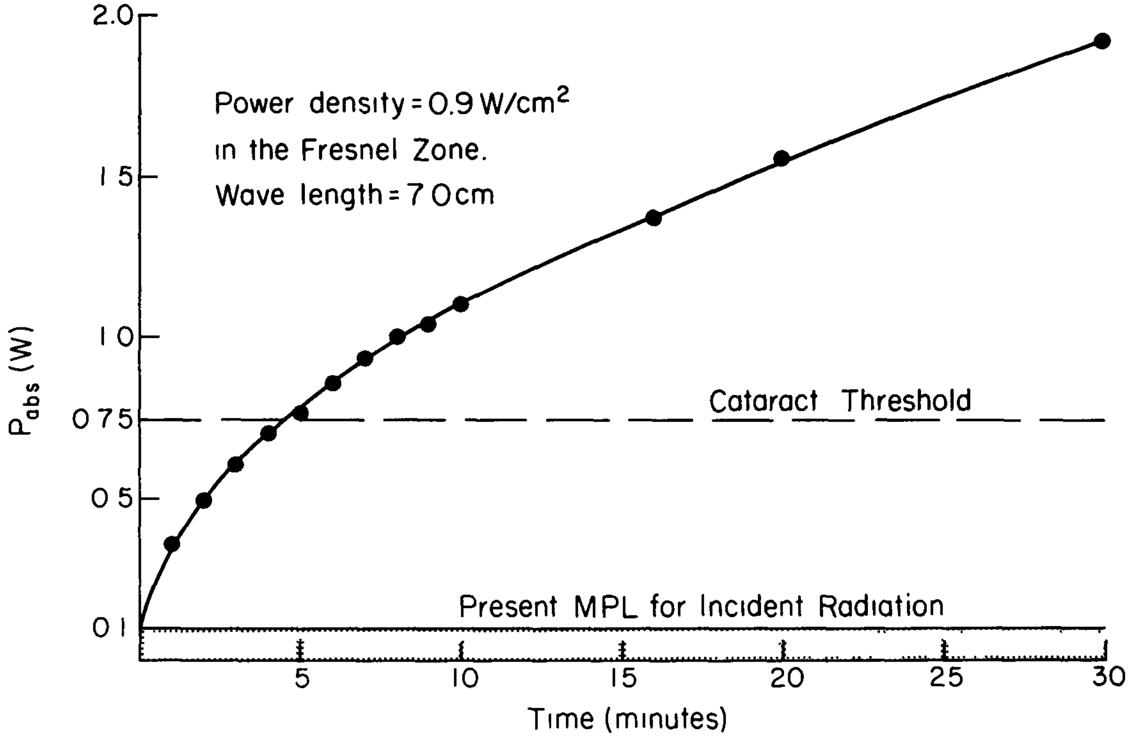

Figure 11. A plot showing the calculated probable absorbed dose as a function of time.

P_o = Peak power (Watts).

A_{eff} = Effective area of the antenna (cm^2).

P_a = Average power density ($Watts/cm^2$).

In this instance the peak power was 500 Watts and the effective area of the antenna was 550 cm^2, so:

$$\frac{500\ W}{500\ cm^2} = 0.9\ W/cm^2$$

It is now possible by using Equation 6 to calculate the probable absorbed dose when the patient's head was in the Fresnel Zone facing the horn for any given period of time. When this is done and plotted one obtains a curve which is shown in Figure 11. If one also plots this data on log-log paper (Figure 12), one obtains a straight line from which an equation can be derived which relates absorbed power to time of exposure. This equation has the form:

8. $P_{abs} = .35\ t^{.497}$

where:

P_{abs} = Absorbed power (Watts).

t = Time of exposure (minutes).

In an earlier graph (Figure 10) the relationship between temperature and time was delineated. By combining these two sets of data one can now plot absorbed power versus lens temperature, since the parameter of time is common to each of them. When one does this on semi-log paper, one obtains a straight line. This plot is shown in Figure 12. It is now possible to derive an expression which describes the slope of the line depicted which has the form:

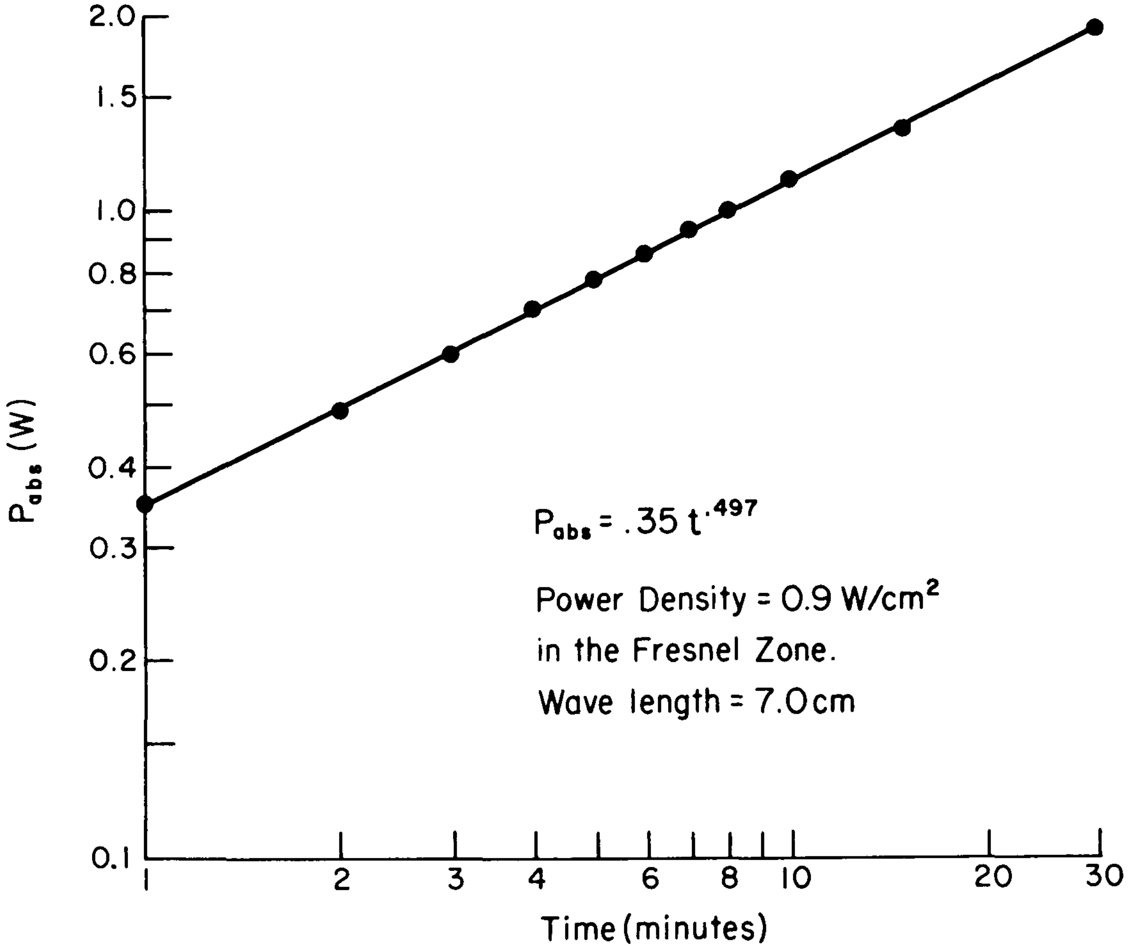

Figure 12. The same data as in figure 11 plotted as a log-log relationship; the slope of the line is described by the equation shown.

9. $T = 51 (P_{abs})^{\frac{1}{5}}$

where:

$T =$ Lens temperature (Degrees C).

$P_{abs} =$ Absorbed power (Watts).

Cogan[9] has stated that when an eye has absorbed about 0.75 W/cm^2 of power development of opacities begins. My own measurements indicate that when a lens reaches 47° C opacification starts. One sees from Figure 13 that when the lens temperature has reached 47 degrees, 0.66 W/cm^2 of radiant energy have been absorbed. To conclude that there is a range between 0.65 W/cm^2 and 0.75 W/cm^2 of absorbed power which is sufficient for the development of a cataract seems justified.

SUMMARY

Using the data at hand one sees that when the patient's head was in the Fresnel Zone for as little as five minutes damaging amounts of power were probably absorbed by his lens tissues. The circumstances of his exposure were such that this situation did occur and frequently. The fact that the left side of his head received a greater exposure to energy than did the right side, coupled with the fact that the damage to the left eye was greater seems to be very significant.

Although one is unable to derive a single number which describes his absorbed dose of radiant energy, there can remain but little doubt that his cataracts and chorio-retinal lesions resulted from absorption of the microwave energy to which he was exposed.

I want to be emphatically clear that the magnitude of the exposure to radiant energy in this instance is unique, and is not of a sort likely to be duplicated

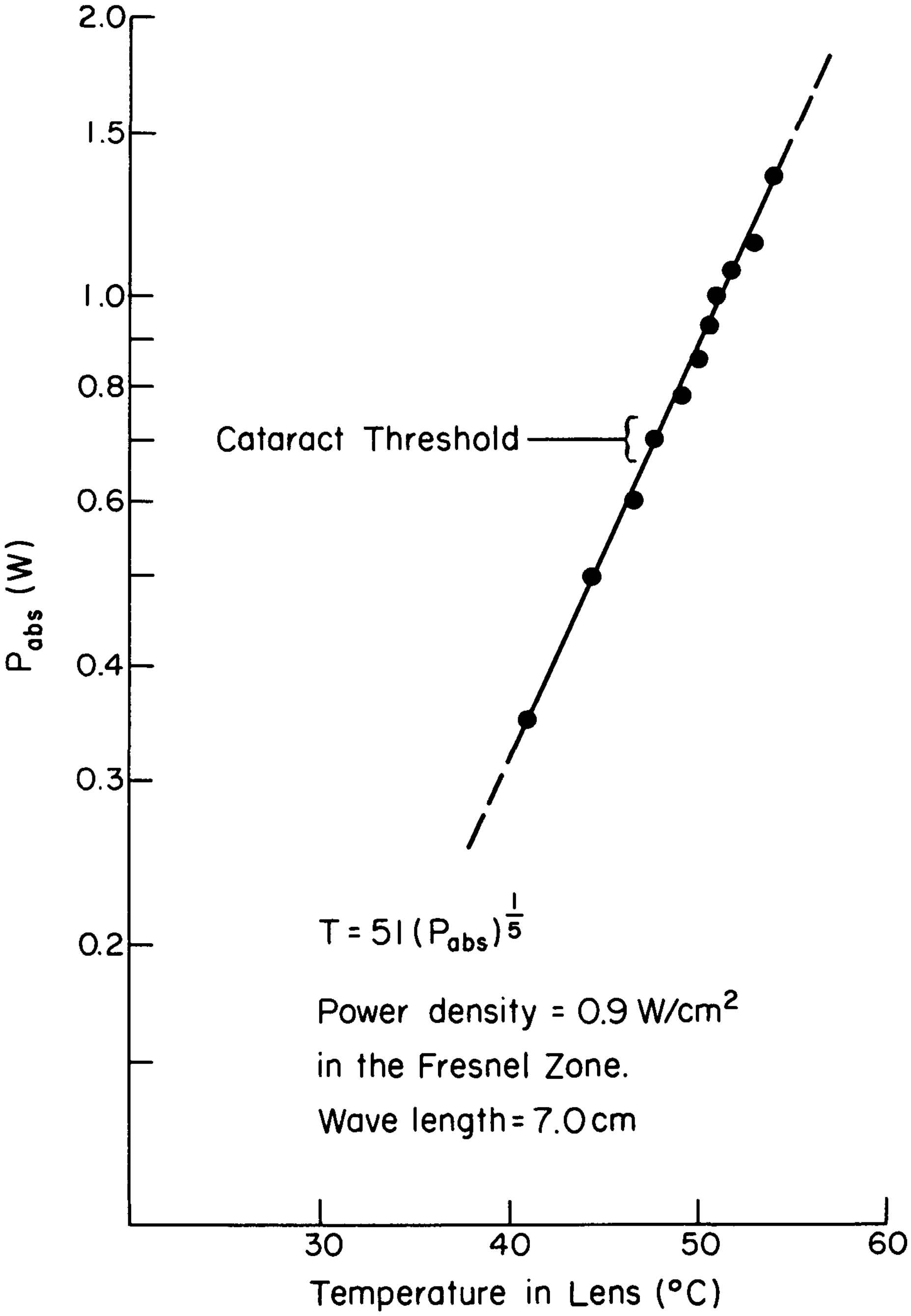

Figure 13. A log-log plot of power absorption versus temperature rise in the lens.

in the usual occupational or operational situation. This case does serve, however, to illustrate what can happen when an excessive amount of RF energy is absorbed by the human eye.

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THE DIPOLE/SLOT RADIATION PATTERN AND ITS USE IN UNDERSTANDING MICROWAVE LEAKAGE AND SURVEY TECHNIQUES

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Introduction

The purpose of this paper is to serve the health physicist as an introduction to microwave exposure measurements. To this end, the radiation pattern of the most basic antenna, the infinitesimal dipole and its dual the infinitesimal slot, is examined. We have applied this theory to monitoring instruments and techniques and where possible have made comparisons with ionizing radiation. This comparison is a natural one. The instruments used for microwave measurements look much like those used for X and gamma radiation and the same survey techniques are applicable to both types of radiation. The major differences are that microwave radiation is coherent and measurements are complicated by resonances, interferences, and elastic reflections. In this respect the behavior is similar to sound waves of equivalent wave length.

There is no rigorous definition of the microwave spectrum, but for our purposes we will consider it to include electromagnetic waves between one millimeter and one meter in length with a frequency between 300 MHz and 300 GHz. Figure 1 illustrates the microwave position in the electromagnetic spectrum. Of the several microwave bands, the one of most interest to the health physicist is the ISM band (industrial, scientific, and medical) at 2450 ± 50 MHz with an energy per photon of 10^{-5} ev. This energy is many orders of magnitude less than required for direct ionization. Therefore, when measuring microwaves we are not interested in individual photons but rather in the electric field (E) and the magnetic field (H) resulting from the superposition of many photons. For microwaves on the order of 2450 MHz, the major biological effect is the thermal heating of the tissue(1). The rate of heat development is directly proportional to E^2. In order to estimate the biological hazard, the most suitable quantity to measure is the power density which is proportional to E^2. The working units of power density are mw/cm^2.

A deterrent to straight forward measurement is the fact that the nature of the microwave field varies with distance from the radiator. The radiation from the microwave generator is characterized by a near field, an intermediate region, and a far field (Figure 2).

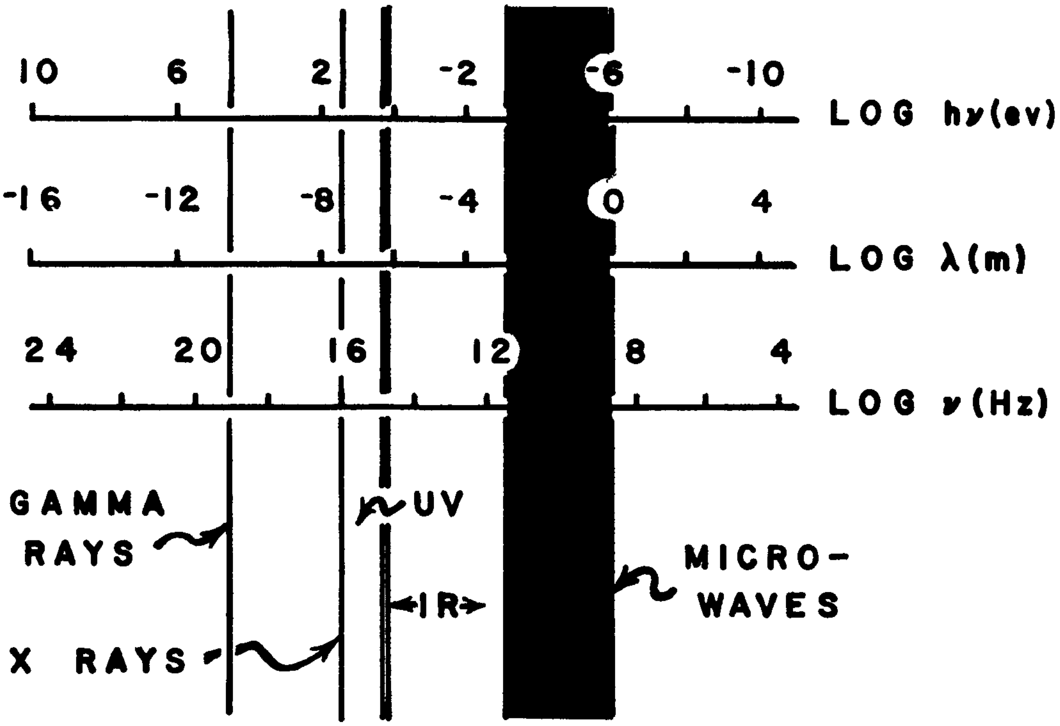

Figure 1. Electromagnetic spectrum.

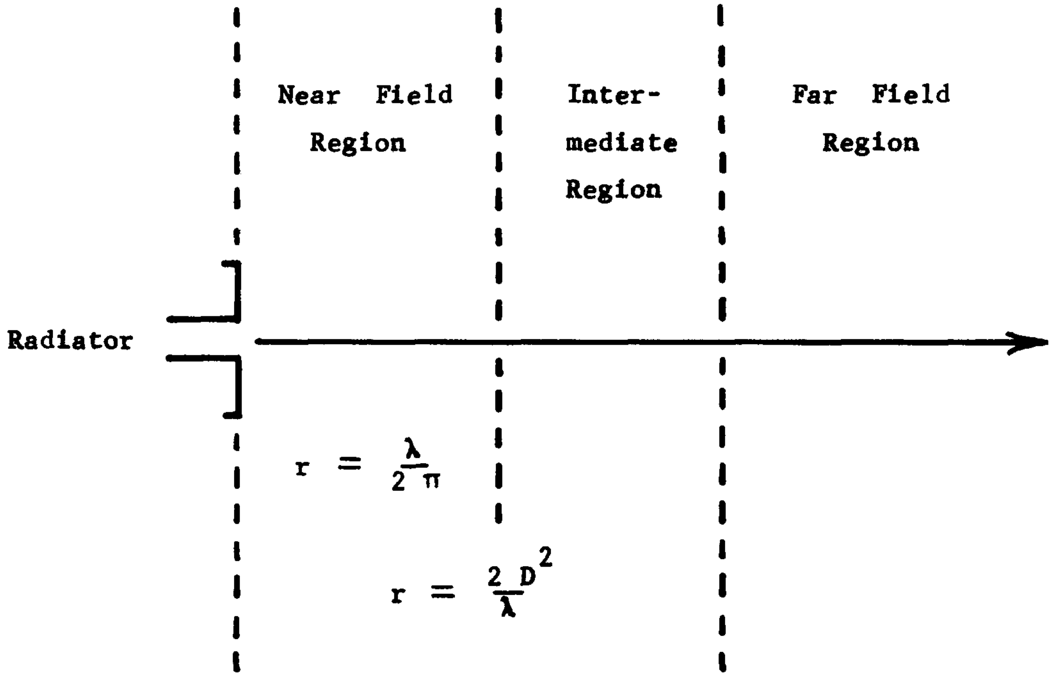

Figure 2. Field regions of an electromagnetic radiator.

In the near field, the non-radiating energy may exceed the radiating energy. This reactive energy corresponds to that stored in capacitors and inductors in low frequency circuits. The stored fields oscillate at the carrier frequency but do not radiate, although the energy can be coupled out into a person or object entering the field. Figure 3 illustrates the electric and magnetic fields very close to a dipole. These fields have different radial characteristics which give rise to a complex behavior in the near field. Near field measurements are also complicated by interactive scattering between the source and detector. These complexities, in addition to basic geometry problems at these small distances, prohibit routine near field measurements. The outer limit for the near field is considered to be a distance of $\lambda/2\pi$. This is the point at which the radiating energy is equal to the stored energy. For the 2450 MHz band this is slightly less than two centimeters.

The outermost region, the far field, receives no significant contribution from the reactive energy, and no significant phase variation exists in the wave front. Here the energy density obeys the inverse square law and the survey techniques for monitoring are similar to those for ionizing radiation. Unlike ionizing radiation, however, the waves are coherent and can be reflected without absorption. There is no energy loss mechanism comparable to the Compton interaction, so that the scattered radiation has the same frequency as the primary.

The intermediate region, the Fresnel zone which derives its name from its optical counterpart, bridges the transition between the near and far fields. At this distance the radiating antenna is of such large dimension that variations in the path length from different regions of the source cause interferences as depicted in Figure 4.(2) At the outer edge of the Fresnel zone an inverse square fall-off in power density obtains. The $1/r^2$ relationship is not maintained as one approaches the near field. Measurements can be made some distance into the Fresnel region depending upon the accuracy required. Assuming an isotropic radiator and a dipole receiving antenna (Figure 5) a criterion can be established. Figure 5 geometrically illustrates that $r = D^2/8\Delta r$ if Δr is assumed to be very small compared to D. It has been found experimentally that a phase shift of 22.5 degrees, that is $\lambda/16$, will cause a gain error of less than 0.1 dB(3). Using this value for Δr we obtain the criteria $r = 2D^2/\lambda$ (where $\lambda \ll D$) for the nearest measurement distance. If the effective aperture is much less than the wave length, as in the case of an infinitesimal dipole, there is no Fresnel region and $2D^2/\lambda$ is meaningless. Thus, when the dimension of the receiving

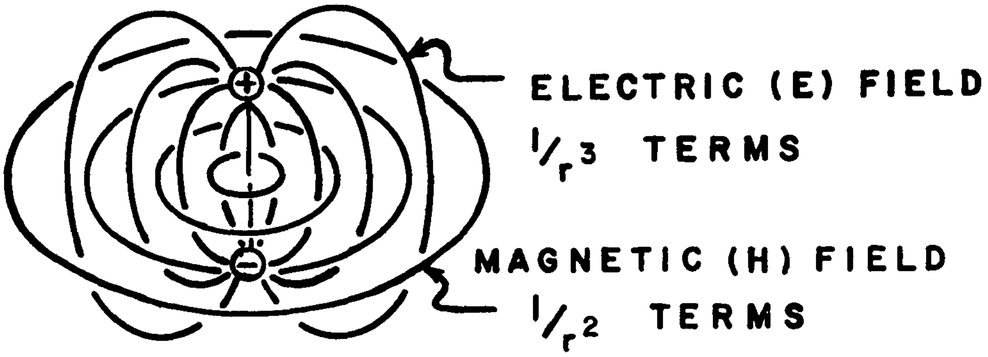

Figure 3. Electric and magnetic field lines very near to a dipole.

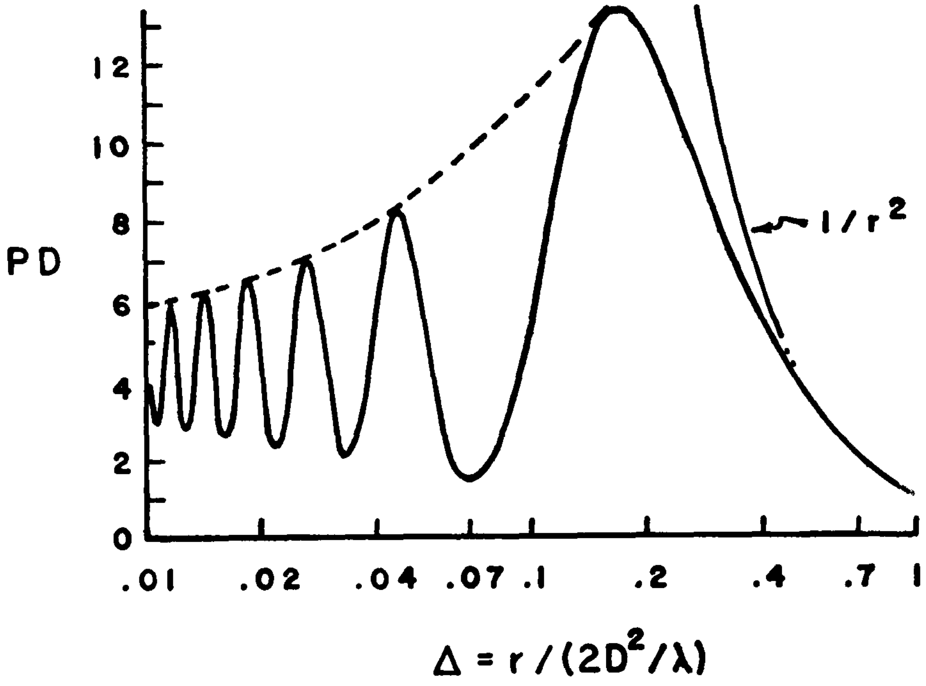

Figure 4. On axis power density for a square aperture.

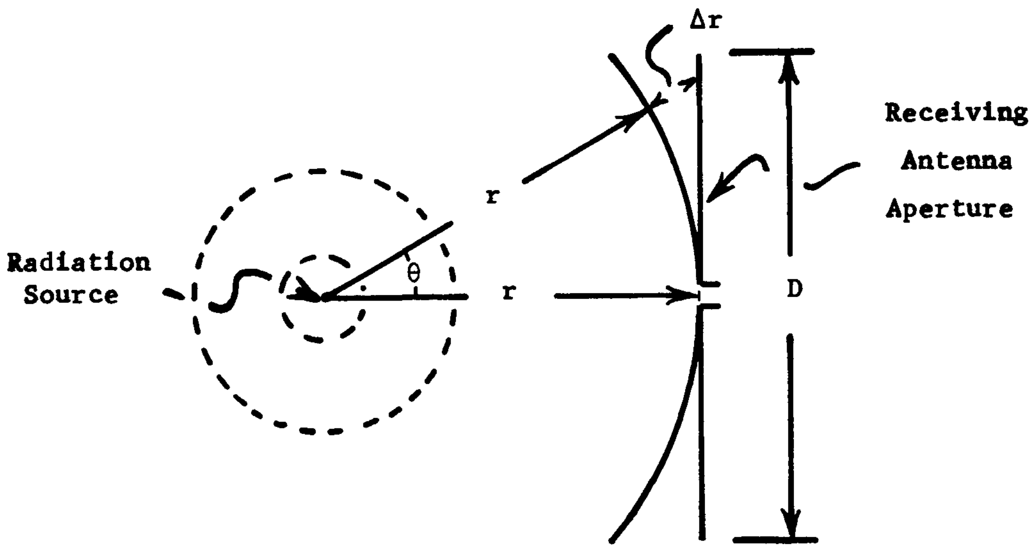

Figure 5. Phase shift error in a receiving antenna.

antenna is larger than the wavelength, the far field calibrated instrument can be used only at distances greater than $2D^2/\lambda$. Alternatively, the size of the antenna in the survey instrument limits the minimum distance of measurement. The same considerations also apply to the radiation source. In general, the larger of the two antennas, either the source or detector, will determine the minimum distance. For most systems the transmitting antenna will be the larger, however, in the case of leakage from small cracks or slots the survey instrument may be the limiting antenna.

Basic Dipole/Slot Radiation Pattern

A basic antenna (either transmitting or receiving) which demonstrates the reactive and radiation properties with coherence is the infinitesimal dipole. It is used in many systems and is fundamental to an understanding of higher gain antennas. The length of the dipole L (Figure 6) is assumed to be small in comparison to the wavelength λ. The solution in polar coordinates for the E and H fields is$^{(4)}$:

$$E_r = \frac{Z_o\beta^2}{2\pi} [I]L \left[\frac{1}{(\beta r)^2} - \frac{1}{(\beta r)^3} \right] \cos\theta$$

$$E_\theta = \frac{Z_o\beta^2}{4\pi} [I]L \left[\frac{1}{(\beta r)} + \frac{1}{(\beta r)^2} - \frac{1}{(\beta r)^3} \right] \sin\theta$$

$$H_\phi = \beta^2 \frac{[I]L}{4\pi} \left[\frac{1}{\beta r} + \frac{1}{(\beta r)^2} \right] \sin\theta$$

$$E_\phi = H_\theta = H_r = 0$$

where Z_o is the wave impedance given by $Z_o = (\mu_o/\epsilon_o)^{1/2}$ (377 ohms for free space), β is the phase constant $2\pi/\lambda$. [I] is the retarded current given by $I = I_o e^{j(\omega t - \beta r)}$, and L is the length of the dipole. It is apparent from these equations that the field components vary in accordance with $1/\beta r$, $1/(\beta r)^2$, and $1/(\beta r)^3$. Since $\beta = 2\pi/\lambda$, at a distance $r - \lambda/2\pi$ all the terms have equal effect. At this point the stored energy is equal to the radiated energy. This is the normal criterior for the outer limit of the near field. When βr is less than one, the terms $1/(\beta r)^2$ and $1/(\beta r)^3$ dominate and a rapid increase in power density, approaching the inverse sixth power, results. When βr is greater than one, the term $1/\beta r$ dominates in the far field, giving the normal inverse square response for E^2. There is no Fresnel zone.

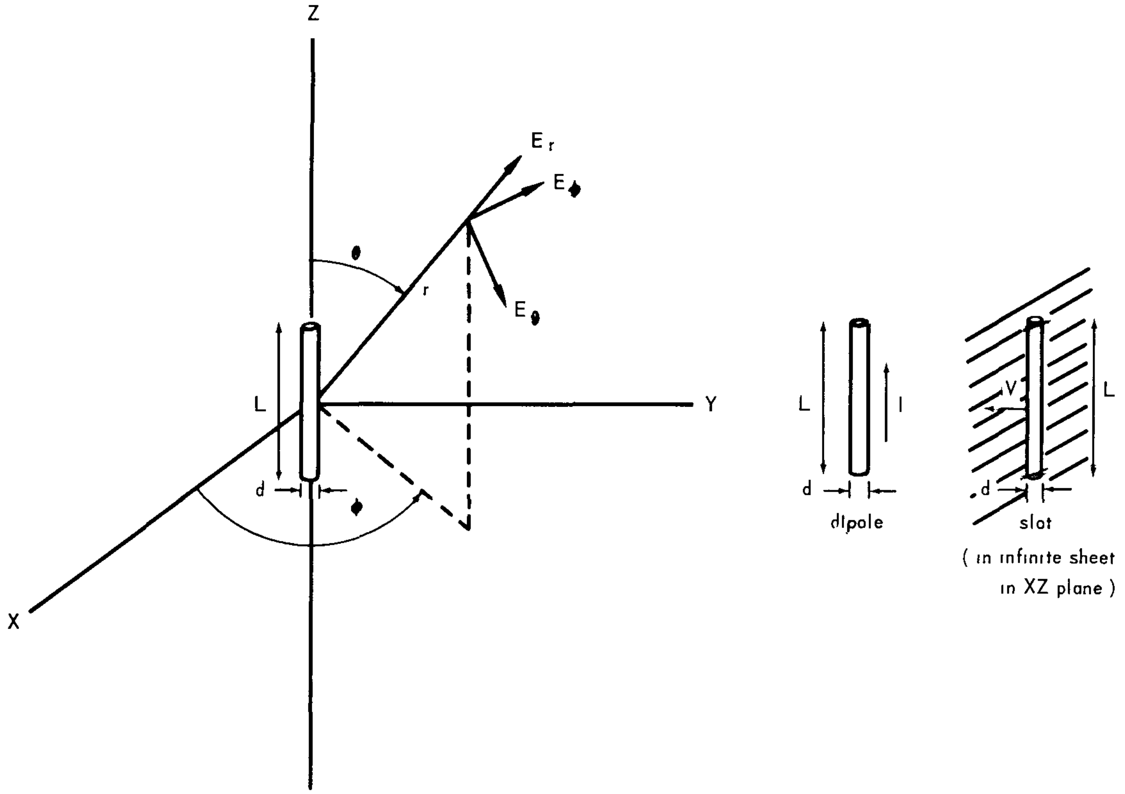

Figure 6. Relation of dipole to coordinates.

In the near field:

$$E_r \sim \left[\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] \cos\theta$$

$$E_\theta \sim \left[\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] \sin\theta$$

$$H_\phi^* \sim \left[\frac{-j}{(\beta r)} + \frac{1}{(\beta r)^2} \right] \sin\theta$$

Here E_θ and H_ϕ^* are both proportional to sin θ, and their cross product yields a component pointing outward from the dipole. Poynting's vector ($\underline{E}$ X $\underline{H}^*$) is the radiation component of the power density. However, E_r X H_ϕ^* has only a θ component and therefor is not radiated. The E_r component is at a maximum off the ends of the dipole, at $\theta = 0°$, while E_θ and H_ϕ have maximum values at $\theta = 90$ degrees.

It should be emphasized that the power density, $\underline{E}$ X $\underline{H}^*$, and the electric field energy density $\varepsilon_0 E^2$, behave differently. The power density is a vector and is in the direction of energy flow. The electric field energy density is a scalar with no directional orientation and is computed from the E field and the permitivity of the material in which the wave is traveling.

In the case of the far field the components behave as follows:

$$E_r = 0$$

$$E_\theta \propto \frac{j}{\beta r} \sin\theta$$

$$H_\phi^* \propto \frac{-j}{\beta r} \sin\theta$$

Here E_θ and H_ϕ are in phase and the radiation is plane. We then have the following relationships:

$$\left|\underline{E} \times \underline{H}^*\right| \approx \frac{Z_o\beta^4}{16\pi^2} \; [I]^2 \; L^2 \; \frac{\sin^2\theta}{(\beta r)^2}$$

and
$$\underline{E} \cdot \underline{E}^* = E^2 \approx \frac{Z^2{}_o\beta^4}{16\pi^2} \; [I]^2 \; L^2 \; \frac{\sin^2}{(\beta r)^2} \; \theta$$

Thus
$$E^2 = Z_o \left|\underline{E} \times \underline{H}^*\right|$$

or
$$\epsilon_o E^2 = \left|\underline{E} \times \underline{H}^*\right| / c$$

The time average E^2 is $\frac{1}{2}$ Re($\underline{E}$ $\underline{E}^*$) and equals

$$1/2 \left[\frac{Z_o\beta^2 I_o L}{4\pi}\right]^2 \; \frac{\sin^2}{(\beta r)^2} \; \theta$$

Since in the far field the power and energy density are angular functions of only sin θ, while in the near field they are functions of both sin θ and cos θ, the field patterns of the two regions differ significantly. Figure 7 illustrates the high degree of the angular dependence of E^2. Note that the figure-eight pattern of the far field is rotated 90 degrees when in the near field. Because of its non-isotropic response, two orthogonal measurements must be summed to obtain the total power density when using the dipole as a detector.

According to Babinet's principle(5), the $\underline{E}$ and $\underline{H}$ fields for an infinitesimal slot in a large conducting plane are described by similar equations with the electric and magnetic fields interchanged, i.e.:

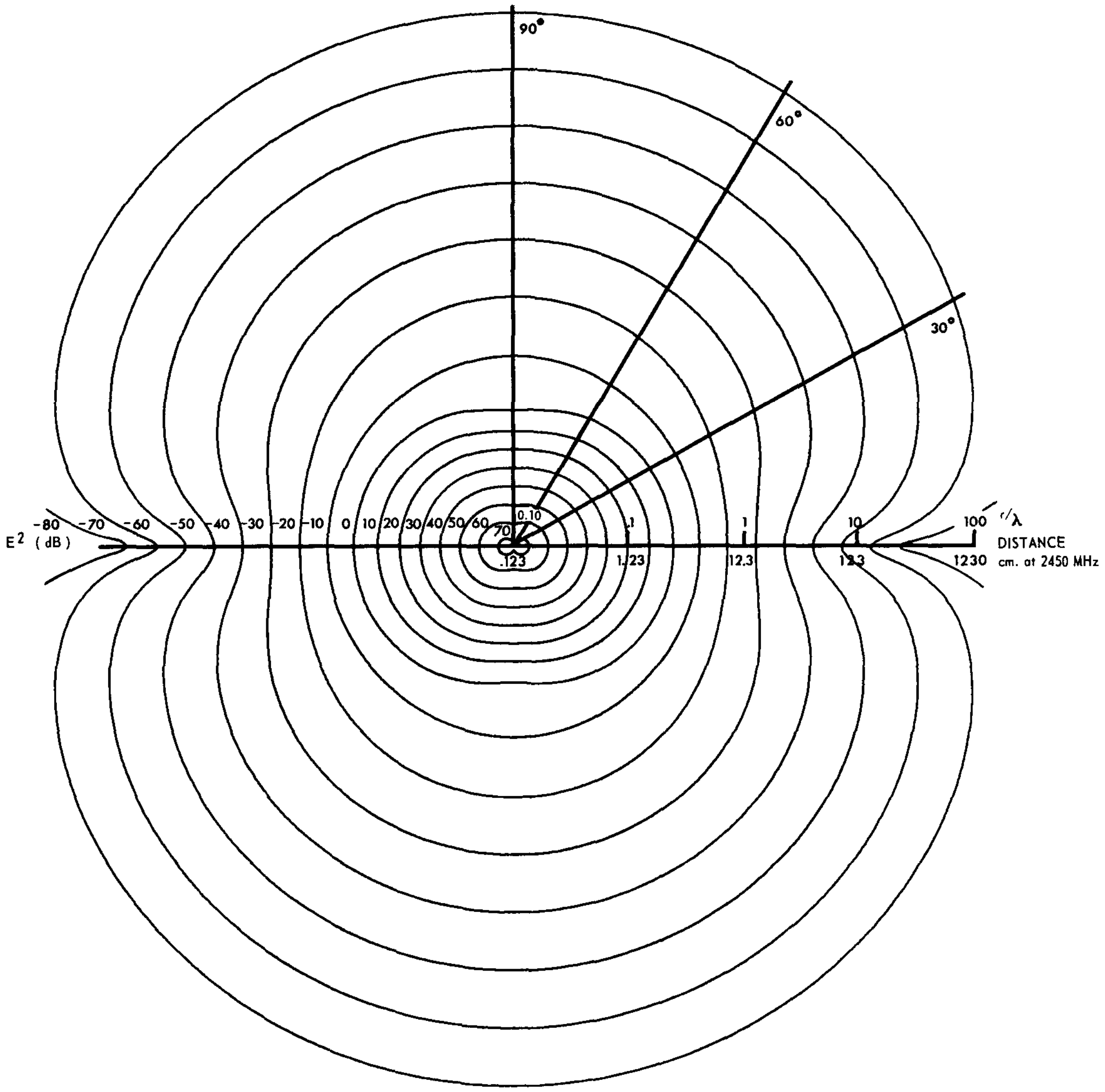

Figure 7. Relative E^2 level in dB for all angles (dipole).

$$H_r = \frac{\beta^2[V]L}{Z_o\pi} \left[\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] \cos\theta$$

$$H_\phi = \frac{\beta^2[V]L}{Z_o 2\pi} \left[\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] \sin\theta$$

$$E_\phi = \frac{-\beta^2[V]L}{2\pi} \left[\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2} \right] \sin\theta$$

$$E_\theta = H_\phi = E_r = 0$$

where Z_o is the wave impedance given by $\left[\frac{\mu_o}{\epsilon_o}\right]^{1/2}$, β is the phase constant $2\pi/\lambda$, $[V] = V_o e^{j(\omega t-\beta r)}$, and L is the length of the slot. The time average energy density for the far field is:

$$\epsilon E^2 = \frac{1}{2}\epsilon\,\mathrm{Re}(\underline{E} \cdot \underline{E}^*)$$

$$= \frac{1}{2}\epsilon \left[\frac{\beta^2 V_o L}{2\pi} \right]^2 \frac{\sin^2\theta}{(\beta r)^2}$$

The slot has little significance as a receiving antenna, but it is interesting to consider it as a model for describing leaks from small cracks or door seals. If the crack is not short, a linear summation of infinitesimal slots may be used. Figure 8 is a plot of the power density E^2 vs distance at $\theta = 0$, 60, and 90 degrees for both the dipole and slot. Both axes are logarithimic. In the near field the dipole approaches a $1/r^6$ rate of fall-off and the slot, missing the cube term, approaches a $1/r^4$ dependence. In the far field both the slot and dipole have the same angular dependence and both obey the inverse square relationship. A point of interest is the inner limit of the inverse square region, as measurements made anywhere in this region can be extrapolated to other distances. The rate of change is more visable in the plot of the derivative of the expression for E^2 in Figure 9. Here the $1/r^2$ region is defined by the right hand horizontal portion of the curve. To about a 10% accuracy, the $1/r^2$ behavior holds into a distance of $\lambda/2$ (6.1 cm at 2450 MHz). Incidentally, the near field criteria of $\lambda/2\pi$ at about 2 cm is clearly located at the inflection point between the near and far field behavior.

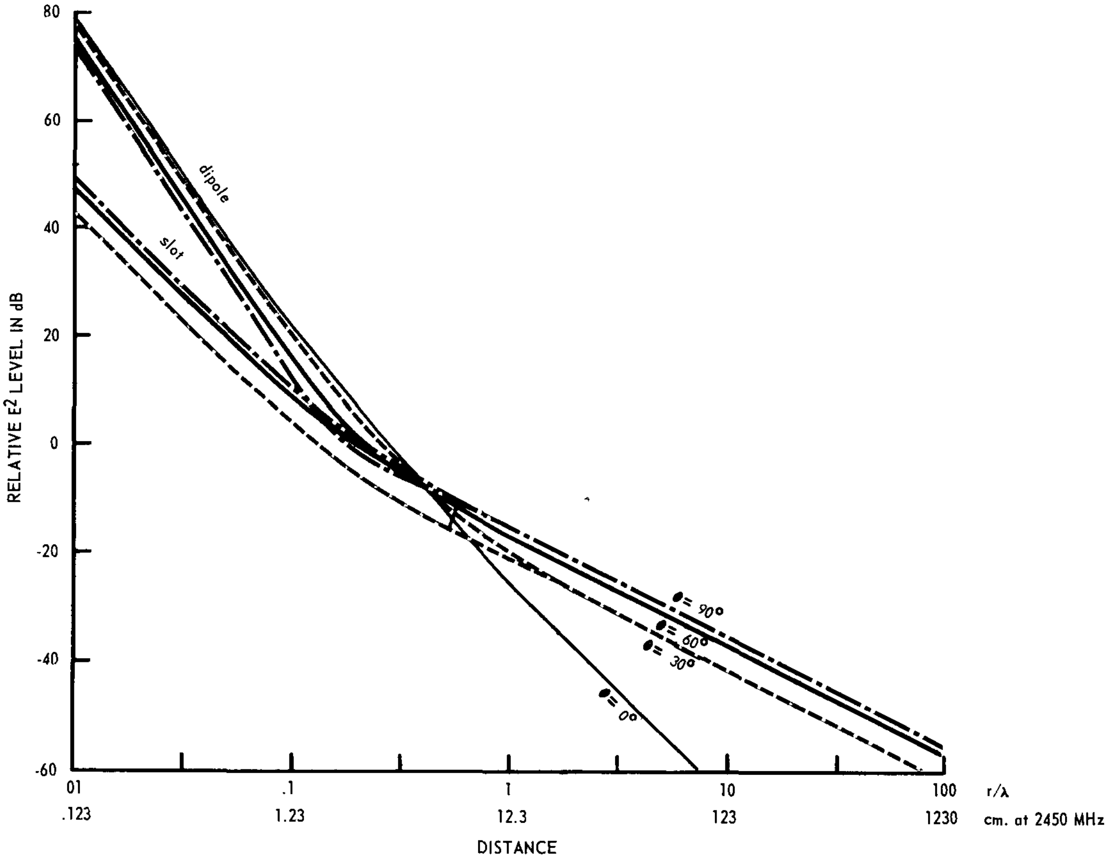

Figure 8. E^2 (which is proportional to the electric field energy density) as a function of angle and distance. Straight line slope indicated $1/r^2$ fall-off at $r/\gamma > 1$. With the dipole and slot interchanged the relative level becomes the magnetic field, H^2.

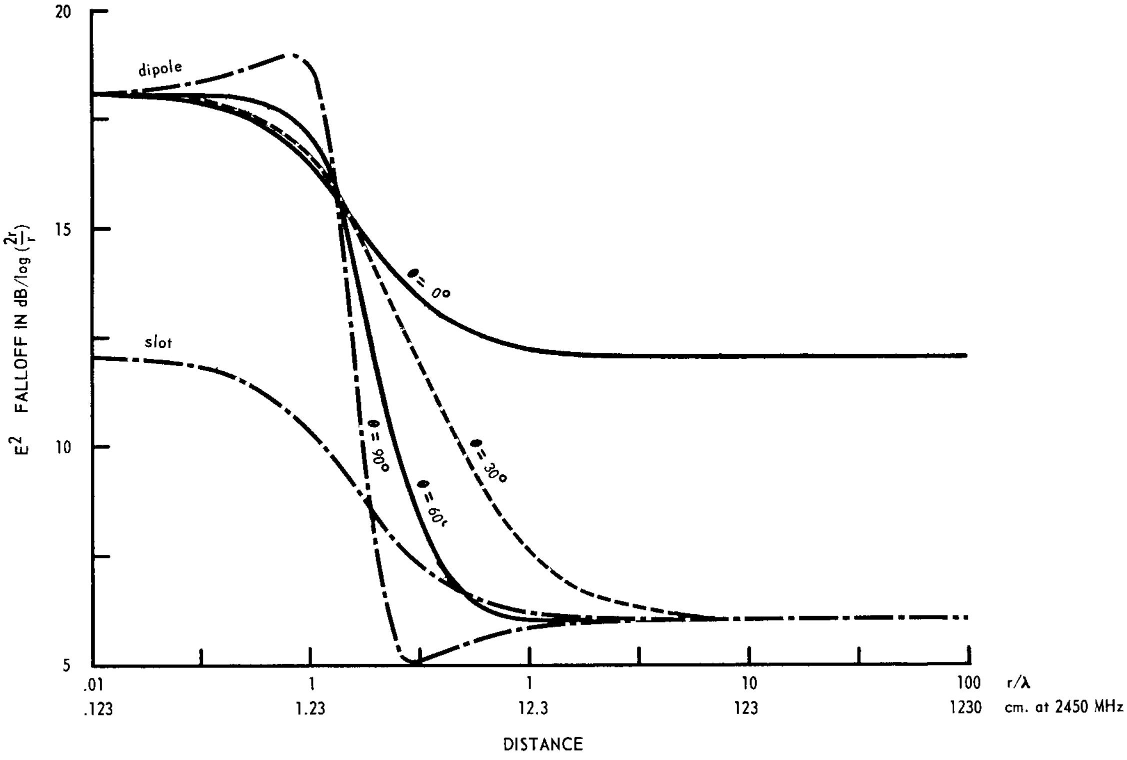

Figure 9. Rate of change of E^2 (from figure 2). Horizontal portion of $r/\gamma > 1$ indicates inverse square relation.

Survey Techniques

Survey meters used to monitor the power density basically consist of an antenna which couples the radiation into a thermistor or thermocouple transducer where a measurement is made of the temperature rise. Such antenna are linearly polarized, i.e., angularly dependent, and two orthogonal measurements must be summed in order to obtain the total power. Dual measurements can be avoided by using two antenna, such as crossed dipoles and having the transducer add the two contributions. As observed in the slot/dipole case the radial component of the far field is zero and if the plane of the crossed dipoles is orthogonal to the radiation field, a third dipole is not required. If the direction of propagation is not known, the probe is merely orientated for maximum response. Another consideration is the frequency response of the antenna. Figure 10 shows the response of a dipole as a function of length(6). For a short dipole the output to a constant load is proportional to the fourth power of the length. A dipole will respond correctly only to the calibrated frequency and ambiguous readings will result if multiple frequencies are present.

An example of a crossed dipole survey meter is the Narda Model 8100 with thermocouple elements at the intersections of the two dipoles(7). This meter is calibrated for 2450 MHz (and 915MHz with a second antenna) using a dipole of approximately $\lambda/10$ and a two-inch spacer to keep the probe out of the near field of small cracks. This meter is designed for microwave oven measurements but it presumably could be calibrated for any frequency above 915 MHz. The normal time constant of the thermocouple is about a tenth of a second which is increased to about one second in the instrument. A time constant of about six seconds is available to reduce fluctuations due to the revolving stirrer in microwave ovens. Experience has shown that the power density fluctuations due to the stirrer action are quite large (as much as 10X), thereby, making average readings difficult on the fast time constant. The six second time constant reduces the error but an even longer time constant would be useful. The meter reads power density directly and with multiple probes provides a range from 0.01 to 200 mw/cm^2. The thermocouple is sensitive to overload burnout and care must be taken not to exceed the rating.

A different type of meter which is independent of polarization and frequency from 400 MHz to 40 GHz is the thin film spherical bolometer(8). This instrument uses two spheres 3 cm

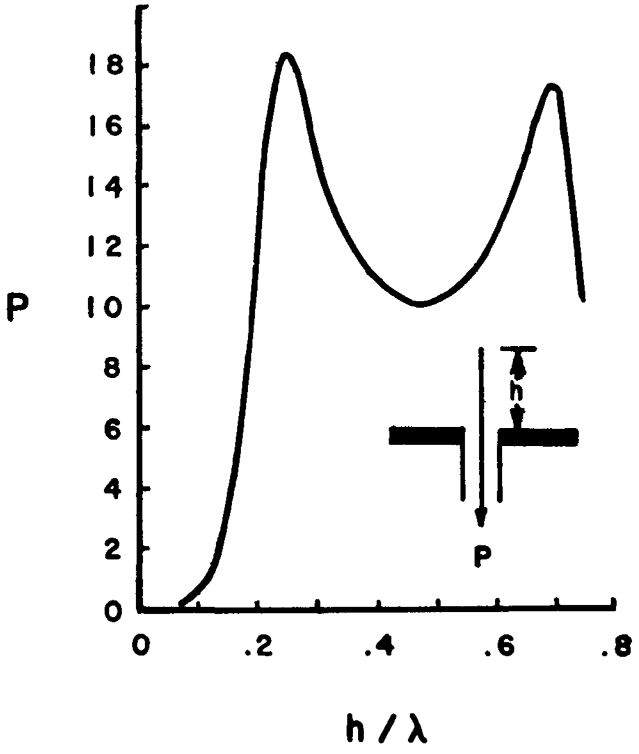

Figure 10. Response of a monopole as a function of length.

in diameter connected by a capillary. One sphere is coated with a thin resistive film which will be heated by conduction current and the other is left uncoated to compensate for changes in the ambient temperature. Impinging radiation changes the pressure in the coated bulb which is read out in power density via a pressure transducer. An interesting feature of this detector is that the impedance of the coating on the bulb can be adjusted to match any desired electrical characteristic.

An aspect of microwave measurements analogous to the tissue equivalent concept in ionizing dosimetry is the problem of measuring not just the power density in free space but rather something related to the human dose resulting from exposure in the field. This is complicated because the presence of the human body significantly distorts the microwave field. Also, one must have a detector electrically similar to the tissue of interest, e.g. the lens of the eye(9). The above mentioned spherical bolometer with its adjustable impedance might provide the basis for development of such a detector. At present such a measuring device does not exist although the need for one clearly does. The health physicist with his experience in tissue dosimetry may be in a unique position to contribute to the solution of this problem.

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MICROWAVE OVEN REPAIR: HAZARD EVALUATION

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SUMMARY

Microwave oven repair should be recognized as hazardous work. Persons attempting to repair microwave ovens are subject to acute damage from sudden, high levels of exposure. Power density measurements around microwave ovens, with outer cabinet panels removed, indicated potential exposures in excess of currently accepted radiation protection guides for radio frequency.

Repairs are attempted by microwave oven owners, radar technicians, electronics servicers, electrical appliance repairmen, restaurant equipment suppliers' service personnel, and food vending firms. There are only a few manufacturers represented by authorized repair firms and their service is often delayed and costly.

Corrective measures should include the provision of adequate training regarding microwave hazards, utilization of microwave detection equipment, protective clothing, and eye protection. The development and use of personnel monitoring for RF and the provision of periodic physical examinations including intensive eye studies for all microwave oven repairmen would provide indications of exposure levels. Shielding and warning labels for microwave tubes would provide further hazard reduction.

INTRODUCTION

Microwaves are a form of electromagnetic energy, possess magnetic and electrical properties, and are propagated in space at the velocity of light. Microwaves differ from other portions of the electromagnetic spectrum in frequency and wavelength and consequently in the effect upon matter. Modern radar for tracking and guiding vessels on land, sea and in the air depend upon the reflection of microwaves by metallic objects. Biological materials absorb, refract and transmit the energy depending upon the nature of the material.

The determination of the portion of the incident energy that is absorbed (transformed) by a human being is complicated by the inhomogeneity of the target, difference in susceptibility of organs and tissues, body mass in relation to the exposed area, and frequency of the microwaves.[1]

Several frequencies have been assigned by the Federal Communications Commission for industrial, scientific and medical uses. Microwave ovens, operating at frequencies of 915 and 2450 megahertz, produce heat very rapidly in foods. This transformation of microwave energy to thermal energy, considerably below the skin in tissues which have little sensation for temperature, has also been recognized as a hazard for biological tissue exposed to microwave radiation. Heat generation and microwave absorption is greatest in those tissues having a high content of water and this is also enhanced locally in the areas adjacent to bone or tough fascial planes which act as reflecting surfaces. The depth of penetration decreases with an increase in frequency or decrease in wavelength on the order of 1/10 of the wave length. At frequencies between 150 and 1000 MHz, approximately 40% of the incident energy is absorbed by the deeper tissues due to the penetration. There is minimal heating of the skin where thermal receptors would provide a warning. The depth of penetration varies with the water content of body tissues for frequencies between 1000 and 3000 MHz. The lens of the eye is known to be especially susceptible to frequencies around 3000 MHz where production of cataracts is an important consideration.[1]

The currently accepted limits for exposure to microwave radiation do not distinguish between the various frequencies due to the limited knowledge of the biological effects. The standard proposed by the C-95 Committee of the United States of America Standards Institute (USASI) is based on energy density of 1 milliwatt-hr/cm^2 for exposure times up to 0.1 hour and on power density of 10 mW/cm^2 for time periods of 0.1 hour or more. U. S. Army and Air Force criteria, applicable between exposure levels of 10 and 100 mW/cm^2, is based upon time as follows: $TP = (6000/W^2)$, where TP is permissible exposure time in minutes during any one hour period and W is power density that personnel are exposed to in mW/cm^2. The Bell Laboratories consider levels above 10 mW/cm^2 potentially hazardous, between 1 and 10 mW/cm^2, safe for incidental or occasional exposures and less than 1 mW/cm^2, safe for indefinitely prolonged exposures.

Recently, Mumford[2] of the Bell Laboratories, and a member of USASI C-95, proposed a modification of the

10mW/cm^2 limit based on enviromental conditions. For conditions of moderate to severe heat stress, he proposed that the guide number be appropriately reduced. Under the conditions of this proposal, the exposure limit would be 10 mW/cm^2 when the temperature-humidity index (THI) is 70 or less; when the THI is between 70 and 79, the limit is (80-THI) mW/cm^2 and when the THI is greater than 79, the limit is 1 mW/cm^2.

Yet, a number of effects have been observed in the absence of demonstrable increase in body or media temperature, or under conditions which prevented increase of temperature during exposure. And in some cases temperature increases of the same magnitude as those produced by irradiation were induced by other means and the microwave effect was not produced by such heating. The possibility of cumulative effects from subthreshold exposures, functional changes from low intensity irradiation as reported by the Russian investigators and possible nonthermal changes need further clarification. Large gaps also exist in the current knowledge of possible genetic implications and the actual long-term effects, if any, of microwave radiation on humans.[1]

MICROWAVE OVENS

Microwave ovens are becoming increasingly popular. Several factors, including the technology of producing an efficient power source for a compact, economical 110-volt microwave oven of exceptional reliability, durability and acceptability with consequent success in the vending of foods, have brought the industry from the nominal to the phenomenal stage in marketing their product.[3] The microwave oven has pervaded the commercial food-service industry and is becoming an increasingly prevalent consumer product appearing in the American home. Home-type microwave ovens represent a multi-million dollar market and the potential is increasing rapidly. Current estimates of the total sales of microwave ovens for both commercial and consumer use approximate 40,000 units per year.[4] Others predict microwave oven purchases as 25% of all ovens purchased in the United States by 1976, or approximately 1.8 million microwave ovens.[1]

The attention of health officials has been directed to microwave ovens by reports in the literature and congressional hearings related to electronic products. The problem of leaking of microwave radiation around oven doors was revealed by various reports.[5-11]

Local health department officials in Florida and responsible microwave oven users have expressed concern for safety in operating ovens currently in use. The manager of a self-service food vending operation in the employees' lounge of an industrial firm expressed concern and requested advice regarding the illumination of hand-held fluorescent tubes used in checking the microwave ovens that are provided for his customers' use. He had been told that the illumination was an indicator of microwave leakage which was harmful for persons near the ovens. A housewife and a hospital dietitian had requested advice regarding the safety of microwave ovens after reading articles appearing in newspapers and food periodicals. These requests for assistance emphasized the need and accelerated our plans for providing a program of evaluation of microwave ovens in use.[12]

PURPOSE

Although there was indication in the literature of oven maintenance by owners,[7] only two reports [13,14] were found of injuries to repairmen. Information gathered during our study of microwave ovens in use indicated that repairing microwave ovens presented a greater hazard potential, especially to the unwary.

We found that owners attempt to repair their own microwave ovens, domestic and commercial. Restaurateurs have stated that repairs by factory authorized service firms are often delayed and costly. Officials of food vending firms contacted in Florida stated that they install, service and repair microwave ovens utilized at their food vending outlets. None indicated receiving any formal training related to microwave hazards. Some have emphasized that microwave detection equipment was scarce and too expensive to be justified. The expense of the available detection equipment was related by Mr. David Hartley, National Automatic Merchandising Association to attendees at a recent meeting of Florida-based officials of several food vending firms. This was a one day seminar on the Health and Sanitation Aspects of Vending Machine Operation conducted by the Florida Division of Health's Sanitation Section in cooperation with the National and Florida Automatic Merchandising Associations. Mr. Hartley indicated that NAMA had distributed an informational bulletin which deals with the hazards of microwave exposures.

We learned from microwave oven owners, dealers, and distributors that radar technicians, electronics servicers, electrical appliance repairmen, and restaurant equipment suppliers' service personnel attempt to repair domestic and commercial model microwave ovens. Only a select few of the microwave oven manufacturers have established factory authorized repair service conveniently located for owners in Florida.

Formal training regarding the hazards of microwave exposure is rare for microwave oven repairmen and microwave detection equipment has been nonexistent in their shops. Fluorescent tubes and neon lamps have been used to indicate microwave leakage, ammeters are available to indicate flow of current in a magnetron and a screw driver was used to locate an arc from microwave leakage, but no quantitative measure of microwave energy released from the oven to the surrounding environment had been made.

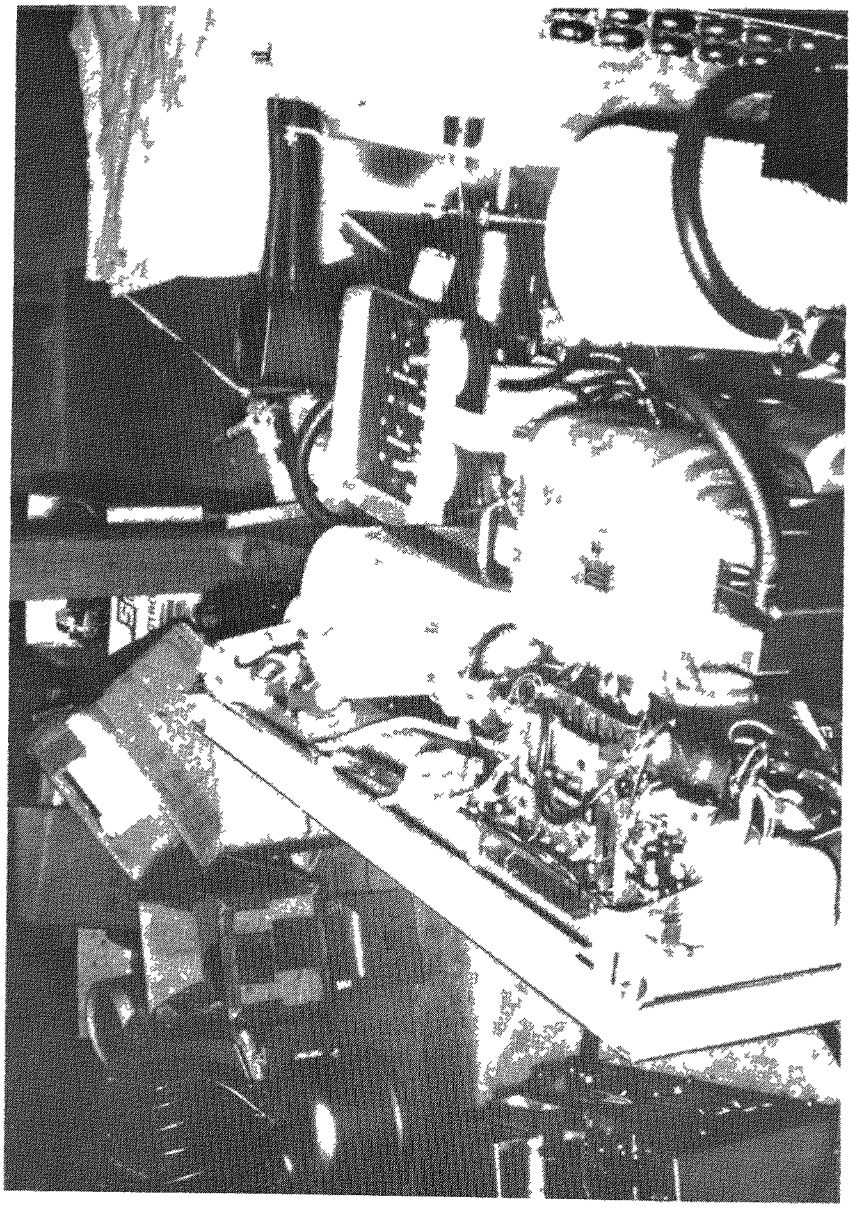
We felt that further evaluation of working conditions was warranted. It was our desire to utilize available instrumentation used to detect microwave energy to determine levels of leakage at the repairman's position during oven repair.

PROCEDURE

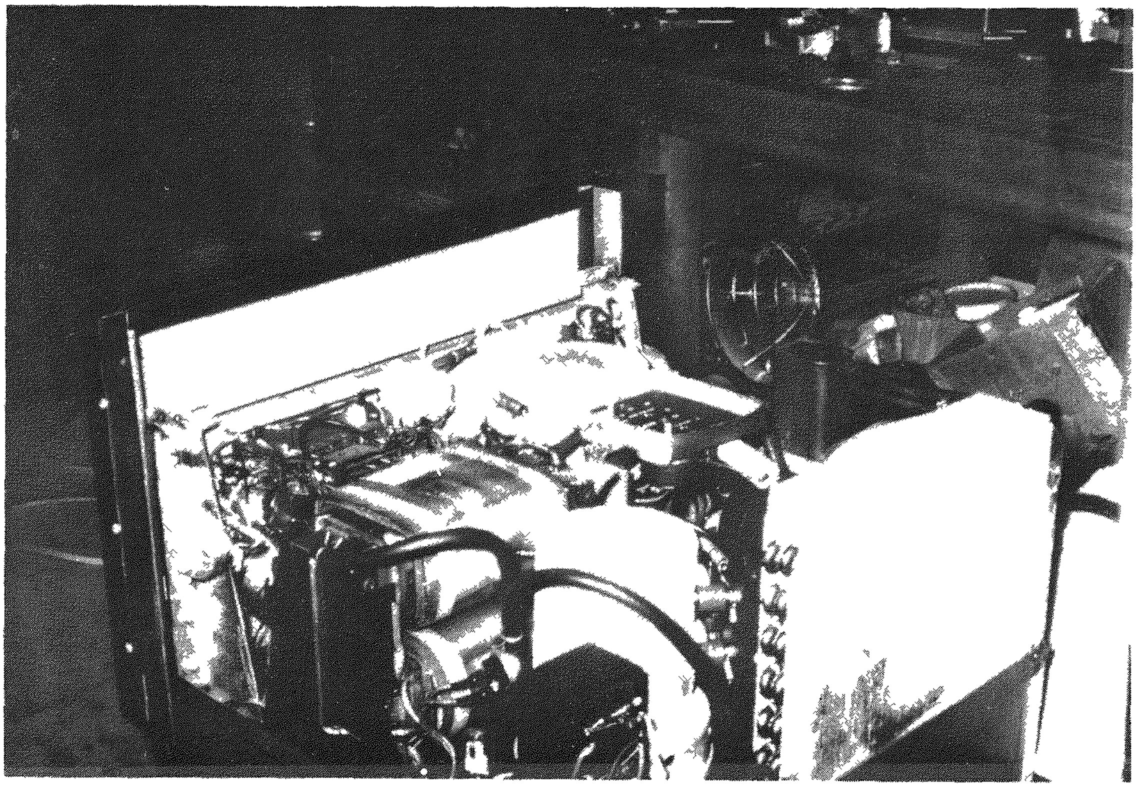
Scheduling of such studies was difficult and tests were made as opportunities were afforded by interested and cooperative repair shop owners. No attempt was made to determine the frequency and nature of work performed per model of oven, nor time spent per day energizing magnetrons, nor measuring distances between magnetrons and body areas of repairmen. It was noted that microwave ovens are not always repaired on waist-high work benches. Photographs 1 and 3 show ovens awaiting repair on the floor and on a low platform.

FINDINGS

The oven portrayed in photographs 1 and 2 was operated with a chinaware bowl of tap water in the cavity. The detection limit of 20 mW/cm^2 was exceeded on the power density meter, Ramcor Model 1200B, with 2450 MHz antenna horn, at approximately 2 feet from the nearest magnetron (located in the perforated metal enclosure at the lower right corner of photograph No. 1). The repair shop owner



Photograph 1. Radarange Mark V Microwave Oven by Raytheon Company.



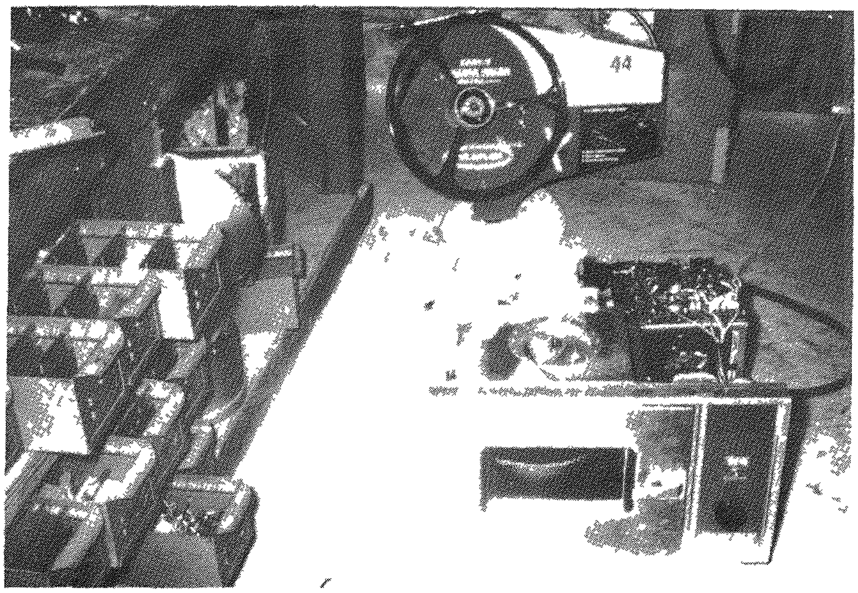
Photograph 2. Radarange Mark V Microwave Oven by Raytheon Company.

sought to verify the existence of microwave energy outside the magnetron enclosure by creating an arc between a screw driver and the copper tubing in the water coolant line between the magnetron and the heat exchange radiator. He produced further evidence of microwave energy by adjusting the bolts retaining the magnetron enclosure to the oven frame or chassis. Tightening the bolts reduced the power density levels detected while loosening the bolts increased the levels to the previous measurements. He stated that the oven was received for repair in this condition.

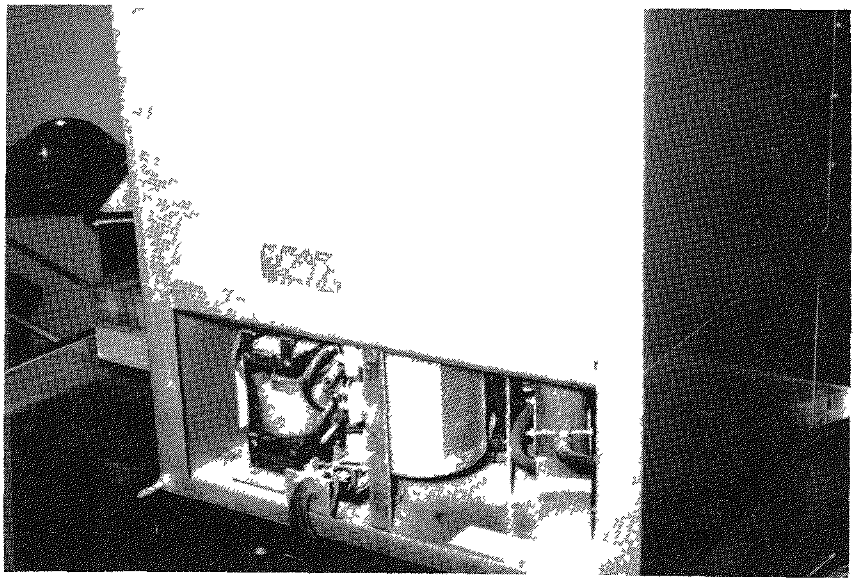
No ionizing radiation was detected with a radio frequency shielded ion chamber survey meter, Victoreen Model 440 RF, around the microwave oven during operation.

An earlier version of the oven pictured in photograph No. 3 was checked for operability in another repair shop. The "load" consisted of 6 ounces of tap water in a styrofoam cup. The repairman had removed the rear access panel from the cabinet, tripped the cabinet panel interlock switch, set the timer, and pressed the operating button in order to check the magnetron for operability. Although the red light indicated that the oven was "cooking", there was no evidence that the magnetron was operable until a popping noise was heard from inside the oven and the power density meter, Narda Model 8100, with a probe calibrated for 2450 MHz, indicated full-scale deflection on its maximum scale of 200 mW/cm^2 at a position between the rear of the oven and the repairman standing about 2 feet behind. The magnetron was apparently sporadic in operation, since the power density meter responded only twice during this checkout procedure. The repairman stated that he had noticed reflections of the magnetron "flash" within the oven during that time. The repairman removed the magnetron assembly and noted that the metal gasket material was bent out of place at the bottom of the joint between the magnetron assembly and the waveguide leading to the oven cavity.

The electrical components are evident through the open area at the rear of the oven in photographs 4 and 5. Some ovens of this model have been observed with hardware cloth over this opening to prevent insertion of hands into the high voltage area. The detection limit of 20 mW/cm^2 was exceeded on the power density meter, Ramcor Model 1200B with 2450 MHz antenna horn, at the open area during operation at a restaurant. This was observed during testing of ovens in public food service establishments as previously reported.[12] The area behind the oven is designated as the "smoke break" for employees. The owner stated that the



Photograph 3. Model 550 Microwave Oven by Litton Industries, Atherton Division.



Photograph 4. Radarange Mark IV Microwave Oven by Raytheon Company.

Photograph 5. Radarange Mark IV Microwave Oven by Raytheon Company.

oven had been repaired within the previous 6 months. A power density level of 5 mW/cm^2 has been measured at openings at front top corners of this model oven when the door was closed during tests for leakage. It is believed that leakage at such positions on this model are due to faulty repairs.

Another example of inferior construction and possible error in repair was found in an oven similar to that one portrayed in photograph No. 3. The power density meter, Ramcor Model 1200B, indicated levels exceeding 20 mW/cm^2 at 2 feet in front of an oven in use at a food vending facility. It was obvious that someone had inverted the pressure plate which serves as an integral part of the door seal and the grid or screen for the view window, leaving an inch gap in the door seal across the bottom of the door.

PROPOSALS

One purpose for this report is to alert public health officials to the need for evaluating neglected aspects of microwave oven surveys. Testing of microwave ovens in use must necessarily include surveys of all accessible external areas for microwave leakage to properly control exposure to users and other personnel near cabinet openings.

It should also seem evident that repair operations need evaluating for hazardous conditions and practices.

Warnings are in order for prospective repairers. An understanding of microwave hazards and means to prevent needless exposure are essential for workers involved in microwave oven repair.

Consideration should be given to providing the necessary training in safety precautions, utilization of microwave detection equipment, protective clothing, and eye shields for person employed in microwave oven service and repair. Licensure of repairmen and certification of repair shops should elevate standards of protection and require higher quality of repair for the consumer.

The development and use of personnel and area monitoring for radio frequency radiation and the provision of periodic physical examinations with emphasis upon thorough eye evaluations for all microwave oven repairmen should provide information related to microwave exposure.

Further hazard reduction could be provided by shielding and warning labels for magnetron tubes. The device consisting of a wooden frame covered with copper mesh screening to cover the oven as described in the report by Rose, et al[14] may be used effectively on some models to reduce exposures, but would encumber the repairman's functions. Similar material or an absorbing dummy load fitted over the magnetron should afford sufficient reduction of microwave energy, provided the device could be securely fastened to the cabinet frame and sealed to prevent leakage as detected from other models. Enclosing only the magnetron with a shielding screen or dummy load would allow freedom to work on other parts of the oven during operation of the magnetron.

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Products and manufacturers are named for identification only, and listing does not imply endorsement by the author nor the Division of Health, Florida State Department of Health and Rehabilitative Services.

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RF Response of Radiation Survey Instruments

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I Introduction A recurring problem in the measurement of ionizing radiation around RF producing equipment is the simultaneous response of the detector to RF radiation.

The problem was first encountered in the nineteen fifties in the measurement of ionizing radiation around high power radar equipment. Klystrons especially were sources of both types of radiation and led to the development of RF shielded ionizing radiation detectors.

In the late nineteen sixties a similar problem has arisen with the detection of ionizing radiation around color TV sets which are also a source of a broad spectrum of electromagnetic energy. A typical set operates with the following frequencies: power frequency: 60 Hz; frequency on the high voltage transformer: 15,750 Hz; IF circuits: 41.25 MHz, 45.75 MHz and the carrier TV frequencies from 54 - 662 MHz for channels 2 - 45. Harmonics and sum and difference frequencies are also possible. That a color TV set can be a potentially troublesome source of RF radiation is attested to by the fact that F.C.C. certification is required on home-built sets.

Other sources of ionizing as well as RF radiation are present in the TV monitors at transmitting stations and TV projection equipment. Because of this wide range of equipment that is encountered in our inspection program, a study was made of the RF response of a selected group of radiation survey instruments.

II Experimental Equipment* A variable source of RF radiation was used to irradiate the survey meters at the following frequencies: 0.085, 0.1, 0.5, 1, 5, 10, 20, 60, 80, 100, 200, 300, 400, 600 and 1,000 MHz. In the frequency range 0.085 - 600 MHz dipole antennas of various lengths were used and at 1000 MHz a log pyramidal horn with parabolic reflector was used. The probe or chamber of the survey instruments was placed at 2.5 and 100 cm. from the dipole antenna and in the case of the horn at 2.5 cm. from the RF source and at 100 cm. from the reflector.

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*Representative products and manufacturers are named for identification only, and listing does not imply endorsement.

The electric field at one meter was standardized at 10 volts per meter for all frequencies. Despite known measurement problems, the Ramcor Densiometer Model 1200 was used and gave the following results: 200 MHz and 2.5 cm: 2.5 mW/cm^2 and 100 cm: $<$ 1 mW/cm^2; 300 MHz and 2.5 cm: 2.5 mW/cm^2 and 100 cm: $<$ 1 mW/cm^2; 400 MHz and 2.5 cm: 2.8 mW/cm^2 and 100 cm: $<$ 1 mW/cm^2; 600 MHz and 2.5 cm: 1.5 mW/cm^2 and 100 cm: $<$ 1 mW/cm^2; 1000 MHz and 2.5 cm: 5 mW/cm^2 and 100 cm: $<$ 1 mW/cm^2. All exposures to RF radiation were made in a copper shielded room.

The three basic types of detectors that were checked for their RF response were the GM, ionization and scintillation type. The Nuclear Chicago Model 2650 was used as the GM type survey meter with a probe containing a thin end-window GM tube. Two different ionization type survey instruments were checked. One was the "Juno" type manufactured by Technical Associates, the other was the Victoreen Co. Models 440 and 444 employing vibrating reed electrometers. The Ludlum Instrument Co. scintillation type survey meter Model 12 with probe Model 44-2 was also checked.

III <u>Results</u> Table 1 summarizes the results for all the instruments checked.

The GM type survey instrument at 2.5 cm. indicated background (BG) at the following frequencies: 0.085, 0.1, 0.5, 1 and 5 MHz with open and closed window. At 10 MHz the meter read very erratically, greater than 100 "mR/hr" with open window but indicated BG with closed window. The positive indications are represented in the form of a bar graph in Figure 1. At 20, 60 and 80 MHz the meter indicated BG with open and closed window. At 100 MHz the meter read a steady 10 "mR/hr" with an open window but BG with closed window. At 200 and 300 MHz the meter indicated BG with open and closed window but at 400 MHz the meter indicated greater than 100 "mR/hr" with open and closed window. At 600 MHz the meter indicated erratically to 0.05 "mR/hr" with open and closed window. At 1000 MHz the meter read BG. The only meter response at 100 cm. was an erratic reading around BG with the closed window at 200 MHz but the meter indicated BG with open window, a somewhat anomalous result. The probe was in its holder on the instrument and hand-held at the 2.5 cm. position but the instrument was placed on the table unheld at the 100 cm. position.

TABLE 1. *Survey instrument response to RF radiation*

Frequency	GM		Scintillation		Ionization Juno		Ionization Model 440		Ionization Model 444	
	r = 100 cm "mR"/hr	r = 2.5 cm "mR"/hr	r = 100 cm cpm	r = 2.5 cm cpm	r = 100 cm "mR"/hr	r = 2.5 cm "mR"/hr	r = 100 cm "mR"/hr	r = 2.5 cm "mR"/hr	r = 100 cm "mR"/hr	r = 2.5 cm "mR"/hr
0.085 MHz	<0.01 O&C	<0.01 O&C	900 (BG)	900 (BG)	0 O&C	0 O&C	0 O&C	0 O&C	0.2 O&C	0.2 O&C
0.1 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0 O&C	0 O&C	0.2 O&C	0.2 O&C
0.5 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0 O&C	0 O&C	0.2 O&C	0.2 O&C
1 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0 O&C	0.4 O&C	0.2 O&C	0.2 O&C
5 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0.1 O&C	0.5 O&C	0.2 O&C	0.2 O&C
10 MHz	<0.01 O&C	O: >100[1] C: <0.01	900	900	0 O&C	0 O&C	0.1 O&C	0.1 O&C	0.2 O&C	0.2 O&C
20 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0.1 O&C	0.1 O&C	0.2 O&C	0.2 O&C
60 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0.1 O&C	0-200[3] erratic	0.2 O&C	0-2[2] erratic
80 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0.1 O&C	0.1 O&C	0.2 O&C	0.2 O&C
100 MHz	<0.01 O&C	O: 10 steady C:<0.01	900	900	0 O&C	<0 erratic O&C	0.1 O&C	0-1 erratic O&C	0-1 pulsing O&C	0-1 pulsing O&C
200 MHz	O:<0.1 C:erratic	<0.01 O&C	900	900	O:0-5 erratic C:0	O:2000 C:5	0-<0 erratic O&C	0-1 erratic O&C	O:0-2 pulsing C:0-1 pulsing	O:0-1 pulsing C:0-6 pulsing
300 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	50[4] O&C	0-5 erratic O&C	erratic O&C	0-5 pulsing O&C	See footnote 5
400 MHz	<0.01 O&C	>100[9] O&C	900	900[8]	0 O&C	5000[6] O&C	0-1[10] erratic O&C	See footnote 11	0-1 pulsing O&C	0-8 erratic O&C
600 MHz	<0.01 O&C	0-0.05 erratic O&C	900	900	O:6 C:8	very erratic could not zero	0-0.2 erratic O&C	0-0.2 erratic O&C	0-2 pulsing O&C	See footnote 7
1000 MHz	<0.01 O&C	<0.01 O&C	900	900	0 O&C	0 O&C	0.1 O&C	0-0.5 erratic O&C	<0-1 erratic O&C	0-80 erratic O&C

---

1. O: >100, very erratic; when free hand touched bench meter dropped off,

2. 0-2, pulsing about 1 per second,

3. 0-200, erratic pulsing about 1 per second,

4. at 2.5 cm, O&C: 50,
   at 100 cm, O&C: 0, as chamber moved toward antenna first indication was at 13 cm: 50,

5. O&C: meter erratic 0 - <0 "mR/hr" & "R/hr" scales occasionally pulsing upscale,

6. at 2.5 cm: O&C: 5000,
   at 20 cm: O&C: 10, 1st indication,
   at 30 cm: O&C: 0,

7. O&C: <0, could not read on "mR/hr" scale, too erratic, 0-60 erratic on "R/hr" scale,

8. With probe away from antenna and meter at 2.5 cm a slight increase of approximately 100 cpm was noted,

9. O&C: at 2.5 cm: >100,
   at 5 cm: >100,
   at 23 cm: 0.8, 1st indication,
   at 28 cm: <0.01,

10. Touching meter on bench causes high reading,

11. O&C: <0 to off scale, erratic.

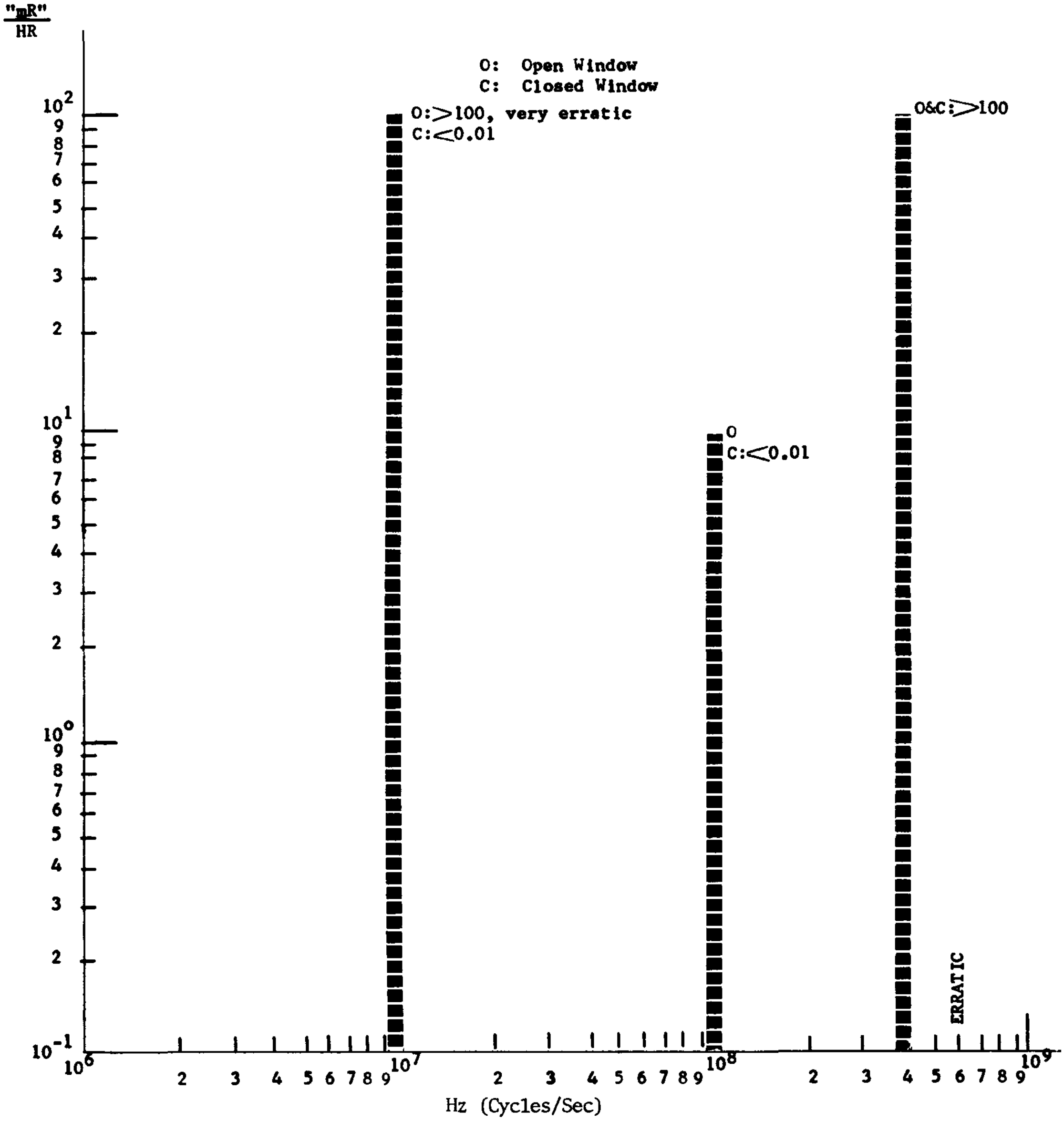

Figure 1. Instrument: Nuclear Chicago Model 2650. Distance of probe from antenna: 2.54 CM. Electric field: 10 volts per meter at 1 meter.

An explanation for this response may arise from the basic electronics of the instrument in which pulses from the GM tube trip a univibrator circuit with the resulting count rate proportional to the number of pulses tripping the univibrator. The RF radiation triggers this circuit at the indicated frequencies and may in effect cause it to act as a free running multivibrator. At frequencies such as 20, 60, 80 and 1000 MHz it is unaffected possibly because of non-resonant conditions in the univibrator circuit. At frequencies such as 10 MHz, 100 MHz and 400 MHz the meter readings are particularly deceptive since there is no erratic movement of the pointer to indicate a possible erroneous reading.

The scintillation type survey instrument was checked at all 15 frequencies and gave a meter indication of 900 cpm at all frequencies which is background for the instrument. At 400 MHz there was a slight increase with detector away from source and the meter case about 2.5 cm. from source. The instrument employs a linear amplifier with pulse amplitude discrimination for pulses from the photomultiplier tube. The integral shield around crystal, photomultiplier tube, and electronic components was effective, together with the discriminator, in shielding out the RF radiation. Since this is an extremely sensitive instrument with an aural monitor we have always used it to locate sources of ionizing radiation around electronic products.

The "Juno" ionization type survey instrument was unaffected at 0.085, 0.1, 0.5, 1, 5, 10, 20, 60 and 80 MHz and 2.5 cm. and 100 cm. from the RF source. As represented in Figure 2 at 2.5 cm. and 100 MHz the instrument gave erratic results around and below zero with open and closed window and indicated zero at 100 cm. At 2.5 cm. and 200, 300 and 400 MHz the meter indicated up to 5000 "mR/hr" with open and closed window. At 100 cm. and 200 MHz the meter indicated erratically to 5 "mR/hr" with open window but zero with closed window. At 2.5 cm. and 600 MHz the meter reading was very erratic and could not be zeroed; at 100 cm. and 600 MHz the meter read 6 "mR/hr" open window and 8 "mR/hr" closed window. No meter response was observed at 1000 MHz. Therefore at 100, 200, 300, 400 and 600 MHz currents are generated in the metal case or in the ion chamber and are detected by the electrometer tube. Apparently the RF radiation interacts with the instrument in such a manner as to give rise to a DC current. Again this is particularly deceptive at 200, 300 and 400 MHz since the meter response is steady.

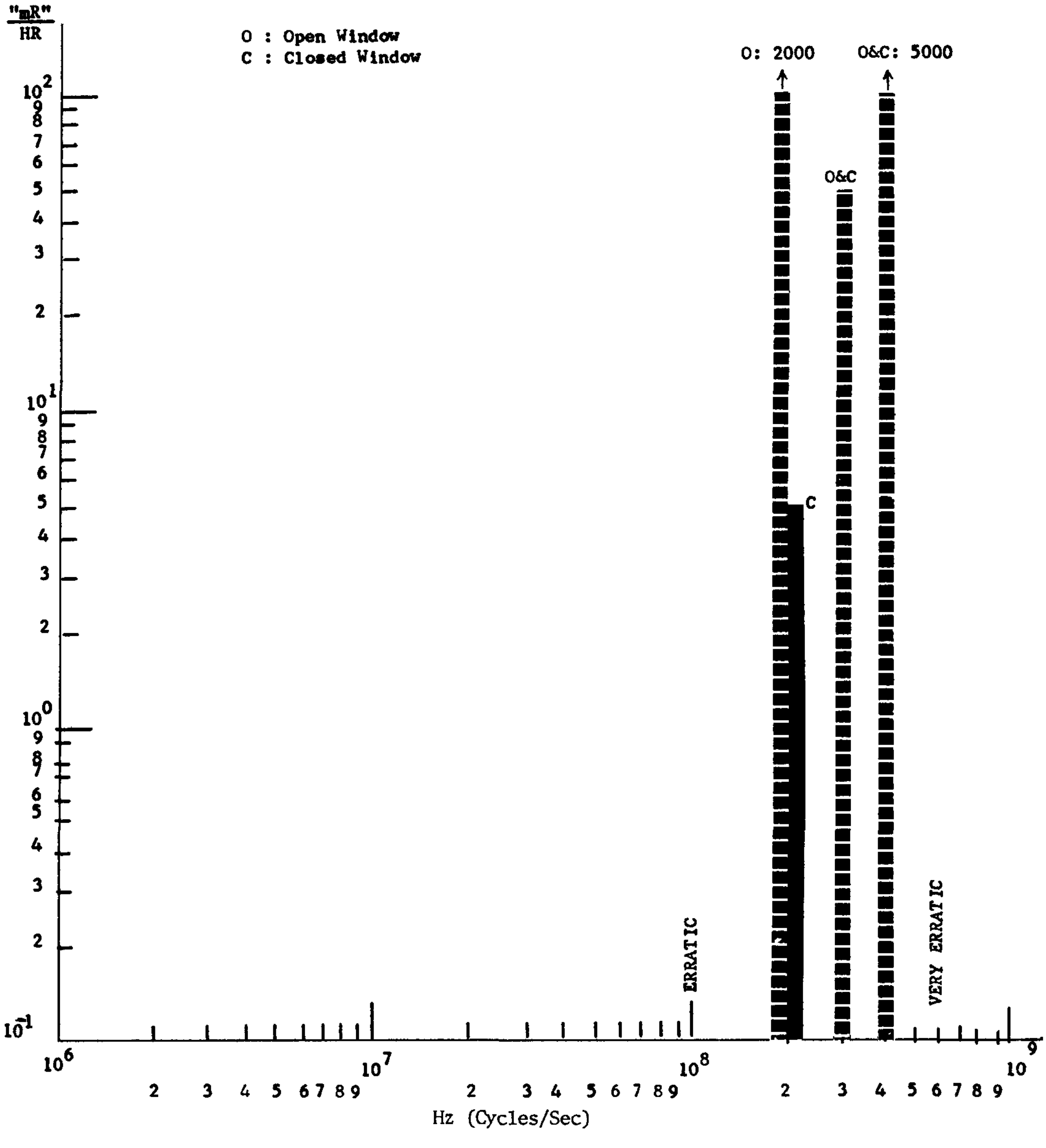

Figure 2. Instrument: Technical Associates "Juno." Distance of chamber from antenna: 2.54 CM. Electric Field: 10 volts per meter at 1 meter.

The survey instruments, which are most affected by the RF radiation through the greatest frequency range, are those employing a vibrating reed electrometer. They do, however, behave erratically in most of the RF fields checked and, therefore, the user is warned of a problem. The results are summarized in Table 1 and represented in Figure 3 for the Model 440. As an example at 2.5 cm. and 60 MHz the meter pulsed erratically once per second between 0 and 200 "mR/hr". The Model 444 behaves in a similar manner as noted in Table 1 but the meter pulsed in a more regular manner.

Since the vibrating reed oscillates at 300 cycles per second in the models checked, and has a tuned circuit at this frequency, it is probable that the observed sensitivity of these instruments to RF radiation is a result of this fact, and the generation of currents in the case of ion chamber noted with the "Juno" ionization type instrument. In support of this observation one notes the greater sensitivity at harmonic multiples of 3.

In summary, the following instruments and frequencies should be used with caution around RF equipment because of a steady response mimicking ionizing radiation: end-window GM type Model 2650, 100 and 400 MHz; "Juno" ionization type, 200, 300, 400 and 600 MHz.

IV <u>TV Repair Shop Survey</u> The results of a TV repair shop survey using instruments that responded only to ionizing radiation will be briefly summarized. A scintillation type survey meter was used to locate sources of ionizing radiation around the TV set and a RF shielded ionization type survey instrument to obtain readings in mR/hr. Initially a 1/8" thick lead shield with a 10 cm^2 circular opening was placed over the front window of the ion chamber to conform to the latest NCRP recommendation.[1] This was soon discarded since it reduced the sensitivity of the chamber by a factor of approximately 5 and at the low dose rates found, no meter response was observed with the shield.

Fifty-two repair shops were surveyed and 108 color sets checked. The sets were checked as they were found at the time of the survey. Of these, 68% were out of the cabinet (i.e., open chassis).

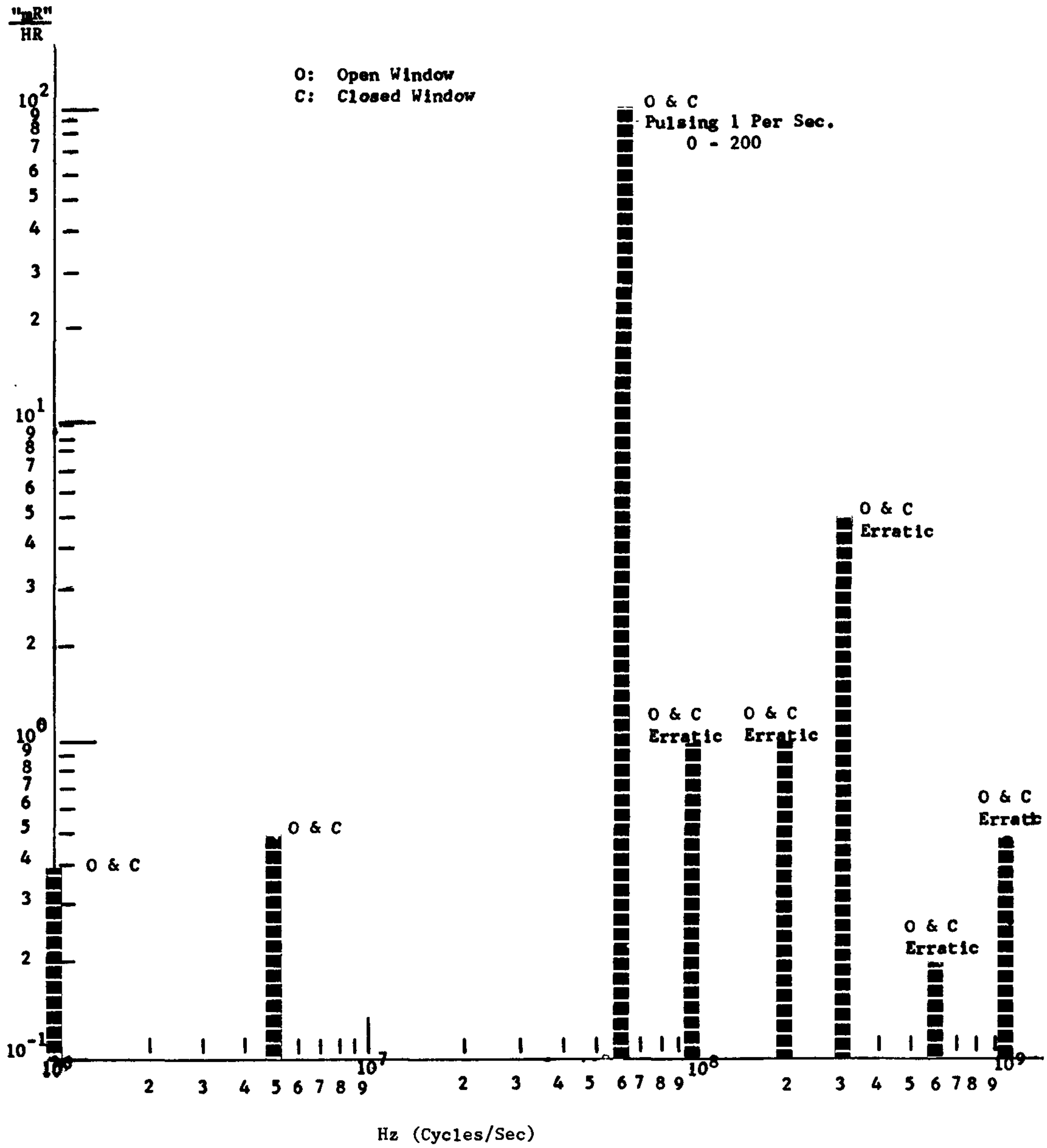

Figure 3. Instrument: Victoreen Model 440. Distance of probe from antenna: 2.54 CM. Electric field: 10 volts per meter at 1 meter.

1.9% or 2 sets were found to be leaking radiation above 0.5 mR/hr. The radiation was in the range 1 - 5 mR/hr. 2.8% were found to be leaking some radiation but below the acceptable standard. 95.3% were at background.

In one of the sets above the recommended NCRP value the radiation came from the picture tube and was caused by excessive high voltage. In the other set the radiation was from the bottom of the set and originated from the shunt regulator tube. In both cases the cause of the excessive radiation was corrected during the visit.

In one repair shop the Ramcor Densiometer Model 1200 and Empire Devices Model NF/157, broad band power density meter were used to check for the presence of RF radiation around 3 sets, but none was found above the lower limit of sensitivity of the instruments.

V A Case of RF Interference In a recent case the RF study was an assist in analyzing the results. In a plant survey a radiophysicist noted a reading of 5 mR/hr with the end-window GM type survey instrument in the vicinity of a spark spectrograph. Since the spectrograph was operating at only 2300 volts, this ruled out ionizing radiation. While the radiophysicist required film badges to determine conclusively whether ionizing radiation was present or not, it was obvious that the GM readings were due to RF radiation. Again the survey reading was especially deceptive because the reading was steady.

Acknowledgements We would like to thank the Dayton-Brown Co. for providing the sources of RF radiation, facilities and the assistance of their personnel during this study.

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X-RAY MEASUREMENTS AROUND HIGH POWER KLYSTRONS

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Introduction and Summary.

Many thousands of high-power klystron tubesare presently in service in radar transmitters and linear high energy particle accelerators, and incidental to their normal function as microwave amplifiers such tubes generate x-rays with internal intensities approaching 1000 times those produced in x-ray tubes. Very little has been written about the problem of stray x-rays around klystrons since the Lockport incident called attention to it almost 10 years ago.[1]

Today manufacturers supply high-power klystrons already fitted with carefully-designed external lead shields around the tube body and collector; moreover, the collector is constructed so that it will locally absorb most of the x-radiation that is generated in it. However, since wave guides, water lines, and power cables penetrate the external shielding of most tubes, usually there are minor breaks and leakage points in the shielding that permit x-rays to scatter out of the tube into working areas. The present study reports measurements made by use of radio-frequency (RF)-shielded ion chambers of the changes in intensity and mean energy of such leakage x-radiation under different klystron operating conditions.

The x-ray intensity near a break in the shielding of a 40 Megawatt UHF klystron tube that was operated at constant pulse rate frequency (PRF) and constant pulse length, was measured as a function of the high voltage with which the tube was pulsed. Under these conditions and with no RF-drive (video pulsing only), the x-ray intensity rose with the ninth power of the high voltage in the 140- to 180-KeV range, and the mean x-ray energy increased from 78 to 108 KeV. When the klystron tube was RF-driven to the level of 12% microwave power output efficiency at fixed high voltage points, the x-ray intensity increased about 5-fold over the undriven values, and the mean x-ray energy rose by about 20%.

Similar measurements were taken near a leakage point in the lead shielding around a 10 Megawatt S-band klystron operated at constant 120KV high voltage. When the tube was video pulsing only, the x-ray intensity rose in direct proportion to the PRF in the range 400 to 3000/sec; the mean x-ray energy increased from 90 to 99 KeV. When the tube was activated by RF-drive to produce the maximum microwave power at a given PRF, the x-ray intensity increased to approximately 30 times the undriven values, and the mean x-ray energy rose by about 50% to values well in excess of the peak tube high voltage.

Equipment and Methods.

Ion recombination and space charge effects are known to distort the responses of ionization chambers operating in pulsed x-ray fields; the problem becomes increasingly important as the chamber volume rises, the collection voltage falls, the duty cycle of the x-ray source decreases, and the source strength increases.[2,3] High-power klystrons are excellent examples of intense, low duty cycle sources of pulsed x-radiation; moreover, when RF-driven they are also sources of pulsed microwave radiation that can induce disabling voltages in the electric circuits of x-ray detection instruments. One of the detectors (the EG&G 8004) used in this work was in fact inoperable for this reason when the UHF tube was RF pulsing. Curiously, its operation was not disturbed by the RF fields around the S-band klystron. For these reasons, RF-insensitive ion chambers having high collector voltage and small volume were used to make the measurements reported here. Some important characteristics of these instruments are listed in Table 1.

The variable quality of the x-ray spectra that the klystrons generate under different operating conditions (see below) also presents difficulties in the interpretation of ion chamber readings unless the x-ray energy response of the instrument is a) flat in the region of interest, or b) known and corrected. The energy response of the modified PIC-6 ion chamber varies strongly in the 70 to 150 KeV region, a property that was made to yield both the mean x-ray energy and the (correct) intensity at the field points. Prior to the present study, the absolute x-ray energy response of the modified PIC-6 instrument was determined with and without a 1/8" thick plate of copper placed against the base of the instrument between the standard x-ray sources and the detector. The ratio of these readings defines the x-ray energy, hence the response correction.

The klystron tubes are described in Table 2. Klystrons are active elements in the electrical circuit; the peak tube current I is related to the pulsed high voltage E by the relation $I = kE^{3/2}$ where k, the perveance, is fixed when the tube is manufactured. The peak (video or diode) power is therefore proportional to the 5/2 power of E. The product of the peak tube current (or power) and the duty cycle gives the average tube current (or power); the x-ray yield is related to these quantities.

The x-ray measurement procedure was as follows: The ion chambers were mounted in arbitrary positions near the break in the lead shielding around a waveguide penetration; the chambers were not disturbed during a given set of measurements. Changes in the x-ray fields as registered by at least two different types of ion chambers were recorded for each step change in the PRF, the high voltage, or the RF output. The mean energies of the x-rays were obtained by use of the PIC-6 instrument and a 1/8" Cu plate as outlined above. Duplicate measurements with this instrument and a 1/16" thick Cu plate helped define the mean energies to ± 1%.

Results:

The x-ray measurements around the UHF klystron are presented in Fig. 1, and those around the S-band klystron are given in Fig. 2. The latter measurements are re-presented in a different format in Fig. 3. A general summary of the results may be found in Table 3.

The measured x-ray intensities were presented on a relative scale for the following reasons:
1) the radiation intensity levels changed greatly with the position of the ion chambers in the neighborhood of the breaks in the lead shielding,
2) the field measurement points were arbitrarily chosen,
3) the amount and the effectiveness of the lead shielding around different types of high-power klystrons varies.
It is therefore clear that only relative changes in x-ray intensity with klystron operating conditions have general significance.

The actual x-ray intensities recorded in this study were between 2 and 260 mr/hr (11r/hr was the maximum instantaneous or m.i. level) for the PIC-6, between 0.6 and 70 mr/hr (4 r/hr m.i.) for the 8004, and between 5 and 25 mr/hr (12 r/hr m.i.) for the 440 RF instrument. The most unstable x-ray field condition was when the RF output of the UHF klystron was varied. During the fine tuning to find the optimum output cavity matching, the x-ray intensity fluctuated by as much as 50% and the mean energy by as much as 8 KeV.

Table 1 Description of the Ion Chambers

Chamber	Eberline Inst. PIC-6 (mod.)	Victoreen Inst. 440RF	EG&G Co. 8004
Volume (cm^3)	11	314	1,200.
Gas (pressure)	propane (.8atm)	air (1 atm)	air (1 atm)
Wall thickness	30 mg/cm^2 steel	22 mg/cm^2 [illegible]	30 mg/cm^2 plastic
Collection volts	2500		600
Energy response	variable, known	flat >13 KeV	flat >10 KeV

Table 2 Description of the Klystron Tubes

Tube type	Varian Assoc. VA938C 5-cavity S-band 2.86 KMc	Litton Ind. L3775 4-cavity UHF 0.400 KMc
Modulator	line type, pulsed cathode	same
Peak power	10 MW video, 4 MW RF	40 MW video, 15 MW RF
Pulse length	10 µs video, 9 µs RF	20 µs video, 15 µs RF
Pulse rate frequency (PRF)	400 to 3000/s	100/s
Microperveance	2.0	3.1
Peak voltage for this study	120 KV	176 KV

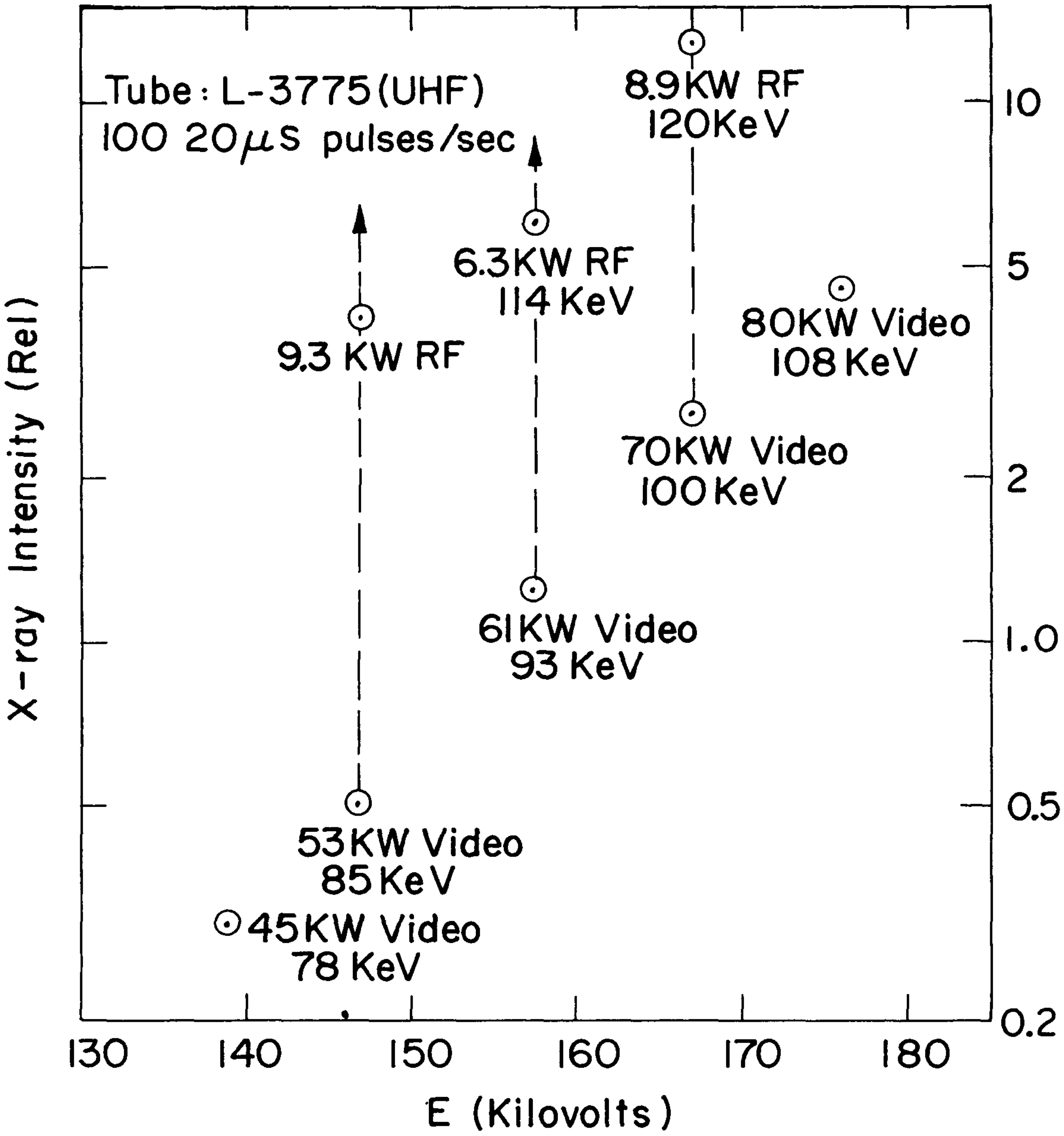


Figure 1. High voltage dependence of x-ray intensity and energy at leakage point near well shielded klystron.

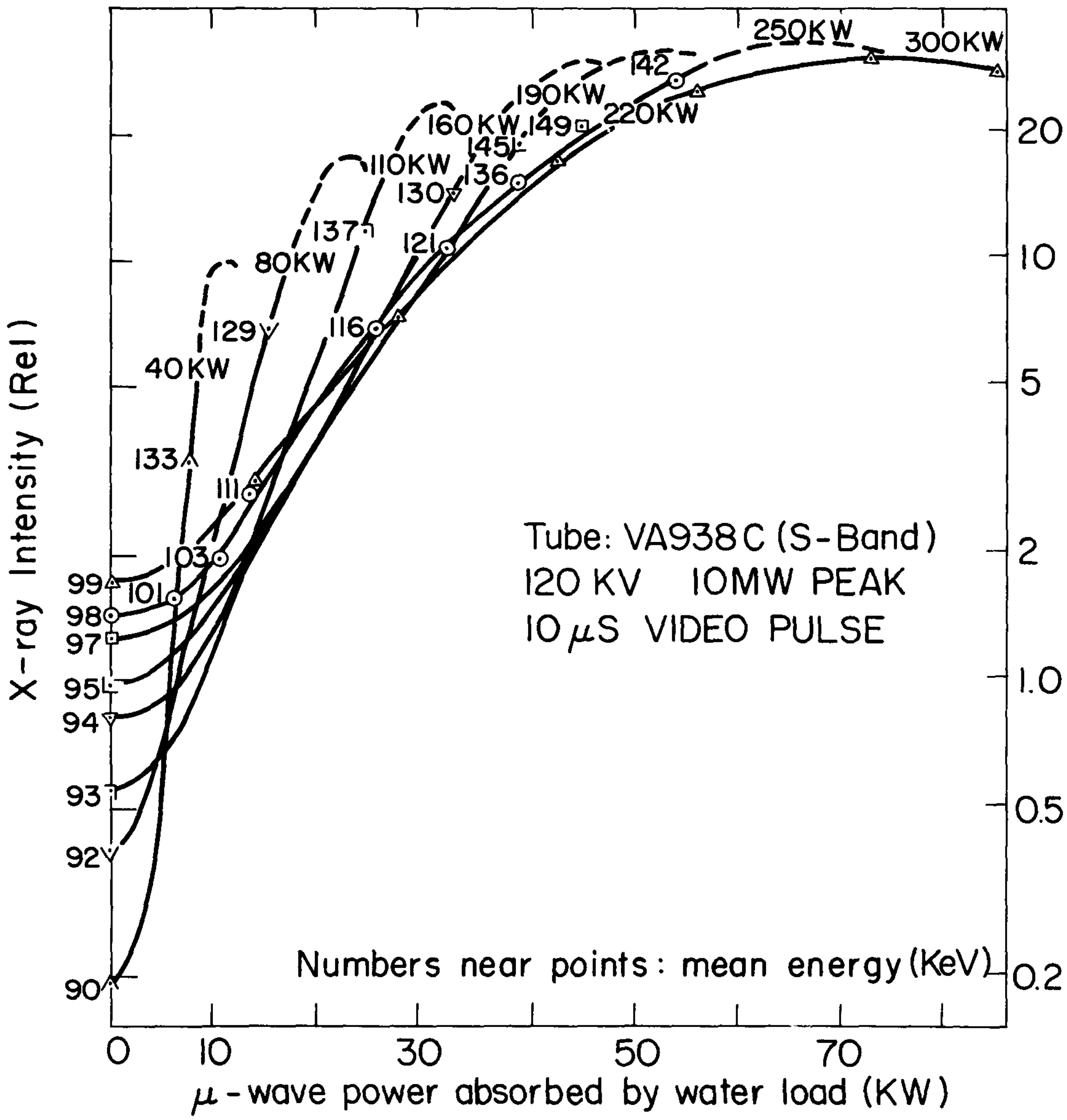


Figure 2. Change in x-ray intensity and energy with RF output at constant high voltage at leakage point near well shielded klystron.

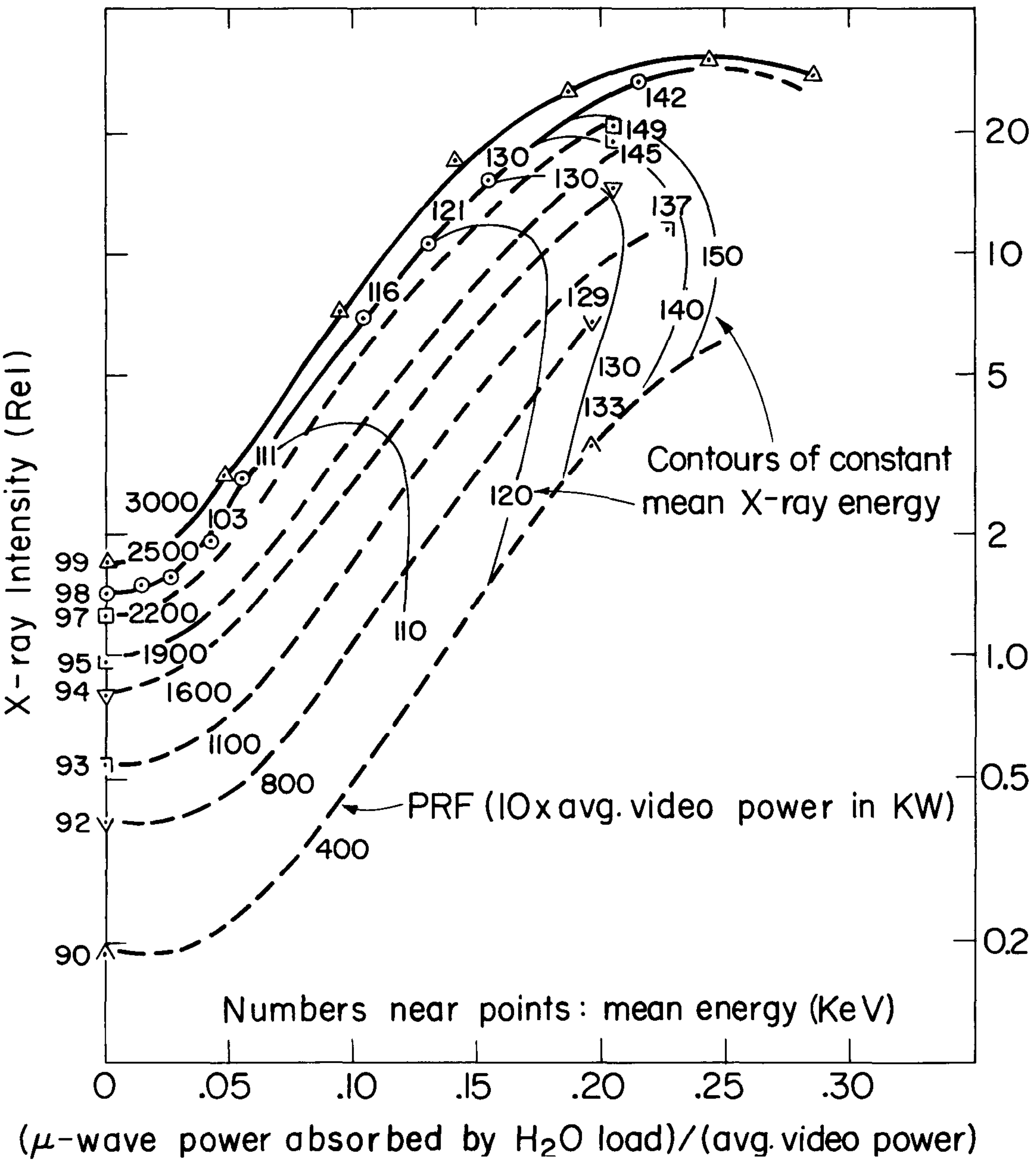


Figure 3. Change in x-ray intensity and energy with increasing relative RF drive.

Table 3. Summary of the Measurements

	Variable*	Values	X-Radiation	
			Intensity	Mean Energy
S-band	$\frac{\text{RF output}}{\text{video power}}$	0 to 0.30	1 to 30x	1 to 1.5x
	PRF	400 to 3000/s	1 to 8x	1 to 1.1x
UHF	$\frac{\text{RF output}}{\text{video power}}$	0 to 0.12	1 to 5x	1 to 1.2x
	High voltage	139 to 176 KV	1 to 13x	1 to 1.5x

*While the given variable was changed over the values given to produce the given relative changes in x-radiation, the other variables were held constant. Because the pulse duration for each klystron was fixed, the PRF was directly proportional to the duty cycle that was constant at 0.002 for the UHF klystron and varied between 0.004 and 0.03 for the S-band klystron.

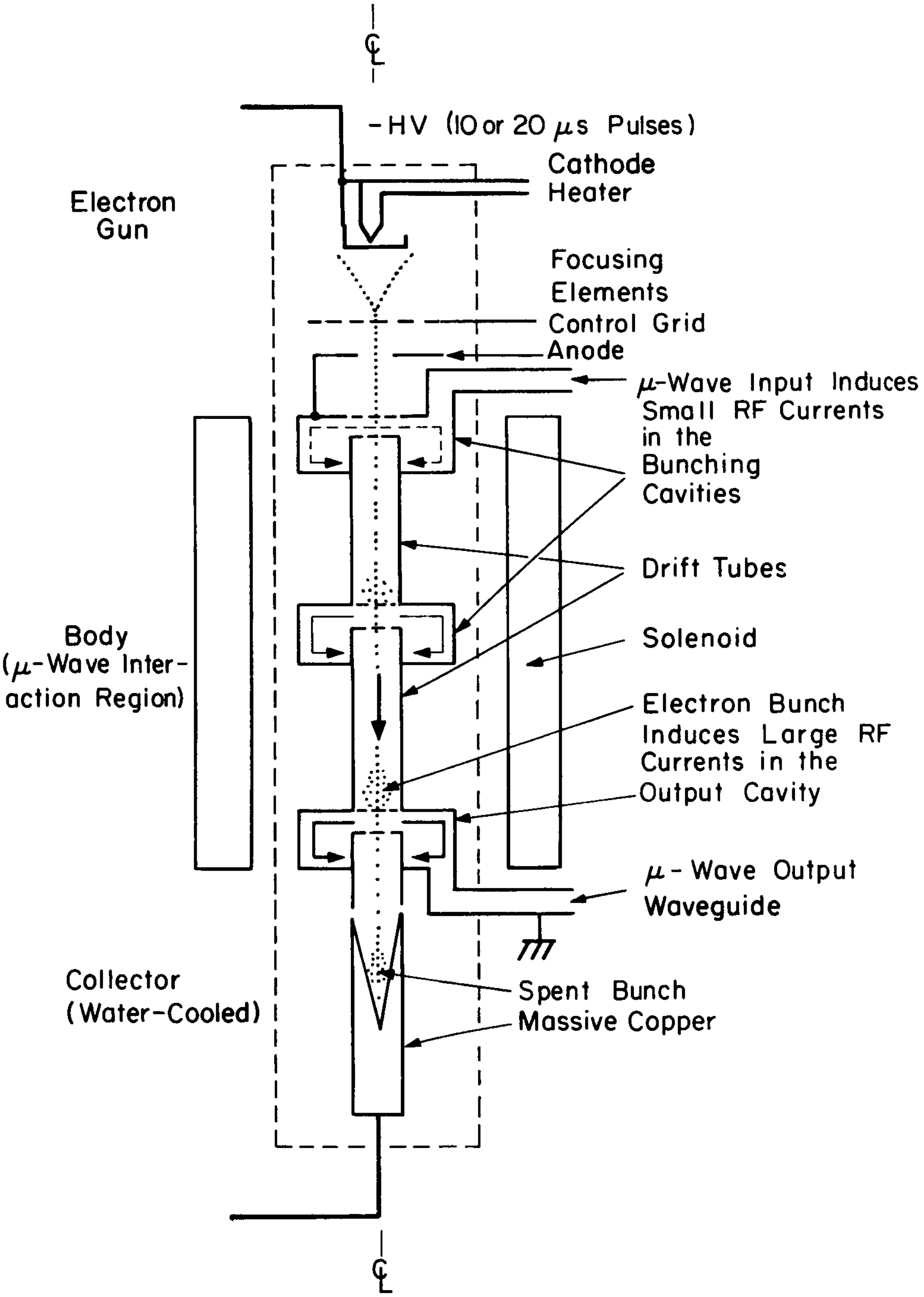


Figure 3. Klystron operation (schematic).

In addition to the other measurements, the klystron tube body current' was recorded. As the UHF tube high voltage was varied from 139 to 176 KV, the body current rose from 0.2 to 0.4 ma when the tube was video pulsing only, and from 1.1 to 4.1 ma when RF drive to 6-10 KW was added. The body current of the S-band tube remained constant at 8µa as the PRF was varied during video pulsing conditions and at PRF's up to 1600/s when RF drive to 25 KW was added. At a PRF of 2500/s, the body current rose from 8 to 13 µa as the RF output climbed from 0 to 55 KW.

Discussion.

1. The changes in x-radiation with PRF (RF-drive and high voltage held constant). The rise in x-ray intensity was found, as expected, to be directly proportional to the PRF, since in this work the PRF was proportional to the duty cycle and therefor to the average tube diode power. However, there was a definite trend upward in the mean x-ray energy with increasing PRF that may partly be explained by a gradual loading of the beam magnetic focusing fields, leading to changes in the beam profile hence to changes in the internal x-ray scattering geometry.

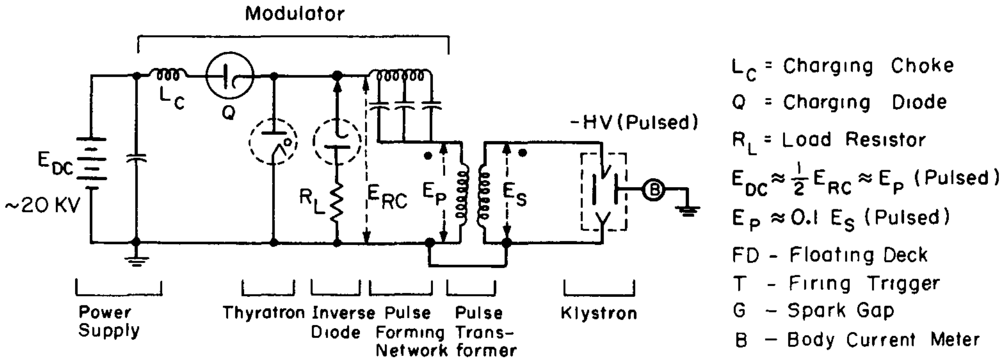
2. The changes in x-radiation with relative RF output (PRF and high voltage held constant). In order to discuss the observed changes it is necessary to list the effects of an impressed RF field on the electron beam in the body of the klystron tube. a) the electron beam is velocity modulated so that intense bunches of electrons arrive simultaneously at the microwave output cavity. In order to accomplish this, the continuous stream of electrons entering the initial bunching cavity is acted upon by a sinusoidally-varying electromagnetic field (the "RF-drive") that differentially decelerates those electrons entering the cavity on the first half of the RF cycle and accelerates those entering on the second half. For S-band 10 cm microwaves and a 50 cm distance between the first and last cavities, the leading electrons must lose 5 cm and the trailing ones must gain 5 cm in the 50 cm transit. Therefore the maximum velocity modulation is ± 10% in this case. If the electrons are initially at 120 KeV (velocity 0.59c), the new velocities will be between 0.53 and 0.65c (90 to 160 KeV) at the output cavity. b) The electron beam is defocused, an effect that increases the number of electrons striking the tube body (thereby increasing body current), and broadens the beam where it strikes the collector. Both these effects change the x-ray source distribution within the klystron tube, hence change the internal scattering geometry. c) The bunched electrons lose energy in crossing the output cavity and arrive partially spent at the collector. Large currents are induced in the walls of the

output cavity as each group of RF-bunched electrons crosses it. These cavity currents generate microwave radiation power that is channeled out of the klystron by use of waveguides. The power thus removed from the klystron is coupled to the bunched electron beam by way of the electromagnetic fields the beam induces in the output cavity. d) Straggling (unbunched) electrons arriving at a favorable phase angle are strongly accelerated in crossing the output cavity. The magnitude of this acceleration depends in a complicated fashion on the tube voltage, the cavity gap transit time, tuning factors, and RF power coupling factors with the output cavity. However, a typical S-band klystron output cavity gap of 2 cm could be charged with accelerating electric fields of the order of 100 KeV/cm.

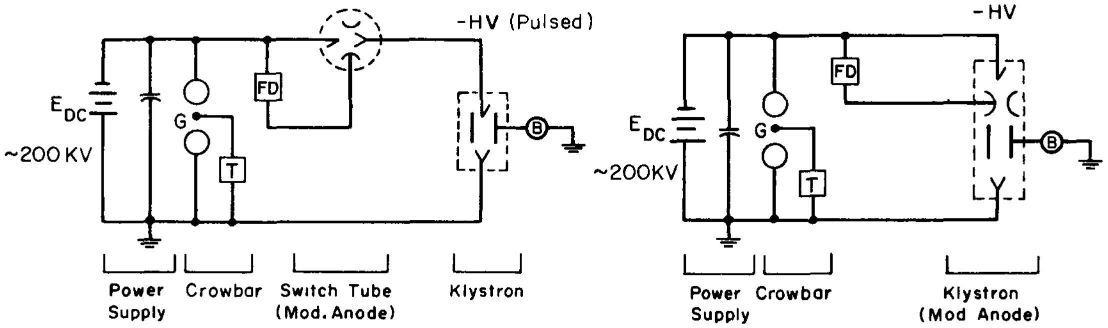
The observed increase in x-radiation intensity with increasing RF-drive is evidence that effects a), b), and d) more than compensate for effect c) on the x-ray yield. Moreover, the dramatic observed rise in the mean energy of the x-rays to values far exceeding the limiting value set by the high voltage in the undriven tube is evidence that effect d) is quite important in RF-driven klystrons.

3. The changes in x-radiation with high voltage (PRF and RF output held constant). The x-ray intensity rose with the 11.5th power of the high voltage E, an extraordinary dependency that is reduced to E^9 when the intensities are normalized to constant video power.

There are three possible high-voltage-dependent factors that could contribute to this effect: the copper target yield of x-rays, the distribution of the internal x-ray sources, and the photoelectric absorbtion cross section in copper and lead. a) the high voltage-dependency of the thick target x-ray yield is difficult to estimate because it depends upon the geometry of the beam-target interaction in the collector; this geometry can't be readily determined inside a klystron. Moreover, the beam-target geometry is expected to vary with high voltage in a fixed (beam focusing) magnetic field. Finally, the relevant yield is only that yield above a certain photon energy, somewhere between 35-50 KeV, that has a significant probability of penetrating the copper wave guide. The total x-ray yields of 1 to 2 - MeV electron beams have been reported to have about E^3 dependences.[4] The total x-ray yields of very low energy electron beams rise as the second power of E. However, since the total low energy beam yield is not relevant for the present problem, it is not helpful to use this relation. In practice, one is forced to ignore the effects of changes in beam geometry and to graphically integrate published spectral curves above an arbitrary cut off value.[5] By this means 3rd to 5th power dependencies on E can be obtained, depending upon which curves are used and the low energy cut off point. b) The effects on the x-ray intensity of changes in the x-ray source distribution with high voltage in a fixed magnetic field are also difficult to analyse in a klystron. Should the principal point where the beam penumbra strikes the tube body shift with high voltage to points closer to the breaks in the external lead shielding, large increases in x-ray intensity would be expected.



1. Pulsed Cathode Mode (Pulse transformer)



2. Pulsed Cathode Mode
(Switch Tube Modulated)

3 Modulated Anode or Continuous Wave Mode

Methods of pulsing a klystron.

These changes could equally well, however, cause a drop in intensity with high voltage. c) The photoelectric effect (PE) absorption resonance in Cu and Pb in the 40 to 200 KeV region leads to an E^3 dependence of scattered (unabsorbed) photons.[6] Moreover, since the absolute cross section for the PE effect is about 15 times that for Rayleigh scattering in these elements (that has an $E^{-3/2}$ dependence), the PE interaction is the dominant internal scattering factor. In order to reach the ion chambers, the x-rays must have suffered one or more scatterings inside the klystron. I an average two scatterings take place an E^6 dependence would be expected; therefore this effect and the source yield can well account for the observed 9th power dependence of x-ray intensity on E.

Finally, the mean x-ray energy rose with approximately the 1.7 power of E. Such a dependence is not unexpected and is interpretable in terms of differential yield and PE absorption.

Acknowledgement.

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RADIATION EMISSIONS FROM DEMONSTRATION TYPE COLD-CATHODE GAS DISCHARGE TUBES

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ABSTRACT

Cold-cathode gas discharge devices used in educational institutions may emit X-radiation and have recently been studied by the Bureau of Radiological Health, USPHS. The National Council on Radiation Protection and Measurement (NCRP) has made recommendations regarding radiation protection in educational institutions in Report #32. It identifies gas discharge tubes, in general, as potential sources of X-rays and specifically mentions cold-cathode X-ray tubes in this regard. However, the NCRP report does not specifically identify other gas discharge tubes that may emit X-rays incidental to their intended use.

The results of laboratory measurements of the X-ray outputs from various tubes will be presented here and a summary of the findings of a recent survey of radiation sources found in secondary schools will be reviewed. Recommendations regarding use of gas discharge tubes based on these data will be given with specific comments directed to the science teacher who uses the equipment, to the distributor, and to the State or local radiological health agencies.

RADIATION EMISSIONS FROM DEMONSTRATION TYPE COLD-CATHODE GAS DISCHARGE TUBES

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Many schools use radiation-producing equipment in their science class demonstrations. The importance of an awareness of radiation hazards and good radiation protection techniques related to the use of such equipment cannot be over-stated. National and international radiation protection organizations emphasize the desirability of keeping radiation exposure to younger age groups as low as possible. The teachers who use the radiation-producing equipment should therefore understand the radiation hazards and should know and practice good radiation protection techniques in the classroom so that exposure to themselves and their students will be kept to a minimum.

Recognizing the possible health implications of using radiation-producing devices in schools, the American Association of Physics Teachers requested the National Council on Radiation Protection and Measurements (NCRP) to provide suitable information on radiation protection. After the NCRP had conducted a questionnaire survey of science teachers, the Division of Radiological Health (now the Bureau of Radiological Health) in 1962 conducted a survey in four schools. An evaluation of these data by a scientific committee appointed by the NCRP concluded that there was a potential problem worthy of NCRP consideration. As a result, the NCRP issued Report #32, "Radiation Protection in Educational Institutions," in which the NCRP recommended maximum permissible doses for students 18 years of age or less while conducting educational activities. The report identifies gas discharge tubes in general as potential sources of X-rays and mentions cold-cathode X-ray tubes, specifically, in this regard. However, the report does not identify gas discharge tubes that may emit X-rays incidental to their intended use.

In addition to NCRP efforts, a number of State radiological health agencies and individuals attempted to identify educational devices that were capable of producing X-rays and to evaluate the potential radiation exposure to students. Radiation measurements were usually made under field conditions. While the results were certainly adequate for the intended purpose of identifying devices capable of producing X-rays, a complete evaluation of the operating and output characteristics of the devices requires conditions of space and equipment which only a laboratory can provide.

In addition, field surveys are necessarily limited to the observation of only one or two types of tubes under constant conditions. As a consequence, the information available was a compilation of fortuitous observations made under various conditions by different individuals using different techniques.

To provide more complete information about the various gas discharge tubes, the X-ray Exposure Control Laboratory undertook a study to identify specific gas discharge devices that emitted X-radiation and to evaluate their X-ray output under controlled conditions of operation.

A variety of commercially available cold-cathode gas dicharge tubes were obtained and tested. The tubes were operated from various commercially available high voltage sources suggested by the tube manufacturer. In addition, the Bureau conducted a joint State-Federal survey in secondary schools throughout the country to assess the type, quantity, and use of radiation emitting sources in science classrooms.

This report describes the laboratory measurements of X-rays from various cold-cathode gas discharge tubes and summarizes the findings of the survey of sources in secondary schools. Based on these data recommendations will be given regarding use of the tubes, specific comments being directed to the science teacher utilizing the equipment, the distributor, and the State or local radiological health agencies.

Gas discharge devices first came into use in the latter half of the nineteenth century. Physical scientists of that time studied the various discharge phenomena in their experiments on the structure and properties of matter. The devices investigated in this study are similar to those used by the early investigators. Today the major application of these tubes is the demonstration of physical phenomena in educational institutions.

A. Cold-Cathode Gas Discharge X-ray Tubes

X-ray tubes can be broadly subdivided into two groups, cold-cathode gas discharge tubes* and vacuum (or Coolidge) tubes. In the gas discharge tubes, electrons are liberated from the cold-cathode surface by positive ion bombardment. These positive ions are generated by ionization of gas atoms contained in the tube. In the Coolidge tube, a high vacuum is obtained and the bombarding electrons are released from a heated filament by thermionic emission.

The cold-cathode gas discharge X-ray tubes currently sold by a number of scientific supply houses in this country are of the so-called "Müller" type (figure 1) (1). Tubes of this type can be purchased for about fifty dollars. A variety of high voltage sources may be used to operate these devices; however, induction coils are the most popular. These coils can be either homemade or purchased from the same suppliers as the tubes. These commercial induction coils, depending on their voltage rating, typically range in cost from ten to one hundred and fifty dollars.

In the laboratory we measured radiation output from cold-cathode gas discharge X-ray tubes and from numerous other gas discharge tubes. A complete description of the tubes and the tests performed has been reported elsewhere by this author (2); a brief summary will be presented here. The tubes were operated first from a handheld Tesla coil and then from two induction coils, one advertised as capable of producing a 3-inch spark and the other a 6-inch spark.

*Note: Field emission tubes, which also employ a cold-cathode, might be considered a third subgroup and should not be confused with the cold-cathode gas discharge tube.

Figure 1. Cold-cathode gas discharge tube.

The dosimeters used in this study were LiF TLD-100 extruded rods measuring approximately 6 mm long x 1 mm diameter. TL dosimeters were used because their size makes possible good point measurements in a radiation field and many such measurements can be made with a single exposure. The TLD reader was an Eberline Model TLR-5. LiF was used because its energy response does not vary greatly at the low energies encountered in the study. Typical energy response curves for LiF show that its sensitivity varies less than 15 percent over the energy range of 20 to 70 keV, which includes the region of interest for our measurements (3). Consequently, errors in the selection of calibration energies would not significantly affect the results.

Three X-ray tubes were tested. These tubes produced X-rays when operated with a forward or reverse potential. Under reverse potential, measured outputs were lower by a factor of 50 to 100. Iso-exposure contours for the three tubes were similar in shape but varied in exposure level, depending on the particular tube and high voltage source used.

Table 1 is a listing of exposure levels and electrical characteristics for the three tubes operated from different high voltage sources. Exposure rates are given for a point 30 cm. from the anode on a line drawn perpendicular to its surface. Isoexposure levels show this to include the region of maximum exposure rate. The kV was estimated by a parallel spark gap method and the mA determined by placing a dc milliammeter, 1 mA full scale, in series with the high voltage supply.

B. Cold-Cathode Gas Discharge Tubes (not designed to produce X-rays)

Examples of gas discharge tubes presently available from scientific supply houses were obtained and operated with various power sources.

X-rays were not detected from samples of the following tubes while operating from an induction coil capable of producing a six-inch spark.

1. Vacuum Discharge Tube (connected to laboratory mechanical piston vacuum pump.)
2. High and Low Vacuum Effect Tube.
3. Goldstein Canal Ray Tube.
4. Geissler Tube.
5. De la Rive Discharge Tube.
6. Kinetic Effects Tube.

Tubes found by our investigation to produce X-rays incidental to their intended use were:

1. Heat Effect Tube.
2. Magnetic Effect Tube.
3. Fluorescence Effect Tube, also known as a Shadow Effect or Maltese Cross Tube.

Table 1. Measured exposure rates and electrical characteristics of three cold-cathode gas discharge X-ray tubes operated from various high voltage sources

Discharge Tube and High Voltage Source	Exposure Rate (R/hr at 30 cm from Anode)	Primary Voltage (volts dc)	Secondary Voltage (kVp)	Current (mA)
Tube #1				
*3" max. spark gap induction coil	9.7	6	65	.03
*6" max. spark gap induction coil	53.9	12	75	.15
Tube #2				
*3" max. spark gap induction coil	72.0	6	50	.18
*6" max. spark gap induction coil	208.0	12	73	.20
Hand-held Tesla coil (tube operated under reverse potential)	0.5**	115	25	.09
Tube #3				
*3" max. spark gap induction coil	13.2	6	65	.10
*6" max. spark gap induction coil	94.4	12	85	.15

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*Maximum spark gap designations are those claimed by the manufacturers and are cited here for identification purposes only.

**Although operated under reverse potential exposure rate was measured 30 cm from the tube structure designated as the anode.

A description of these three tubes and the results of laboratory observations are presented below.

1. Heat Effect Tube

The heat effect tube (fig. 2) is used to demonstrate that cathode rays consist of rapidly moving electrons whose kinetic energy is converted to heat upon collision with an object. The tube consists of an evacuated glass bulb with a thin foil target positioned between opposed electrodes. The cathode has a concave surface to focus the electrons on a small spot of the foil.

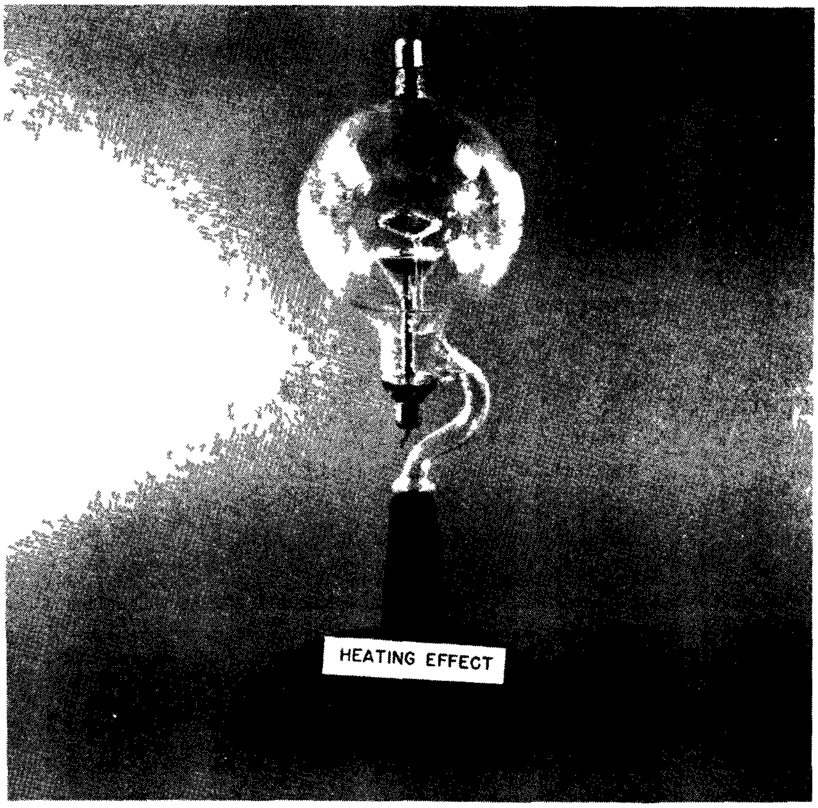

Figure 2. Heat effect tube.

A brand new heat effect tube was tested using an induction coil capable of a three-inch spark as the voltage source. When operated with the proper polarity the tube ran at about 15 kV, as measured by a parallel spark gap, and the focal spot glowed a brilliant red but no X-rays were detected.

Upon reversing the polarity the tube ran at about 55 kV and, as expected, showed no signs of operating as a heat effect tube. Instead, a faint blue discharge filled the tube and X-rays were observed. After a few minutes of operation with reverse potential, the tube was reconnected to operate under a forward potential. However, no change from the reverse potential characteristic was observed: the tube still operated at approximately 55 kV, produced X-rays, and did not show the heat effect. The operation under reverse potential had caused the tube to evacuate due to an internal getter action. For the first few tests, it was possible to heat the tube, thereby outgassing internal parts restoring it to its original operation for demonstrating the heat effect. After continued use the tube's designed operating characteristic was permanently destroyed and it operated only as an X-ray tube.

Measurements of X-ray output with both forward and reverse polarity were made using thermoluminescent dosimeters. Typical conditions gave exposure rates of up to 2 R/hr measured at 30 cm from the target with the tube operating from the small induction coil, the one capable of a three-inch spark. Operation with the larger coil, the one capable of a six-inch spark, showed an increase by a factor of six in the X-ray intensity and an increase in estimated voltage to 75 kV.

2. Magnetic Effect Tube

The magnetic or deflection effect tube (figure 3) demonstrates that cathode rays carry an electrical charge and can be deflected by a magnetic field. It consists of an evacuated glass cylinder with an electrode at each end. An aluminum strip, coated with fluorescent material, with a collimating slit at the cathode end is positioned between the electrodes. In a magnetic field the luminous line produced by electron bombardment of the fluorescent strip is deflected up or down according to the polarity of the magnet.

When the magnetic effect tube was used with the small induction coil it operated at 50 kV but dropped to approximately 15 kV within a few minutes. Exposure rates of approximately 1 R/hr were initially measured at a point 30 cm from the cathode but dropped to less than 1 mR/hr reflecting the lower operating voltage.

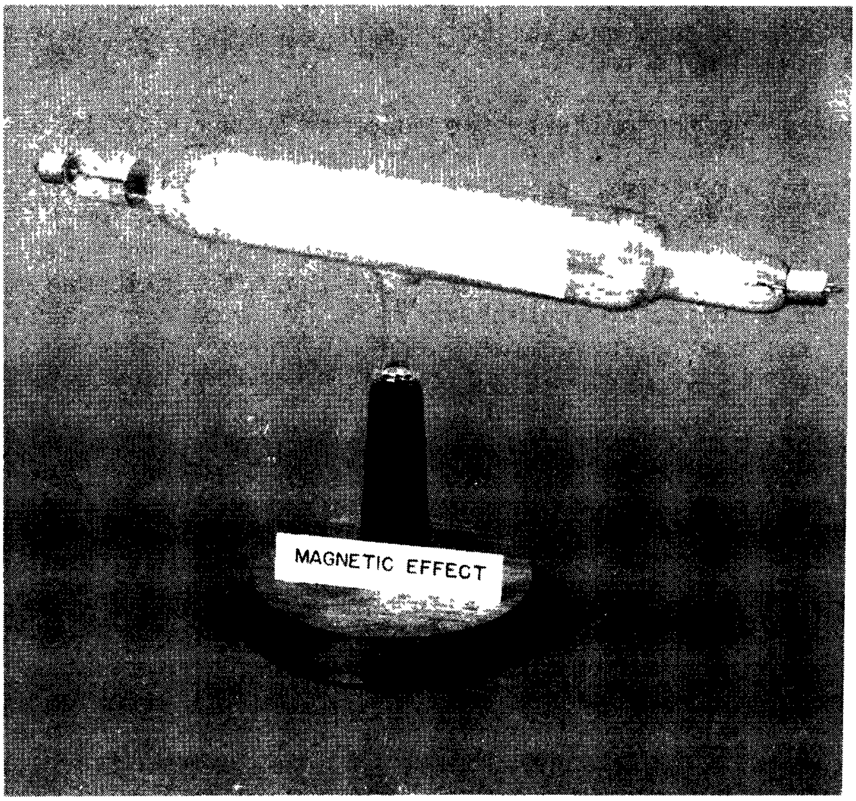

Figure 3. Magnetic effect tube.

3. Fluorescence Effect Tube

The fluorescence or shadow effect tube (fig. 4) demonstrates that cathode ray energy may be converted into visible radiations by fluorescence of the glass walls of the tube resulting from electron bombardment. A metallic object such as a Maltese cross is placed so that its shadow can be cast on the glass wall of the tube. From observation of this shadow it can be shown that the cathode rays producing this pattern travel in straight lines.

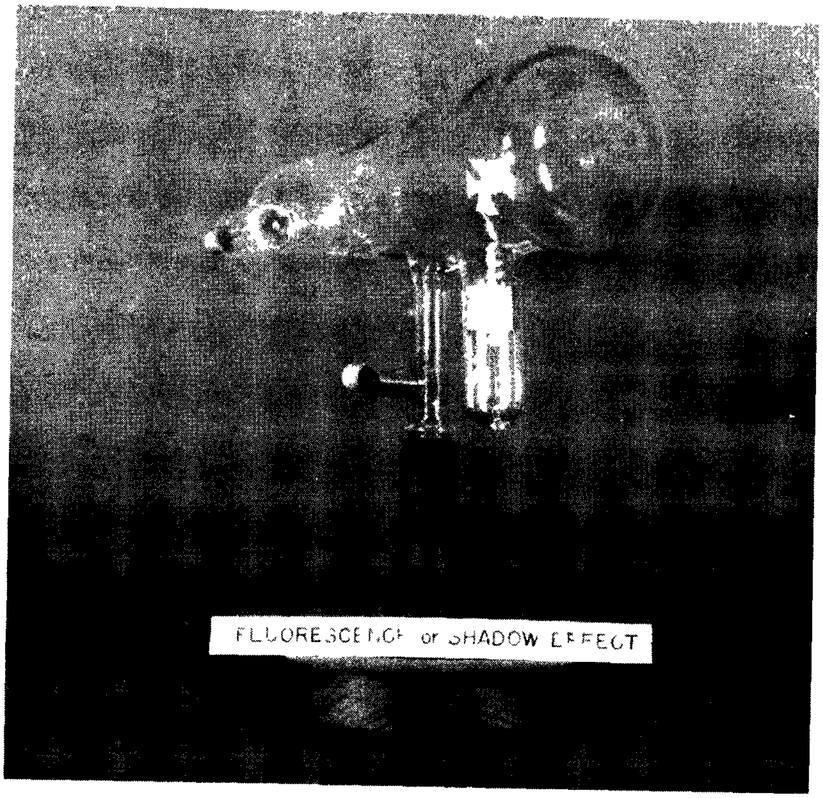

Figure 4. Fluorescence effect tube.

Three fluorescence effect tubes were tested in the laboratory but none operated correctly because of insufficient evacuation. A spot check was made in the field on a tube of this type that showed an exposure rate of 300 mR/hr. The measurement was made at a point 30 cm from the tube on a line perpendicular to the tube axis and through the center of the tube. This confirms the findings of Parsons (4), who reported X-ray production from this type of tube. He reported rates of 31 rem/hr (sic.) at the face of the tube and 0.79 rem/hr (sic.) at a distance of 25 cm from the face as measured with film.

With regard to X-ray production from gas discharge tubes, the following may be concluded:

1. X-ray output is sporadic. Under identical conditions of operation, it may vary from one tube to another, and for the same tube from day to day. In addition, the rate of output may vary during a given period of operation.

2. Gas pressure within the tube is one of the controlling factors in X-ray production.

3. Tube construction plays an important part in the X-ray output obtainable from a tube. The efficiency of X-ray production is partly a function of the target material. In addition, the thickness and composition of the tube walls will affect the exposure rates observed.

4. The output of the tube is strongly dependent on the voltage and current capabilities of the power source and the polarity of the voltage.

5. It is not possible to predict whether a tube will produce X-rays, how long it will produce X-rays, or in what quantity. Even in the case of identical tubes, one may be an X-ray producer and the other not, while both are operating properly in the manner for which they were designed. Therefore, proper operation cannot be used as a criterion for whether or not the tube may be producing X-rays.

Tube polarity was investigated as part of our laboratory observations since it is easy to apply improper polarity to a tube when using Tesla coils and induction coils similar to those found in teaching institutions. As suspected, this one factor determines to a large extent the X-ray output. Improper polarity can damage the tube, increase the production of X-rays, or both. It is important that this be understood by the user of these devices and that the determination of proper polarity not be accomplished through a process of elimination.

C. Survey of Radiation Sources Found in Secondary Schools

The 1969 survey (5) was conducted in the nine Department of Health, Education, and Welfare regions and employed nine teams of radiological health specialists consisting of one person from the Bureau of Radiological Health and one person from the respective State radiological health programs. In one region it was necessary to use two Bureau team members because of the unavailability of a State representative.

Measurements were not taken for each cold cathode gas discharge tube because of time limitations of the survey teams and of school personnel; in some cases, a suitable power supply was not available to activate the tubes. The instrument used for measuring ionizing radiation was the Nucor CS-40A with a specially designed radio frequency interference shield (2). The survey results are summarized below.

1. X-ray Tubes

In the 181 schools surveyed, 103 X-ray tubes were found of which 97 were unshielded cold-cathode tubes. The six shielded tubes were components of functional radiographic and fluoroscopic units.

Radiation emission was measured on 21 of the 97 unshielded cold-cathode tubes. The exposure rates at the voltage applied ranged from zero to a calculated high of 108 roentgens per hour at 60 cm from the midpoint of the tube. Fifty-five percent of the tested X-ray tubes emitted at levels of roentgens per hour at 60 cm from the X-ray tube anode.

2. Heat Effect Tubes

Thirty-three heat effect tubes were found in the survey. Radiation measurements were made on 14 of the 33 tubes. Of these, 50 percent produced X-rays with a maximum measured exposure level of 4 R/hr at a distance of 30 cm from the anode reported.

3. Magnetic Effect Tubes

One hundred and forty-nine magnetic effect tubes were observed in the secondary schools. Radiation measurements were made on 97 of them and 71 percent emitted measurable radiation. Exposure rates of up to 1.5 R/hr measured at 15 cm from the midpoint of the tubes were reported.

4. Fluorescence Effect Tubes

Of 119 fluorescence effect tubes found in the survey, measurements were made on 64. Seventy-seven percent of the tubes measured were found to emit radiation with a maximum exposure rate of 5 R/hr measured at 30 cm.

5. Other Cold-Cathode Gas Discharge Tubes

Other tubes, such as the kinetic energy, canal ray, vacuum discharge, cathode ray display and Geissler tubes were found to produce no measurable X-radiation at the voltages applied to them.

SUMMARY AND RECOMMENDATIONS

Based on our findings and the recommendations of the NCRP (6) regarding radiation exposure to students 18 years of age or less, it was determined that appropriate safeguards were not currently available and that a potential radiation exposure problem did exist.

Under the authority established through P.L. 90-602, "The Radiation Control for Health and Safety Act of 1968," a performance standard for devices of this description has been developed. This standard permits an exposure rate no greater than 10 mR/hr at a distance of thirty (30) centimeters from any point on the external surface of the tube or its permanent enclosure. This exposure rate must be met for the application of forward and reverse potential when operated from power sources specified by the manufacturer. For tubes designed to produce X-rays, an exit beam is allowed. The divergence of this beam cannot exceed π (Pi) steradians and the enclosure must be equipped with a beam-blocking device. The standard also requires that the tubes be supplied with appropriate safety instructions together with instruction for use of the device. Each tube must be labelled as to the intended polarity of its terminals. Tube designed to produce X-rays must be identified as such; tubes that may produce X-rays incidental to their use must have a warning that application of power in excess of that specified may result in the production of X-rays in excess of allowable limits.

Cold-cathode gas discharge tubes sold in accordance with this standard and operated in a recommended manner should not present a significant radiation hazard. On the other hand it is well recognized that the standard is in no way a guarantee of safe exposure conditions and that improper use could still create a problem. There exist also a great number of cold-cathode tubes sold prior to the establishment of this standard that must be considered. With these current problems in mind, we offer the following recommendations regarding use and sale of gas discharge devices.

A. Recommendations to Educational Institutions

Instructors responsible for the use of radiation-producing devices should be familiar with NCRP Report No. 32, "Radiation Protection in Educational Institutions." They should be conversant with the biological effects and other matters related to radiation safety. This information should be passed on to the student as part of the teaching process related to the study of X-rays. Specific recommendations with regard to the use of these devices under special conditions are given below.

1. Unshielded Cold-Cathode Gas Discharge X-ray Tubes

The use of an unshielded cold-cathode X-ray tube in a classroom demonstration should never be considered acceptable.

2. Shielded Cold-Cathode Gas Discharge X-ray Tubes

a. The maximum exposure rate at any point through the shielding should not exceed 10 mR per hour at a distance of 30 cm from the surface.

Note: This value shall be met with a beam-blocking device restricting the primary beam. An exit beam whose divergence is no greater than π (Pi) steradians is recommended.

b. The primary beam from the beam port shall always be directed away from the class and instructor.

c. No student shall use this equipment without appropriate on-the-spot supervision by the teacher.

d. No experiment should result in an exposure greater than 10 mR to any student.

3. Gas Discharge Tubes not Primarily Intended to Produce X-rays

As reported above, certain tubes in this category produce X-rays incidental to their intended use. Although measurements indicate that the output exposure rates from such tubes were significantly less than would be expected from a cold-cathode X-ray tube (often by a factor of 100 or more), the potential for student exposure does exist. The educational benefit derived from these devices is gained by visual observation of their operation. The effects of external magnetic or electric fields are often of interest and require access to the tube while operating. To meet these requirements, unshielded operation of these devices may be required. The recommendations for use of tubes in the category suspected of producing X-rays are based on these considerations and are as follows:

a. No student shall use this equipment without appropriate on-the-spot supervision by the teacher.

b. Tubes should always be operated at lowest current and voltage possible and time of operation kept to a minimum.

c. No experiment should result in an exposure greater than 10 mR to any student.

B. Recommendations to Distributors

1. The purchaser should be informed of NCRP Report #32 or provided a copy with each purchase.

2. The purchaser should be informed that equipment designed to produce X-rays may require registration with the appropriate State or local radiological health agency.

3. The appropriate radiological health agency should be notified of the sale of cold-cathode gas discharge X-ray tubes and other cold-cathode tubes that have been shown to produce X-rays.

C. Recommendations to State or Local Radiological Health Programs

1. The appropriate agency should register all devices designed for the production of X-rays.

2. Instruction and assistance in the recommended methods of use and operation of gas discharge tubes should be offered to teachers using this equipment. This instruction should include radiation protection principles aimed to eliminate or reduce radiation exposure to students.

3. The appropriate agency should assist science instructors in determining if older tubes, obtained prior to the development of the standard, and other devices that might create potential radiation hazards can be operated safely.

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U.L. X-RADIATION REQUIREMENTS FOR COLOR TV RECEIVERS

by

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I should like to begin my remarks this afternoon with the simple statement that the X-radiation requirements employed by Underwriters' Laboratories, Inc. in the safety evaluation of color television receivers submitted to us for test and listing are 100 per cent in agreement with the Federal Regulation which became effective January 15, 1970. I think you all realize that it would be extremely foolish, perhaps even illegal, for us to do otherwise.

In the few minutes available for this presentation, we do not have time to read the Regulation in entirety but the requirements pertinent to the emission of X-radiation from a television receiver can be briefly stated as follows:

1. X-radiation exposure rates shall not exceed 0.5 mR/hr at a distance of 5 cm from any point on the external surface of the receiver;

2. Measurements shall be made with an instrument, the radiation sensitive volume of which shall have a cross section parallel to the external surface of the receiver of an area of 10 sq cm and no dimension larger than 5 cm;

3. All measurements should be made with the receiver displaying a usable picture, with the power source adjusted to the maximum rated voltage of the receiver and with all user controls adjusted so as to produce maximum X-radiation emissions.

3A. After June 1, 1970 measurements shall be made with the receiver operated and adjusted in compliance with the above-named conditions and, in addition with all serviceman controls adjusted to combinations which result in the production of maximum X-radiation emissions;

3B. After June 1, 1971 measurements shall be made with the receiver operated and adjusted in compliance with the above-named conditions and, in addition, the receiver shall be set up to reproduce conditions identical to those which result from that component or circuit failure which maximizes X-radiation emissions.

The Federal Regulations also define in detail the "external surface of the receiver" and specify that the "maximum rated voltage" means 130 v RMS if the receiver is intended to operate from nominal 110-120 v RMS, power sources. The Regulations further specify that if the receiver is intended to operate from a power source having some voltage other than nominal 110-120 v RMS, "maximum rated voltage" means 110 per cent of the nominal RMS voltage rating specified for the receiver by the manufacturer.

The Federal Regulations also define "user controls" as those controls provided by the manufacturer for purposes of adjustment; which on a fully assembled receiver under normal usage are accessible to the user; "service controls" as those controls provided by the manufacturer for purposes of adjustment, which under normal usage are not accessible to the user; and "usable picture" as a picture in synchronism and transmitting viewable intelligence.

From the standpoint of testing procedures normally followed by the Laboratories, the Federal Regulations are quite complete and follow, almost identically in some cases, requirements made effective by Underwriters' Laboratories on October 27, 1969. Only two additional items appear in the UL requirements as necessary information for the testing of a receiver:

1. To eliminate variations in X-radiation measurements produced by actual television program material, the UL Standard specifies that the "usable picture" is obtained by injecting picture information into the receiver antenna terminals by means of a suitable signal generator provided with a stationary Indian head or equivalent test pattern. This arrangement provides a stable standard picture of program quality, available to all persons making X-radiation measurements and providing a standard basis for such measurements.

2. Until a thin window ionization chamber rate meter that is relatively energy independent and complies with the area specification contained in the UL Standard and the Federal Regulations is commercially available, the Laboratories is using the Victoreen Instrument Company Model 440RF Survey Meter or its equivalent. The Victoreen Model 440RF-C meter, with a smaller chamber, is now available and is also being used.

Probably the most important contribution which Underwriters' Laboratories is making to the X-radiation safety of color television receivers is the factory Follow-UP Inspection program carried out at factories producing UL-Listed television receivers. While no exact figures are available, we estimate that 95 percent of the receivers on today's market are UL-Listed and all major television receiver manufacturers subscribe to our Testing and Inspection Service.

The investigation of a receiver model starts with the testing of one or more samples, usually prototypes submitted before start of production. The testing includes measurement of X-radiation emission from these samples. When production starts, a UL engineer visits the plant to make sure that construction meets UL requirements and any improvements called for during the investigation of the prototype have been included in production. At that time, a special report describing those items which directly relate to the reduction of X-radiation emission to acceptable limits, is prepared for use by specially instructed, Follow-Up Service Inspectors in subsequent inspection checks. Once each month, these Inspectors call on all factories producing UL-Listed color television receivers and check on the performance and construction of the receivers with respect to X-radiation emission.

This inspection consists of making a review of the log of all X-radiation measurements made by the manufacturer on his products since the previous inspection, also the witnessing of an X-radiation measurement conducted for the Inspector by the manufacturer in accordance with the manufacturer's regular procedure, upon a sample receiver selected by the Inspector from the production line or from stock. If any log entries, or the measurements on the receiver being inspected, exceed the 0.5 mR/hr limit, a careful investigation is made to determine that the manufacturer has made the necessary corrections to reduce the X-radiation emission within the limits. The Laboratories has suggested to the manufacturers that they made measurements on at least one receiver per production line per day - for a large manufacturer with perhaps 10 or 12 lines, this might include as high as 250 measurements per month on production receivers.

Our Follow-Up Inspector fills out a special report and all reports are reviewed and tabulated by one person in the UL organization. The record indicates that during 1969, 33 factories where visited and a total of 298 inspections were made. As a result, X-radiation measurement records on several tens of thousands of color television receivers were reviewed. During these inspections, only 7 receivers were noted to exceed the 0.5 mR/hr limit and 5 of these were designs not UL-Listed. The maximum measurement noted was 1.6 mR/hr. The vast majority of the measurements made and noted were very low, within the range of 0-0.1 mR/hr.

In view of the severe Federal penalties which manufacturers face for the distribution of faulty television receivers which emit X-radiation in excess of the specified limit, most manufacturers are currently checking larger percentage of their production than has been mentioned. However, the bottleneck is instrumentation. The delay-time of the Victoreen instruments is relatively long, in the neighborhood of several seconds. This slowness of response, coupled with the 10 sq cm sensitive area requirement, results in a time interval of a good portion of an hour to completely and accurately scan the over-all surface of a large color television receiver. Of course, time can be saved by first scanning the receiver surface with a "wand-type" instrument like that developed by the National Center for Radiological Health, but the fact remains that no direct-reading instrument is currently available which can accurately survey all surfaces of a conventional receiver in a short time, perhaps 5 minutes. Such instrumentation is badly needed.

Underwriters' Laboratories is also giving consideration to a program of separately testing, for X-radiation emission, components which through poor design or construction could cause receivers in which they are used to emit excessive X-radiation. These components include high voltage regulator and high voltage rectifier tubes and picture tubes. The UL-Listing of such components could then lead to a UL requirement that a UL-Listed color television receiver must be so constructed that only UL-Listed components of known and certified characteristics could be employed. This program, however, is presently in only a preliminary discussion stage and its outcome is uncertain.

We believe that Underwriters' Laboratories, Inc. is effectively assisting this industry to meet the present public demand for safe color television receivers and we appreciate this opportunity to describe our operations to you.

RADIATION HAZARD ASSESSMENT OF PRIVATELY OWNED COLOUR TELEVISION RECEIVERS IN CANADA

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Introduction

Several public health agencies in the United States have studied the problem of radiation emission from color television sets. (1) (2) For example Becker (3) examined nearly 5,000 sets in Suffolk County, New York and found that 19.9 percent emitted radiation in excess of the acceptable level (0.5 mR/hr) recommended by the International Commission on Radiological Protection. This survey was widely reported in the press and caused considerable public concern. As a result the Canadian Department of National Health and Welfare decided to carry out a similar survey in Canada.

Method

In most of the U.S. surveys ionization chamber instruments were used. For the Canadian survey a photographic method was chosen. This choice made it feasible to conduct the survey over a wide area, because the test exposures could be carried out by the set owners themselves, using film packs sent to them by mail. The test method is simple and, since the exposure time can be varied at will, the method provides maximum sensitivity.

Sampling:- To obtain a sample which would provide maximum information on makes and models, the cooperation of the public was solicited. The response was good and about 2000 owners volunteered to have their sets tested. A questionnaire was sent to each respondant asking relevant data such as make, model, year of purchase and details of repairs and modifications. On the basis of the information received, 500 sets were then selected for examination. These were chosen on a statistical pattern to give approximately equal samples for each year-of-purchase. No attempt was made to obtain equal numbers of each different make but most models available in Canada were included.

Exposures:- Since the highest radiation levels are normally encountered close to the voltage regulator and rectifier tubes, a few suitably located films were considered sufficient for the purposes of the survey. The participant was asked to attach four 10'' x 12'' radiographic films to the outer surface of the cabinet at specified locations chosen to be as close as possible to the tubes in question. It was not considered necessary to monitor the face of the set because the glass safety plate of the picture tube normally provides effective shielding. Thus the testing procedure did not interfere with normal viewing.

A minimum film exposure time of 20 hours was chosen, based on the recommended maximum permissible emission rate and the sensitivity of the film. The owner was requested to return the films after this viewing time or, if exceeded, to report the actual time.

Processing:- The film-packs used in the survey were Kodak Royal Blue ready-pack medical X-ray films. Variations in receiver operating voltage introduce complications in calibrations, because the response of X-ray film is highly dependent on radiation quality. However, Davies and Robart (4) had found that if the above film is calibrated with an average voltage setting of 27 kv, the errors introduced by variation of voltage within a range of from 21 to 33 kv with various filtrations was not greater than 20 percent (see Fig. 1)

The exposed films were processed under standard conditions along with calibration films. Films with no detectable exposure were reported as being less than 0.1 mR/hr. The gross optical densities of films registering measurable exposures were determined using a MacBeth Ansco densitometer, model 12 with a 3 mm. diameter aperature. After correcting for background fog, the optical densities were determined from the calibration curve shown in Fig. 1.

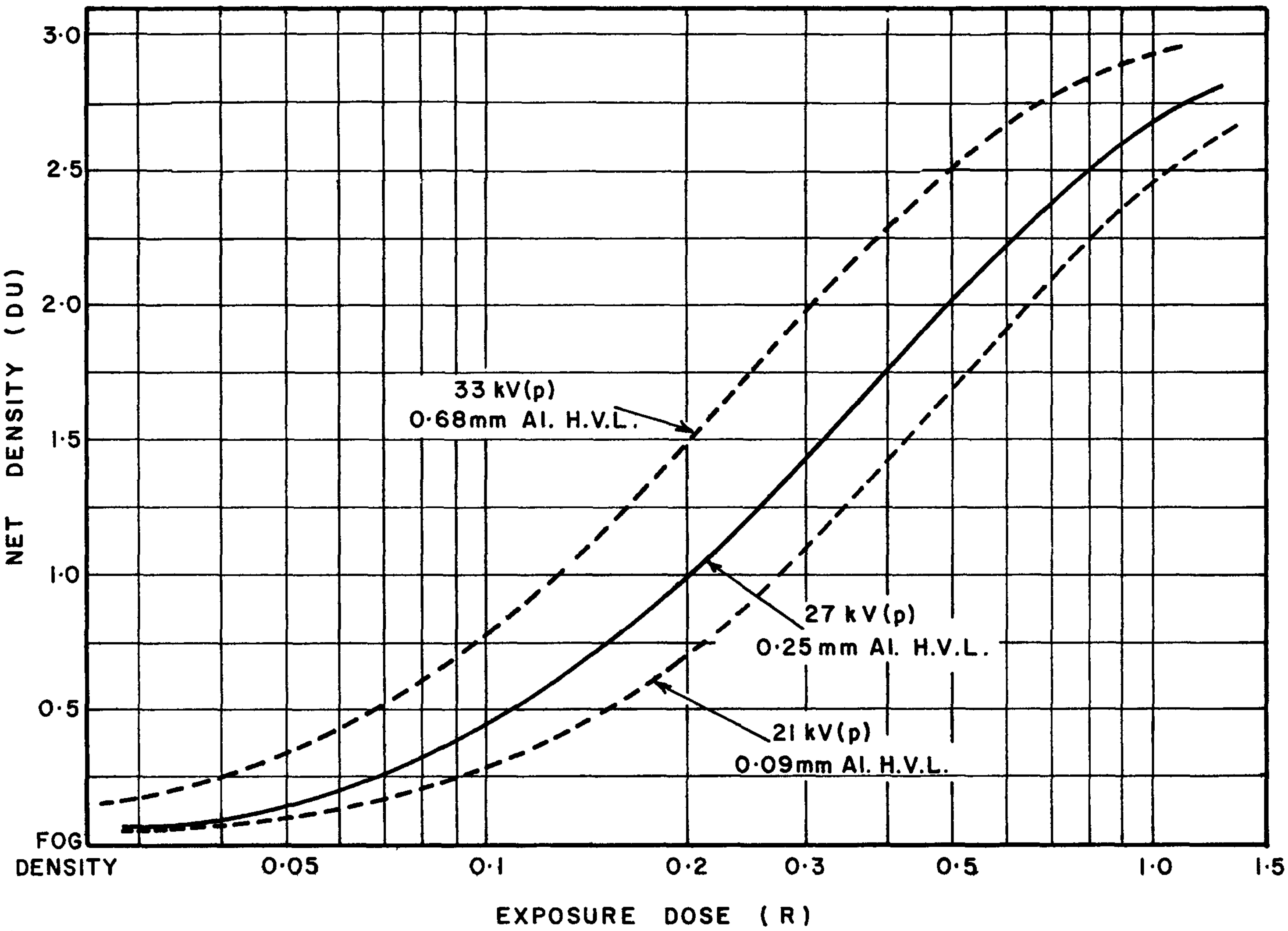


Figure 1. Average calibration curve of R B x-ray film for color television surveys.

Results and Discussion

Of the 459 sets of film returned by owners, 128 or 28 percent showed detectable darkening due to exposure to X-rays. The X-ray dose-rates from TV sets categorized by year of purchase are given in Table I. The percentage of sets with emission rates greater than 0.5 mR/hr (averaged over 10 cm^2) has declined in successive years since 1966. This is brought out clearly in Figure 2. The general level of the dose-rates also tends to be lower in the newer models. The breakdown for sets by manufacturer is given in Table II, but because the number sampled was small, the relative frequency of excessive emission among particular makes is not statistically significant.

It will be seen from Table III that the most common location for maximum radiation emission was at the bottom; an appreciable number of sets showed high levels at the rear but only a few on the sides. In Fig. 3, typical examples of exposed film are shown. In most cases where radiation levels were higher than the accepted standard, the areas of blackening on the film were considerably larger than 10 cm^2 and were observed on more than one of the four films.

An attempt was made to determine if there was a correlation between the occurrence of high emission rates with reported repairs to the set, but no evidence for such a correlation was noted.

Summary and Conclusions

The results of this survey were generally in conformity with those obtained in the U.S. studies. Overall, about 11 percent of the sets emitted above the accepted standard. The number of sets tested was too small to permit any conclusions as to correlation with particular makes and models, or the effect of maintenance operations, line voltages and other factors which are thought to play a part in the problem. It is clear, however, that emission rates are greatest in the older sets, later models showing a very marked improvement.

TABLE 1

X-Radiation Emission Levels Distributed by Age Groups

Year (Purchased)	Total Sets Tested To Date	X-Radiation Exposure Levels					
		Not Detectable <0.1 mR/hr		Detectable ≥0.1-0.5 mR/hr		Significant >0.5 mR/hr	
		No. of Sets	Percentage*	No. of Sets	Percentage*	No. of Sets	Percentage*
1966 and older	113	66	59%	26	23%	21	19%
1967	114	81	71%	20	18%	13	11%
1968	118	88	75%	19	16%	11	9%
1969	114	96	84%	14	12%	4	4%
Totals	459	331	72%	79	17%	49	11%

* Refers to percentage based on the sets "returned" in each "group".

Note: The above indicates that based on the returns to date (96% of total being tested) the average percentage of sets with X-radiation in excess of 0.5 mR/hr is 11%. The highest is in 1966 and the lowest in 1969 (4%).

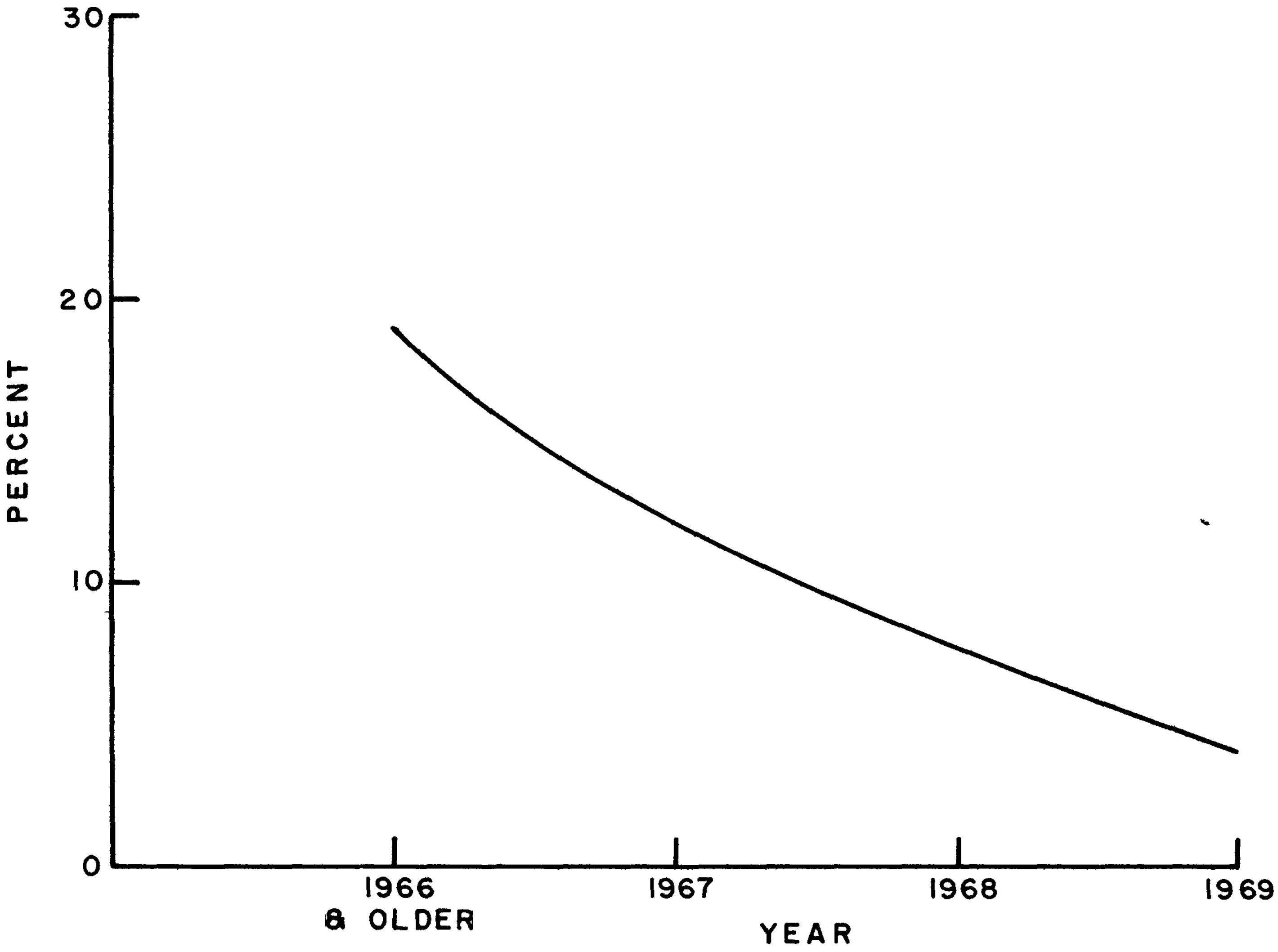


Figure 2. Curve representing percentage of sets emitting radiation in excess of 0.5 mR/hr.

TABLE 2

X-Radiation Emission from Color Television Receivers Distributed by Manufacturers and/or Brand Names (all models)

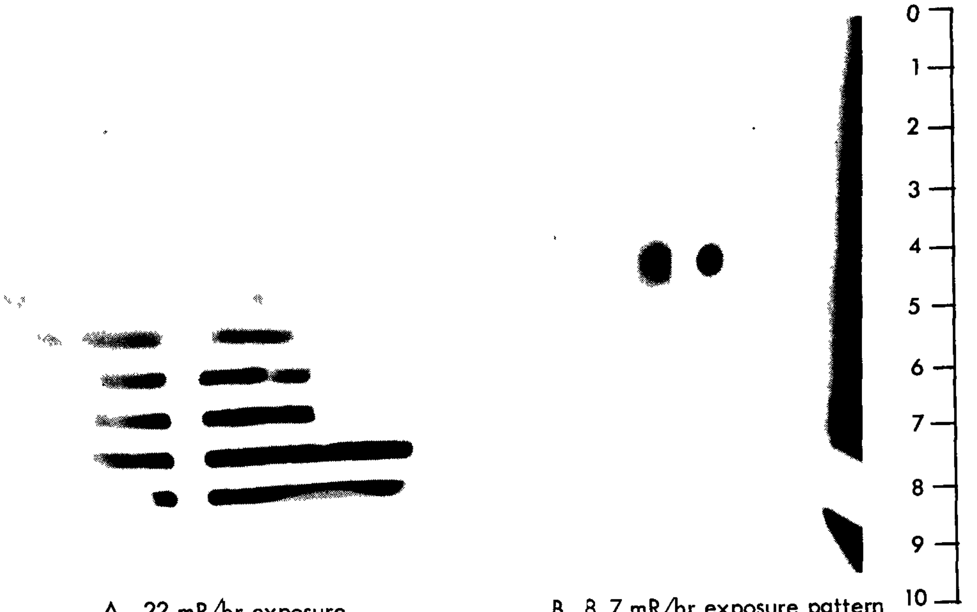
Make	Number Tested	X-Radiation Exposure Levels <0.1 mR/hr Zero	 ≥0.1-0.5 mR/hr Detectable	 >0.5 mR/hr Significant	Percentage of Sets Over ICRP Recommendation (>0.5 mR/hr)
A	63	46	11	6	10%
B	12	10	1	1	8%
C	7	5	1	1	14%
D	5	4	1	0	0
E	42	23	12	7	17%
F	8	6	1	1	12%
G	41	30	7	4	10%
H	10	9	1	0	0
I	31	28	3	0	0
J	25	25	0	0	0
K	72	51	13	8	11%
L	21	15	6	0	0
M	28	15	10	3	10%
N	13	12	1	0	0
O	9	5	3	1	11%
P	72	39	16	17	23%
Totals	459	323	87	49	11%

TABLE 3

Location of Maximum Radiation Dose-Rate
Distributed by Age Groups

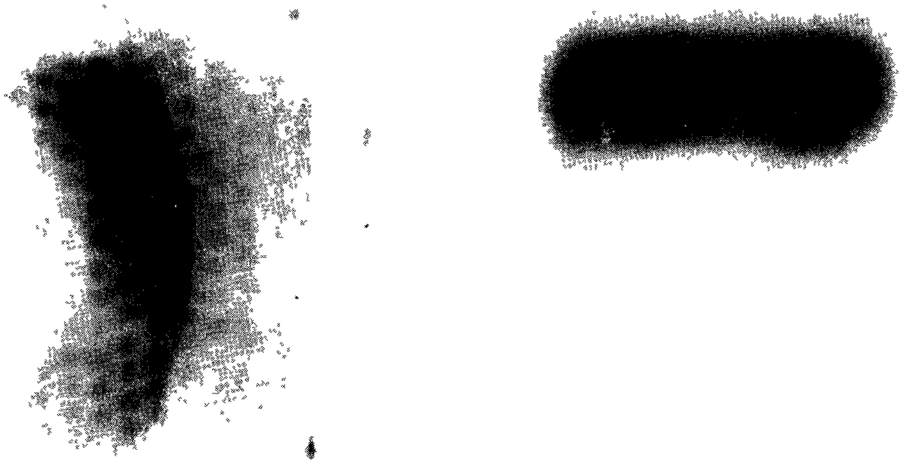
Year (purchased)	Bottom	Rear	Right*	Left*	Total
1966 and older	8	8	2	3	21
1967	7	3	1	2	13
1968	2	5	0	4	11
1969	3	0	0	1	4
Total	20	16	3	10	49

* Left and right as viewed from the rear of the set.



A. 22 mR/hr exposure from bottom of set

B. 8.7 mR/hr exposure pattern from rear of set



C. 2.3 mR/hr exposure pattern from rear of set

D. 5.5 mR/hr exposure pattern from side of set

Figure 3. Photographs of radiographic films exposed to x radiation from color television receiver.

Following the survey the Department of National Health and Welfare published a news release reporting the results and suggesting ''Rules for Color TV Viewers''. These rules cautioned against do-it-yourself maintenance, and suggested that the service man be asked to check voltage settings and shielding on his next visit. They also advised viewers to cultivate good viewing habits -- not to sit too close to the picture tube, not to let children sit with their legs stretched out under the set and not to locate chairs in close proximity to the side or back of the set. In the opinion of the Department observance of these rules would provide adequate assurance of safe viewing.

Acknowledgements

The authors are grateful to Dr. A.H. Booth, Chief, Radiation Protection Division for his interest and encouragement in carrying out this survey. They are thankful to Mr. R. Khandkar for his assistance in statistical selection of sets, and to Dr. D.J. Hurley, Chief Radiologist, Riverside Hospital for allowing the use of his automatic film processing facilities.

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SESSION III. LASER RADIATION, INVITED PAPERS

Chairman: C. F. Tedford

Characteristics of Lasers
R. J. Rockwell, Jr.

Laser Instrumentation and Dosimetry
R. C. Honey

Biological Effects of Laser Energy on the Eye
W. T. Ham, Jr.

Laser Hazard Control Procedures
G. M. Wilkening

CHARACTERISTICS OF LASERS

R. James Rockwell, Jr.
Laser Laboratories, Medical Center, University of Cincinnati

The list of known substances which can generate laser- (Light Amplification by Stimulated Emission of Radiation) type emission has experienced a rather impressive growth. Since the announcement in 1960 of the first laser device by Maiman,[1] well over 150 different laser systems have been reported.[2] Of these, however, only about a dozen are now available commercially. Reference to the Table will disclose that these available laser devices generate not only a wide variation of output power levels but also a broad range of spectral characteristics. There are, nonetheless, features in the properties of the radiation produced by all laser devices which make them distinctive among all other sources of optical radiation. Never before has a source of electromagnetic radiation been available which can produce such a powerful emission of such a high degree of temporal and spatial coherence. The many unique applications of the laser beam which are now being considered in the fields of communications, metal-working, photography, medicine, chemistry, data processing, etc., are possible not because laser radiation is some new form of energy -- but because there was never previously available a light beam which simultaneously displayed all the unique characteristics produced by a laser. This discussion will be a synopsis of those important features of laser devices and the radiation they emit which have made these applications possible.

Characteristics of Laser Systems

A. Fundamental Aspects of Laser Devices. The list of substances which can produce laser emission is comprised of an impressive number of different solids, liquids, gases, and junction diodes. There are, however, several features (Figure 1) which are common to the configuration of all types of lasers, namely:

1. The Laser Media. -- This is the substance, either solid, liquid, gas, or junction between two dissimilar metals, which is capable (because of its atomic and/or molecular makeup) of sustaining stimulated emission.

TYPICAL LASER CHARACTERISTICS

Laser Media	Predominant Wavelengths (nanometers)	Active Media	Common Method of Operation	Continuous Power (w)	Peak Power (megawatts)	Beam Divergence (milliradians)
Ruby	694.3	Solid	Pulsed	1.0	1-1000	0.5-20
Neodymium-glass	1,060	Solid	Pulsed		1-500	0.5-20
Neodymium-YAG	1,060	Solid	CW	1-100	1-10	0.5-10
Helium-neon	632.8 1,150 3,390	Gas	CW	0.001-0.100		0.1-1.0
Argon ion	476.5 488.0 514.5	Gas	CW	1-20	10^{-4}	1.0-3.0
Krypton ion	647.1 568.2 520.8 476.2	Gas	CW	0.5-2.0		1.0-3.0
Helium-Cadmium	325.0 441.6	Metal Vapor	CW	0.015 0.05		0.5
Neon ion	332.4	Gas	CW	0.250		1.0-3.0
Neon-pulsed E field	504.1	Gas	Quasi-CW	.003	10^{-2}	Rectangular beam 2 x 30
Carbon-dioxide	10,600	Gas	CW	10-5000	10^{-2}	1.0-5.0
Nitrogen-pulsed E field	337.1	Gas	Quasi-CW	0.100	$10^{-2}-10^{-1}$	Rectangular beam 2 x 30
Gallium-arsenide	840.0	Semiconductor	Quasi-CW	1-20		Rectangular beam 1-10

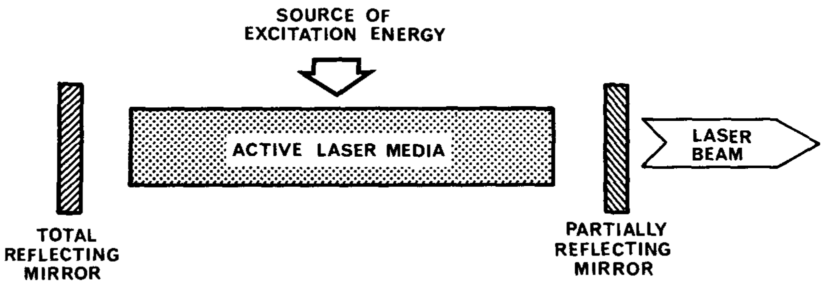


Figure 1. Fundamental laser configuration.

2. The Source of Excitation Energy. -- In order to generate a laser beam a redistribution is required in the number of atoms which normally exist in certain atomic energy levels of the laser media. This requires an external source of excitation energy often called the "pump" energy.

3. A Fabry-Pèrot Interferometer. -- This device is a pair of mirrors which are aligned plane-parallel to one another. In the case of the laser, one mirror is placed at each end of the laser media. Usually one mirror is a total reflector, the other a partial reflector (ie, it allows part of the laser beam which is generated within the active media to pass outside the interferometer).

In the most general manner, the following describes how a laser operates: Excitation energy is vigorously supplied to the active media to produce the specific condition called a population inversion. In this condition, more atoms of the laser media are in a specific excited-state energy level than in the lowest "ground-state" level. This condition is contrary to the normal population of states of a system in thermal equilibrium. One manner for an atom in an excited state to release excess energy is by the spontaneous emission of light in discrete units called photons. The unique feature of a laser device lies in the fact that because of the population inversion the energy release may be accomplished by the process known as stimulated emission. In this case a photon released by one excited atom will cause (stimulate) an excited atom it may encounter in its path also to release a photon of excess energy. The result of this interaction is the combination of two photons with identical coherence properties (phase relationships) so that they add completely together to produce a beam of twice the intensity. As the beam progresses through the excited laser media, its amplitude will be rapidly increased while its coherence properties remain unaltered. Upon reaching the total reflection mirror the beam direction is completely reversed, thus allowing another pass through the excited laser media so that the beam may be further amplified. Upon reaching the partial reflecting mirror, a portion of the beam escapes. This escaping portion is the active emission from the laser. The process will continue for as long as sufficient pump energy is supplied to the laser media.

The following sections will review the most important laser devices in use today. Special emphasis will be placed upon the variations possible in the outputs which these devices may produce.

B. Pulsed Laser Devices. Lasers which use a solid-state media are generally operated in a pulsed mode. The most common solids used are ruby crystals and neodymium-doped glass and neodymium-doped crystals such as Yttrium Aluminum Garnet (YAG). In the present state of the art, the pulse envelope is generated in one of the following manners:

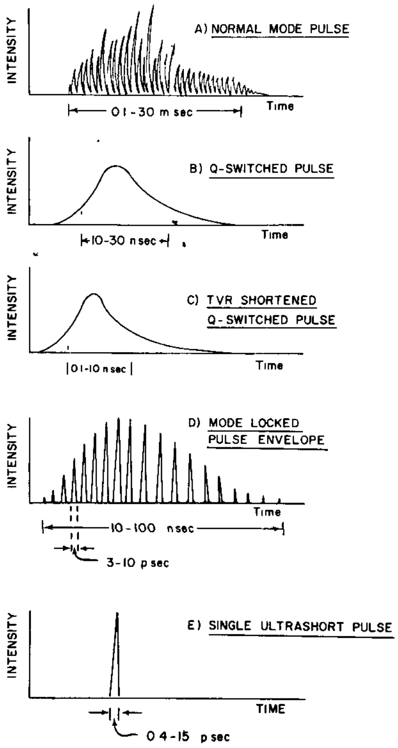


Figure 2. Types of pulsed laser emissions.

1. A millisecond or multi-millisecond pulse envelope comprised of many random pulse spikes of sub-microsecond duration.

2. A single multi-nanosecond high power pulse.

3. A single nanosecond or sub-nanosecond high power pulse.

4. A train of evenly spaced ultrashort, sub-nanosecond pulses.

5. A single ultrashort, picosecond pulse.

The distinction of the type of pulses becomes exceedingly important in the evaluation of the interaction phenomenon of pulsed laser radiation, where the rate of energy delivery is the critical factor. The following will review the most common variations in pulse characteristics produced by commercially available laser systems:

a. Normal Mode Operation. -- The pulse envelope from a long-pulse or so called "normal mode" solid-state laser will appear, when viewed photoelectrically, as a series of random "spikes." Although this sporadic spiking behavior is not completely understood, it is believed to be a consequence of interaction which occurs between the excited ions in the active laser media and regions of strong electromagnetic fields of the laser beam inside the media. This produces a sporadic de-population of the excited ions, which are observed as random pulsations during the laser burst. Each spike has a duration of 300 to 400 nanoseconds and the average spacing between spikes is in the order of a few microseconds, as shown in Figure 3. Recent reports[3] have shown that each spike may consist of a large number of even shorter pulses which may last from three to ten picoseconds (10^{-12} seconds).

Ruby or neodymium laser-systems derive the excitation energy from xenon arc flashlamps that are usually placed in a highly reflecting housing so as to actually focus the lamp emission onto the laser rod. The pulse of the normal mode laser output is, in the first approximation, about equal to the length of time that the xenon flashlamp is excited; providing, of course, that the emission from the lamp is sufficient to sustain a population inversion in the laser media. The duration of the current pulse in the lamp is determined by the time-constant of the inductance-capacitance (LC) network which drives the flashlamp circuit.

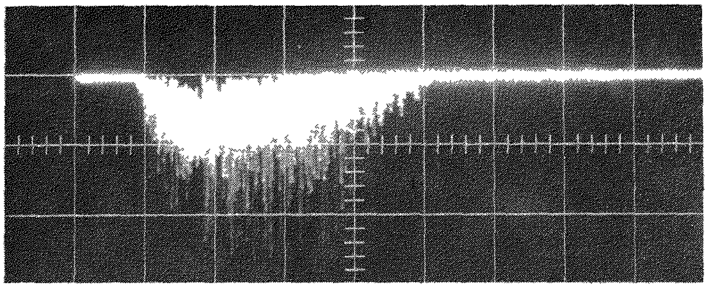


Figure 3. Characteristic spiking behavior of pulsed solid-state laser. Total pulse duration approximately 1.8 msec.

There are methods to stretch the pulse-length in normal mode operation. The most common is to use additional inductance-capacitance sections which will serve to increase the pulse-length monotomically; with this technique, normal mode laser pulses have been stretched to 30 msec for some laser welding applications (fig. 4).

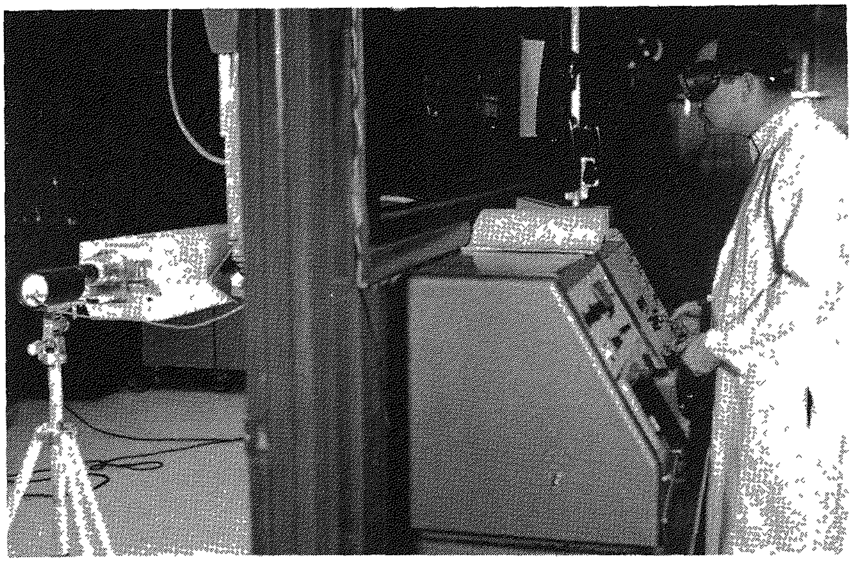


Figure 4. Normal mode pulsed Ruby Laser. Photo shows system during calibration procedure. Laser used for medical treatments at author's laboratory.

b. Q-Switched Operations. -- Pulsed laser operation is also possible in a second mode of operation. In 1961 McClung and Hellwarth[4] announced the technique known as "Q-Switching." The term "Q" is a carry over from the radio wave and microwave terminology, and it relates to the so called "quality factor" of a resonating system. A "low Q" would refer to a system that would not easily support oscillation; thus to switch (or spoil) from a low to a high Q (viz, Q-Switching) means to change rapidly from a condition in which the laser cannot lase to a condition in which it will. The mechanics of Q-spoiling usually incorporate some form of electro-optical or electromechanical shutter between the mirrors of the laser cavity.[5] Recent reports, however, indicate that Q-Switching can be accomplished also by a simple misalignment of the Fabry-Pérot mirrors.[6] The effect of Q-spoiling is to force the laser to operate in a condition of maximum gain. This occurs because the overpopulation in the metastable state will be larger than in the case of normal mode laser action due to the fact that no stimulated de-population can occur in the low Q cavity. When the "switch is thrown," so to speak, de-population by stimulated emission will rapidly occur, causing the emission of an intense giant pulse, or train of two or three pulses, each lasting from ten to 50 nanoseconds. The result of such short bursts of light is the production of enormous peak-power outputs. With this method it is possible to produce instantaneous light levels exceeding 100 million watts in a single burst of light.

Because of the desire for even high peak powers, the damage threshold was soon reached for most solid state laser materials and investigations immediately began on amplifier devices into which a Q-Switched laser pulse could be passed so as to experience still further amplification without damage to the system. (Figure 5) This oscillator-amplifier concept[7] is one in which a Q-Switched pulse from the first laser (the oscillator) is passed into a second (larger diameter) laser system (the amplifier). Consequently, the amplifier section will receive signals substantially below the damage levels of the active laser media. With single amplifier system, peak pulse powers up to 500 megawatts are easily achieved using ruby and neodymium-glass lasers. Systems are now available which employ three or four amplifiers, and produce hundreds of gigawatts (10^9) per pulse.

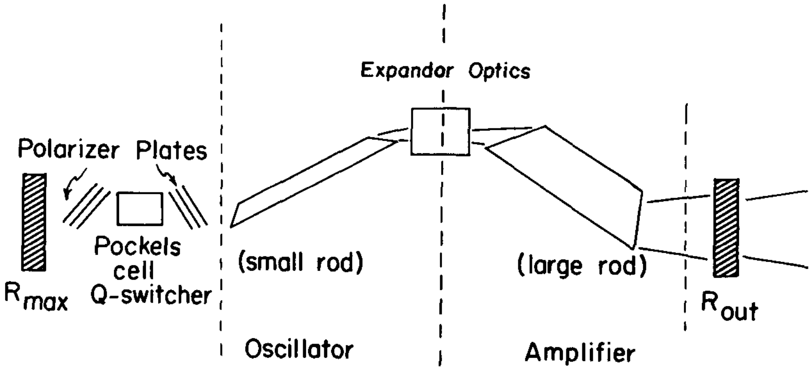


Figure 5. Basic oscillator — amplifier system.

c. Time Variable Reflectivity. -- The concept of controlling Q-Switched laser outputs with a time-variable reflectivity (TVR) was first introduced by Vuylsteke[8] in 1963 with his pulse-transmission-mode (PTM) Q-Switched laser. In this device, the Fabry-Pérot mirrors were both initially 100% reflective then, at the proper time, one mirror is changed to maximum transmission to allow the laser pulse circulating in the cavity to escape. This basic concept has been used in both neodymium[9] and ruby[10] lasers to generate giant pulses in a range from 1.0 to 10 nanoseconds. (Figure 2C)

The technique of TVR is accomplished with the Kerr electro-optic effect. This phenomena is observed in both liquids (nitrobenzene) and solids (potassium dihydrogen phosphate: KDP) which are placed in a large electric field. Under these condition, the material is changed into a double refracting media. Consequently, a linearly polarized light wave passing through the media will be changed into a circular, elliptical, or orthagonally linearly polarized beam depending upon the degree of retardation imposed.

The Kerr effect device most commonly used with pulsed lasers is called a Pockel's Cell; and usually employ the crystal KDP as the media. In this case, application of a large electric field (in the direction of propagation) will change a lineraly polarized laser beam into a circular polarization. Upon reflection from a 100% reflector the sense of circular polarization is reversed, thus, when the beam re-enters the Pockel's Cell it is changed back into a linear polarization, but the direction of the electric field vector will be orthagonal to the original beam polarization. Consequently, insertion of a polarization sensitive prism inside the resonant cavity of the laser (vis: a calcite prism or Glan-Thompson prism) will allow the laser pulse to be reflected out of the cavity from the side. (Figure 6)

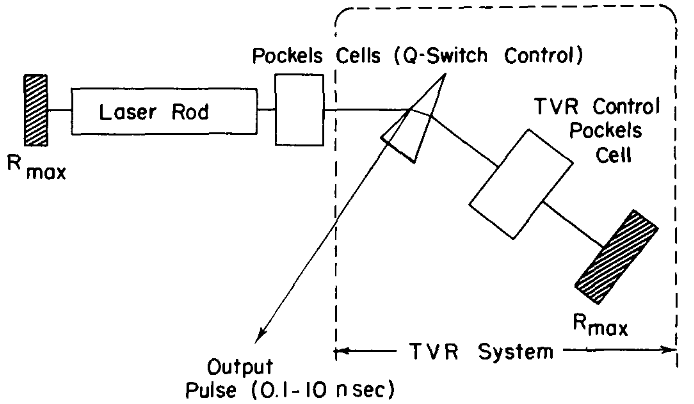


Figure 6. Basic time variable reflectivity laser system.

The principal advantage of TVR switching is that the energy of the output pulse is independent of the cavity gain characteristics and the duration of the output pulse is solely dependent on the separation between the resonator mirrors. The laser pulse length is equivalent to the time for the pulse to make a round trip circuit in the cavity. Consequently, laser pulses which last only 2 to 5 nanoseconds are easily generated (without loss of pulse energy) from standard Q-Switched ruby lasers which would normally produce pulses which are 10 nanoseconds or longer. In this manner, the peak power of the pulse is increased by at least a factor of five over standard Q-Switched systems.

d. Mode-Locked Laser Systems. -- A laser device is a resonant oscillator of electromagnetic waves. Consequently, it can support standing wave patterns in a manner somewhat analogous to the resonance of an organ pipe. The laser "standing waves" are produced when an integral number of half-wavelengths exactly fit into the separation between the mirrors of the Fabry-Pérot cavity. In all lasers this spacing is many, many orders of magnitude larger than one laser wavelength, thus, there are many slightly different standing wave frequencies which can fit within the narrow linewidth of a laser source. This gives rise to many distinct spectral components or longitudinal "cavity modes" each with individual amplitude, frequency, and phase characteristics. In the event that the phases of these different frequency modes are synchronized in some manner (e.g.: the phases of the different longitudinal modes become "locked together") the different modes will then interfere with one another to generate a beat effect. The result will be a laser output which is observed as regularly spaced, periodic intensity pulsations.[11] (See Figure 2D)

Mode locking is usually accomplished by inserting an ultrafast intensity dependent "switch," such as a bleachable dye, inside the resonant laser cavity (ie: between the mirrors). The overall system operation may be explained as follows: The active laser media serves as a light amplifier, the resonance of the Fabry-Pérot Etalon and the natural line width of the laser act as a selective frequency filter. The time for the laser beam to travel the cavity length twice will serve as an optical delay line. The bleachable dye is sometimes referred to as the "expandor element," meaning that it serves as a non-linear absorber, since it provides less loss for a high intensity signal than a low level signal.

Thus, a pulse circulating intra-cavity will be amplified only if it has sufficient intensity to cause the dye to momentarily bleach to transparency. The dye also serves to produce optimum mode coupling, provided its relaxation time is shorter than the time for a pulse to make round trip in the cavity. Since many of these dyes may be "switched" in less than 10^{-13} seconds, it becomes theoretically possible to produce individual laser pulses in this time range. The individual pulses which are contained in the pulse train of a mode locked laser are "ultrashort" picosecond (10^{-12} seconds) pulses. The separation between successive pulses is that of a round trip of the beam between the Fabry-Pérot mirrors.

e. Ultrashort Pulses. -- In 1967, Bell Telephone Laboratory scientists Duguay, Shapiro, and Rentzepis[12] discovered that pico-second duration pulses may actually be present in the output from many standard solid-state Q-Switched lasers. Because these pulses are of such a brief duration, it is almost impossible (prior to the unique measurement techniques such as they devised) to individually observe these pulses; although it was suspected that they did exist. Since most solid-state lasers do have a definite width to the spectral line (or, in other terms, many cavity modes) it is possible by mode-locking techniques to generate very short duration intensity pulsations. The broader the spectral width of the laser line, the more harmonic components that will occur in the interference phenomena, and thus, the shorter will be the duration of the beats which occur. As a result, the amplitude or the peak power will increase as the width of the pulse decreases. The neodymium-glass laser is of particular interest in the generation of mode locked pulses because of its quite broad (100-200 Å) bandwidth. This would theoretically allow for the generation of subpicosecond high peak power laser pulses.

Special techniques can be used to isolate an individual ultrashort pulse. The importance of such pulse widths lies in the peak power of the pulse. For example, using a neodymium-glass oscillator-amplifier laser system, peak powers of 30-40 gigawatts (10^9W) in a pulse width of 10-15 psec. have been observed. (See Figure 2E)

Scientists at the United Aircraft Research Laboratories, recently observed an ultrashort laser pulse of only 0.4 picosecond duration.[13] A neodymium-glass laser was used which was simultaneously mode locked and Q-Switched by a saturable absorber. Although it had been known for some time that the theoretical limit of the pulse width from a neodymium mode locked laser would be in the order of about one third of a picosecond, pulse widths previously observed were usually in the order of 4 to 10 picoseconds. This discrepancy between measured and the theoretical pulse length suggested the existence of an amplitude or carrier wave modulation in the pulses themselves. The experiments confirmed this fact and showed that most of the measured spectral content of the pulse was due to an almost linear relation between the frequency of the carrier wave and the laser wavelength. The modulation was about one per cent larger at the beginning of the pulse than at the end. As a result, the pulses could be compressed to a length approaching the reciprocal of the bandwidth by passing them through a dispersing system which also had a linear relation between time and wavelength. In this manner, ultrashort pulses were compressed into a range of 0.4×10^{-12} seconds, near the theoretical limit.

Thus, it is seen that there is an enormous variation in pulse durations generated from the many available laser systems. The spread in time of the overall pulse envelope from the normal mode pulse (See Figure 2A) to the single ultrashort pulse (See Figure 2E)may be as great as 10^{10}. The specification of such pulse characteristics is extremely important, especially in any critical evaluation of the inter-action phenomenon of laser energy.

f. Wavelength Variation with Pulsed Lasers. -- The advent of Q-Switched laser systems with their associated enormous electromagnetic fields, also introduced the more common use of frequency shifting with two non-linear techniques; namely, second harmonic generation[14] (SHG) and Stimulated Raman Scattering[15]. The non-linear polarization field induced in non-centrosymmetric crystals such as quartz, potassium Dihydrogen Phosphate (KDP), and Barium Sodium Niobate can actually generate harmonic components of the fundamental laser frequency. In this manner, high power pulses in the ultraviolet spectrum may be produced: 347 nM with the ruby laser and 265 nM using two frequency doubling crystals and a Q-Switched neodymium laser.

Commercial systems are also available which employ Stimulated Raman Scattering to produce additional wavelengths. In one such system, (Geoscience Instruments) produces three Stokes (longer wavelength) and four Anti-Stokes (shorter wavelength) shifts. Using the ruby laser as the source, the available wavelengths are 432 nM, 492 nM, 577 nM, 694 nM, 871 nM, 1167 nM, 1768 nM, and 365 nM. It is evident that by combining both SHG and Raman shifting techniques together, one may achieve laser frequencies in almost any desired region of the spectrum with a single laser source.

C. Continuous and Quasi-Continuous Wave Laser. Simulated emission is possible when the necessary condition of population inversion is met in the active media. Although there are, in general, many competive processes which may limit continuous laser operation (eg, heating of the media, "self-quenching" effects, etc.), it is often possible to achieve continuous or high repetition-rate operation with mnay materials that have heretofore been considered as only "pulsed" laser media. The limiting factors are (1) the low efficiency of converting pump energy into laser emission, (2) retention of heat by the laser media, and (3) degradation of the components used for continuous optical "pumping." This does not mean, however, that the same levels of power as achieved instantaneously in the pulsed operation will be achieved in CW operation. The rapid de-population and subsequent high power achieved, for example, in a normal mode ruby laser will produce instantaneous power levels in the multikilowatt range, whereas the quasi-continuous (60 pulse per second (pps) operation of a ruby crystal will only reach a few watts -- even in the most ideal system.

The most successful medias for pure continuous wave operation have been gases (or gaseous mixtures) and the many diode lasers. The media for quasi-continuous lasers include most of the solids common in pulsed operation as well as many gases.

The first CW system was the helium-neon gas mixture.[16] Although its first successful operation was at an infrared wavelength of 1150 nM, the helium-neon (He-Ne) laser is most well known operating at the red (632.8 nanometers) transition. The earlier He-Ne lasers were excited by radio frequency (RF) discharge. In this case, the He atoms were excited from the ground state by the RF field. This energy excess is coupled to an unexcited neon atom by a collisional process with the net result of an inversion in the neon atom population, thus allowing laser action to begin. The more recent He-Ne gas laser designs have used direct current excitation. Power levels available from the low efficiency He-Ne laser ranges from a fraction of a milliwatt to about 75 milliwatts in the largest available systems. The He-Ne laser is noted for its high-frequency stability and single-mode operation.

The family of ion lasers (argon, krypton, xenon, and neon) provides a source for over 35 different laser frequencies, ranging from the near ultraviolet (neon at 332.4 nm) to the near-infrared (krypton at 799.3 nm).[17, 18] It is possible to mix the gases, for example, argon and krypton in which lasing may occur simultaneously at ten different wavelengths, ranging from the violet through the red spectral region. Such an output is truly a "white light" laser. Reference to the Table will review the most important wavelengths available from the family of ion lasers.

There are many other gases which can generate laser emission. The carbon dioxide laser is the most efficient, and consequently the most powerful of all CW laser devices. Continuous powers have been reported above 1,000 w at the infrared 10,600 nm wavelength.[19] Nitrogen gas may be operated in a rapid-pulse or quasi-continuous manner. The beam is emitted in a continuous train of 8-10 nanosecond pulses of kilowatt power levels at pulse repetition rates of 100 pps, producing a maximum average power level of about 100 mw at the ultraviolet 337.1 nm wavelength.[20] Neon gas, operated with same transverse field method, produces green pulses of 3-5 nsec. duration for an average power of 3 mW at 100 pps.

Recent development of a metal vapor laser has been sucessful using Helium and Cadmium, which is placed into vapor distribution by a cataphoresis technique.[21] This laser produces emission at either a dark blue (441.6 nm) or an ultraviolet (325 nm) wavelength at maximum powers of 50 mW and 15 mW, respectively.

One of the most promising laser sources of the day uses a neodymium-doped crystal yttrium-aluminum-garnet (commonly called YAG).[22] This device is optically pumped either by special tungsten or krypton flash lamps and is capable of CW outputs approaching 50 w at the 1,060 nm wavelength. The recent emergence to popularity of the YAG laser has been made possible by better growth techniques of the YAG crystals. Sufficient crystal lengths can now be obtained to provide for high CW power levels.

Most of the diode lasers are also operated on a continuous wave basis. The most common diode device uses a gallium-arsenide junction which emits a fan shaped infrared beam at 840 nm.[23]

Normal mode and Q-Switched solid-state lasers are often designed for a high repetition-rate operation. Usually the specific parameters of operation are dictated by the application. For example, normal mode ruby lasers operating 1 pps at 150 joules per pulse are used in high-speed dynamic balancing metal removal applications. As the repetition rate increases, the allowable exit energy per pulse necessarily decreases. Systems are in operation, for example, which produce ten joules per pulse at a repetition rate of 4 pps. A similar ruby, operated in the Q-Switched mode, could produce a one megawatt per pulse at a rate up to ten pulses per minute.

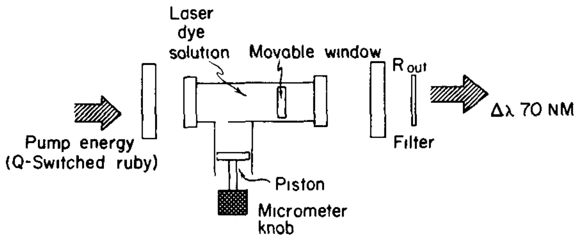
a. Frequency Expansion Using Non-Linear Techniques. Methods of converting high power CW outputs into new frequencies with harmonic generation techniques have also been most successful. Probably the most significant development has been the high power continuous frequency doubling from the neodymium-YAG laser, using the crystal: Barium Sodium Niobate ($Ba_2NaNb_5O_{15}$), commonly referred to as the "Banana Crystal." Continuous powers of 1 watt at the green frequency doubled wavelength of 530 nM have been obtained using an intracavity doubling crystal.[24]

A further expansion of output frequencies is available if the output of the CW frequency doubled YAG-Nd laser is directed into a parametric oscillator. This device also uses "Banana Crystals" which, when temperature-controlled in a range from 97 to 103° C, will allow a tunable output in a range from 980 to 1160 nM. Using 300 mW of 530 nM input power, such a parametric oscillator can produce up to 3 mW at selected wavelengths in the range from 980 nM to 1160 nM. Smith and Geusic of Bell Telephone Laboratories indicate[25] that proper choice of oscillator mirror reflectances in a parametric oscillator, could allow the tunable range to cover a range from 650 to 4000 nM.

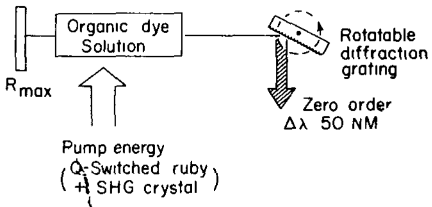
b. Emergence of Tunable, Liquid and Diode Lasers. The first multi-wavelength liquid laser was introduced in 1966 by Sorokin, and his associates at IBM.[26] The device, using three different organic dyes, was capable of producing red, green, and yellow laser emission. The key development in this system was the excitation by an ultrafast pulse of incoherent "pumping" light. Previous liquid laser systems required excitation using very short laser pulses. Sorokin's studies had shown that lasing of organic dyes required a very fast optical pumping pulse (300 nsec. rise). Consequently, a special flashlamp system was used which delivered pulses of 400 nsec. duration at repetition rates of 1 pps. Power outputs in his early system were 1 MW/pulse with 0.2 joules/pulse.

Sorokin's early data had shown that the principal central wavelength of organic dye lasers is a function of the dye concentration. This was quantitatively shown by Schaefer, Schmidt, and Voltze[27] using a 5 MW 10 nsec. Q-Switched ruby laser to optically pump a DTTC - Bromide dye solution. Variation in concentration from 10^{-5} to 10^{-3} mol/liter produced a change from 805 to 865 nM in the principal laser wavelength. The output was also found to be dependent upon the cavity "Q"; with shorter wavelengths characteristic of a low "Q" cavity.

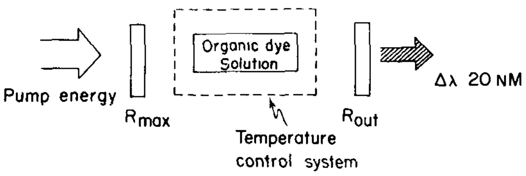
Several techniques have recently been demonstrated which provide a unique "tunable" control of the dye laser output frequency. (Figure 7) One such system is the movable piston concept devised by Kagan[28] (IBM). Movement of the piston actually changes the length of the lasing media, and, since the emission from a nonuniformly pumped dye laser is also dependent upon path length, a lower frequency will be produced. The longer path length serves as a passive absorber of pump energy, thus changing the ratio of emitting to absorbing molecules. As a result, there will be an upshift in wavelength due to the decreased absorption in the organic molecules at the longer wavelengths.



A) PISTON CONTROLLED SYSTEM



B) ROTATING DIFFRACTION GRATING



C) TEMPERATURE CONTROLLED SYSTEM

Figure 7. Methods of tunable dye lasers.

Soffer and McFarland[29] (Korad) proposed a diffraction grating resonating cavity to obtain spectral narrowing and tunability. Using dyes in the xanthene and carbocyanine families, a 40 nM shift was obtained in rhodamine 6G pumped by a frequency doubled ruby laser (347 nM in 10 nsec. @ 10 MW/cm^2). Variation in the inclination of the grating served to selectively produce high cavity gain at a given wavelength. Additionally, a significant narrowing is obtained (approximately: 0.06 nM) in contrast to the 5-6 nM spectral width of normal dye lasers. Tunable organic lasers have also been controlled simply by changing the temperature of the dye media.[30] Schappert has shown that an organic dye (DTTC in Ethanol) will display at least a 20 nM wavelength shift when the temperature is varied from -117° C to +78° C.

The first continuously tunable diode laser was announced[31] in 1968 by Hinkley and his associates at the Massachusetts Institute of Technology. The central output frequency could be tuned continuously over a range of 50 gigahertz by simple variation in the diode current. The diode systems were fabricated from crystals of the mixed semiconductor lead tin and telluride; formed by a vapor deposition process from lead telluride seeding crystals. The emission could be varied from 6500 nM to 28000 nM by simply changing the chemical composition of the diodes. The central output frequency of the diodes may be changed by simply controlling the current which passes through the diode.

D. Remarks. There are now available numerous different laser devices which produce a wide range of wavelengths and power levels. As a result, the industrious researcher or applications engineer can often select a set of laser output parameters which will correspond to the exact requirements of a specific experimental design or applications requirement.

This situation does impose serious problems in providing safety protection for laser workers, since the advantages introduced by a broad spectrum of available laser sources is, of itself, a disadvantage when attempting to provide a uniform "all purpose" laser safety code. As a result, the personnel using lasers, whether in the laboratory or a field application; as well as the health officers responsible for enforcement of laser safety regulations, will require more detailed and specific data regarding:

1. The operational parameters of the laser(s) in use.

2. The safe exposure criteria for each laser, and

3. The correct protective devices necessary for these lasers.

Similarly, those responsible for establishing levels for safe exposures as well as those who manufacture protection devices must also keep pace with the advances in the technology.

The preceeding review of laser systems emphasized only those "most common" types which are presently available commercially and is by no means representative of the vast number of different lasers which are under study in research laboratories. This brief listing should reveal that even these most common laser types produce a wide range of output levels and specific beam characteristics which are dependent in a complex way upon the particular laser media and the manner in which it is operated. This makes a general broad comparison of all laser devices a difficult, if not impossible task.

Lasers can, perhaps, be best classified by first describing the manner in which the radiation is emitted (eg, pulsed, continuous wave) and then describing specific characteristics of the radiation as defined in the following sections.

UNIQUE PROPERTIES OF LASER RADIATION

A. Fundamental Aspects of Laser Radiation. The following six properties are common to the beams emitted from all laser types and are the factors which, when combined together, distinguish laser outputs from other sources of electromagnetic radiation:

1. A nearly single frequency operation of low bandwidth (ie, an almost pure monochromatic light beam).

2. Emission of a nearly parallel beam with well defined wavefronts.

3. A beam of enormous intensity.

4. A beam which maintains a high degree of temporal and spatial coherence.

5. A beam that is, in many laser devices, highly plane polarized.

6. A beam with enormous electromagnetic field strengths.

Each of these characteristic laser beam properties is briefly reviewed in the following sections.

a. Single Frequency Operation (monochromaticity). The frequency of any electro-magnetic wave relates to the number of cycles the electric or magnetic field undergo each second. A completely coherent, monochromatic wave could then be visualized as a pure (unmodulated) sine wave oscillating exactly at a constant frequency. Most laser systems display a multifrequency characteristic. This frequency spread is, however, vary narrow when compared to the average laser frequency. In most lasers, the frequency degeneracy is solely dependent upon the quantum transition characteristics of the active media, and the geometry of the Fabry-Pèrot resonator. In this sense, the laser media may be considered as a hugh number of isolated light generators placed between the two mirrors. The electromagnetic field developed between the mirrors may be regarded as a superposition of plane waves at each of the slightly different frequencies which the laser media generates and allows to oscillate. These different frequencies are termed the "modes" of the laser resonator and relate to those stable electromagnetic field configurations which can exist between the two mirrors. (Figure 8)

The mode structure of an electromagnetic wave may be considered rigorously by solving Maxwell's equations under the limits

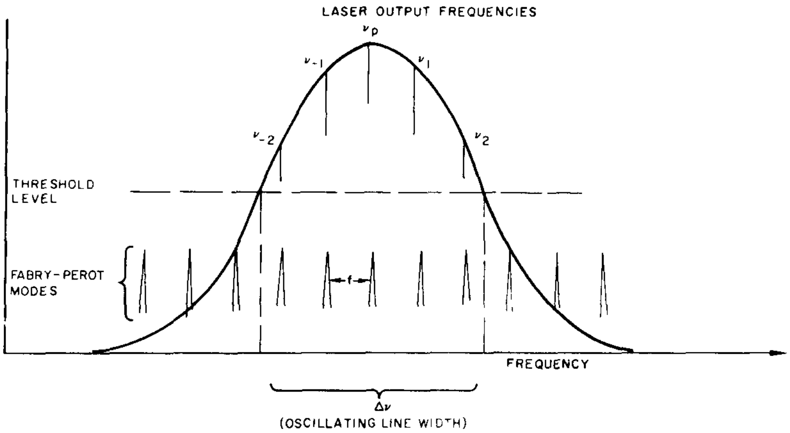


Figure 8. Schematic diagram showing typical multimode laser operation.

set by the boundary conditions imposed by confining the field between the mirrors.[32] The result of this argument gives rise to three integer numbers (eigenvalues) which characterize each of the possible self-reproducing field patterns (modes) which are possible. One of the integers relates the number of axial or longitudinal modes while the other two distinguish the transverse modes. The mode pattern is usually designated TEM_{pqn} where p and q are the transverse (or spatial) mode integers and n is the longitudinal (or temporal) mode number. The abbreviation TEM signifies that the modes represent uniform plane waves which are real transverse electromagnetic waves.

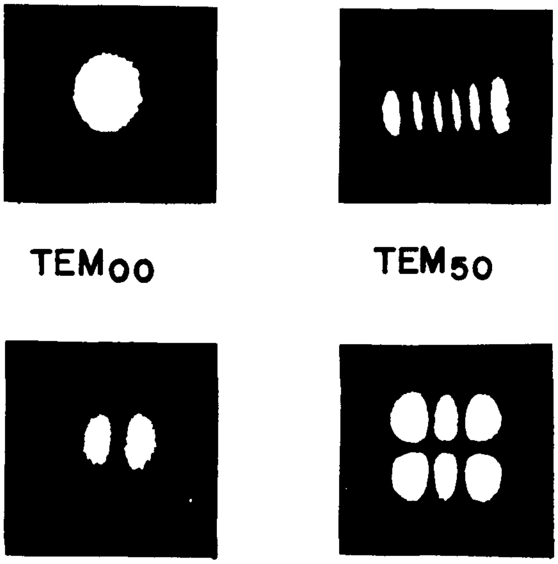
These two types of modes may be conceptually considered as axial (longitudinal) and off=axis (transverse) modes. The axial modes can be considered as a result of the many possible standing wave patterns produced by reinforcement when the mirror separation is set at integral multiples of half-wavelengths. This is expressed by the equation: $n\lambda = 2L$, where λ is the wavelength, L is the mirror separation, and n is the mode integer. For example, for a nominal ruby laser which is six inches in length, n = 400,000. This corresponds to a fractional variation in the wavelength between axial modes of approximately 0.001 nanometers. The bandwidth of the energy levels of most laser medias can easily encompass a number of such axial mode frequency variations.

The off-axis modes result from plane waves propagating at an angle with respect to the axis of the resonator. These different modes are produced by diffraction effects in the Fabry-Perot cavity. The lowest order axial mode is designated as the TEM_{oo} mode. This mode has the lowest diffraction losses and consequently will often be the predominant mode of oscillation. For each transverse mode there will be many longitudinal modes which can oscillate; hence the output of a multimode laser will actually contain a superposition of plane waves oscillating at many discrete frequencies. However, as previously mentioned, this frequency spread will be very small.

For most cases the average wavelength at which the laser oscillates is sufficient to describe its operation. If more precision is needed, then the frequency spread or bandwidth is given. Depending on the type of laser, bandwidths range typically from 10^{-4} to 10^{-9} times the average frequency of the laser; although bandwidths as low as 0.1 cycles per second (cps) have been reported for stabilized gas lasers.

b. Spatial Distribution of the Beam. The intensity profile across a TEM_{oo} laser beam will be in the form of a bell-shaped or Gaussian distribution. The decrease in intensity near the edge of the beam is the result of diffraction effects produced at the edge of the laser mirrors. Departure from the Gaussian type distribution arise when independent oscillation occurs within the resonator at one of the higher order modes. For example, gas lasers may be designed to have sufficient gain to support simultaneous oscillation in many different transverse modes. Mode selection may often be accomplished by slight adjustment of the mirror alignments. With this technique, one can observe the different complex intensity distributions of each mode (Figure 9). The lowest order TEM_{oo} mode with the nearly Gaussian intensity distribution has the lowest cavity loses and hence will generally be the dominant mode of oscillation. The spatial intensity distribution of this mode may be expressed by the equation[33]

$$I(R) = I_o \exp\left[-\frac{2R^2}{W^2}\right]$$



TEM$_{00}$ TEM$_{50}$

TEM$_{10}$ TEM$_{21}$

Figure 9. Transverse mode patterns.

where R is the radium and W is a constant which defines the mean radium and is commonly referred to as the "spot size." At this point the intensity has fallen to $1/e^2$ of the peak intensity at the center of distribution.

Optically pumped solid-state lasers -- such as the pulsed ruby laser -- usually display a randomly varing mode output. Thermal gradients in the optical media (ie, the ruby crystal) caused by nonuniform absorption of the pump light give rise to lens effects in the crystal which change during the pumping cycle. The result is a sporadic switching of transverse modes during the laser pulse. The time average is generally a bell-shaped distribution which is dependent upon the optical purity of the laser crystal, the pumping scheme, and the level at which the system is operated above lasing threshold.

Some pumping schemes produce more pronounced "hot spots" in the intensity distributions than do others. For long range transmission, atmospheric effects can also produce intensity variations by a factor of ten over localized regions of the beam.[34] Such nonuniformities in distribution make it difficult to specify the cross-sectional area of the beam. As a result, an average value of beam radius must be chosen. Typically, this is often (1) the half-power point; (2) the $1/e$ power point; or (3) the $1/e^2$ power point. A common laboratory practice is to measure the diameter of the burn produced on black mat paper or developed, but unexposed, polaroid film. A more meaningful method is to measure the diameter at the $1/e^2$ power point on a densitometer recording obtained from a direct photograph of the output beam.

In the case of optically pumped solid-state lasers, the size of the beam cross-section is generally a function of the pumping level of the laser, eg, the higher the pumping level, the wider the beam size. Such behavior is directly related to the onset of higher order transverse mode oscillation at the higher pumping levels. Only when pulsed lasers are operated near threshold, or in special cavity conditions, will the zero order mode (lowest beam spread) predominate.[35]

The beam from an ideal laser, ie, a laser which emits a truly coherent wave, can be considered to emit a diffraction-limited beam. In this case, divergence of the beam is limited to the effects of diffraction at the mirror edges. The emission from such a laser will display a nearly parallel beam up to a distance $L = D^2/1.22\lambda$ where D is the diameter of the emergent laser radiation. Thus the TEM_{oo} beam from an idealized helium-neon laser will display virtually zero beam spread for a distance of about a meter from the laser.

Due to the high degree of coherence of a laser beam, it is theoretically possible to focus the beam to the diffraction limit of the wavelength of light. Typically, however, the laser will have a finite beam spread and can be expressed by the simple equations of geometrical optics. In this case, the focal spot size will be given by $\underline{d} = f\theta$

where d = spot diameter
f = focal length of lens
θ = beam spread (radians).

As the spot diameter approaches the order of magnitude of the wavelength of light, the spot becomes diffraction-limited. For example, the beam from a highly coherent single transverse mode (TEM_{oo}) gas laser will produce an airy disk diffraction pattern when focused. This distribution may be described mathematically by the following equation in which about 80% of the beam energy will be contained in a diameter:

$$d_{TEM_{oo}} = \frac{2.44\, f\lambda}{D}$$

Where

λ = Wavelength of light

D = Diameter of the beam.

The important consequences of this discussion are:

1. The smallest possible spot size of a focused laser beam will be no smaller than the wavelength of light.

2. The power density of a focused laser beam will vary inversely with the square of the focal length of the lens.

3. The power density of a focused laser beam will vary inversely with the square of the beam divergence angle

Consequently, either a reduction in the focal length of the lens used to focus the beam or a reduction in the beam spread by a factor of ten will produce a one-hundredfold increase in power density at the focal phane of the lens. Simultaneous reduction of both by a factor of ten would increase the power density by a factor of 10^4.

In practice, however, it is the beam divergence that limits the focal spot diameter. This is especially true with pulsed laser systems. To achieve high energy outputs, the laser crystal is usually pumped well over threshold; consequently, the beam will contain a conglomerate of high order "off-axis" modes which substantially increase the beam divergence.

Typical beam divergence values for gas lasers (helium-neon, argon, etc.) will be a milliradian, or less (1 milliradian - 3.44 minutes or arc). Solid-state ruby and neodymium lasers generally have a higher beam spread (1-30 milliradians), due primarily to the high beam divergence associated with the random multimode operation of such devices.

c. Intensity of Laser Emission. In many applications, the most important laser beam characteristic is the enormous intensity of the beam. Intensity is related by the power of the beam, the cross-sectional area it covers, and the manner in which the beam spreads from one point in space to the next.

Power, by definition, is the time-rate at which work is done; specifically, it is the rate at which energy is used or produced. Energy relates the ability to do work. As with other forms of energy (eg, chemical, mechanical, electrical), electromagnetic energy (light energy) is a conserved quantity. The relationship between energy, power, and time is defined by the integral equation

$$E = \int_0^T P\ (t)\ dt$$

Where

E = Energy expressed in joules
P = Power expressed in watts
dt = Time increment expressed in seconds
T = Pulse duration in seconds.

Thus, 1 w is the equivalent of 1 joule per second.

In pulsed laser operation, instantaneous power densities in excess of 100,000 w/cm^2 are quite easily generated in an unfocused high-energy ruby laser pulse. If this output were contained within a typical beam divergence of 20 milliradians and focused by only moderate power optics, the power density at the focal plane would be increased at least one-hundredfold.

The intensity of the laser is usually expressed by the irradiance or power density of the beam. This is determined by dividing the average value of beam power by the average value of the beam cross-section. The units are expressed in watts per square centimeter.

Radiance is another expression which is useful to relate the far-field brightness of the laser output. This is, by definition, the power density per unit solid angle (watts per square centimeter per steradian). The unit of solid angle is defined such that all space about a point source (ie, the source of light) will encompass 4 steradians. That is, the number of radians in space are equal to the area of a spherical surface enveloping the point, divided by the square of the radius. A radian is a unit of angular measure which is defined as that angle (57.4°) bounded by an arc equal in length to the radius of the circle. For small divergence angles, over uniform beam distributions, the solid angle of a laser beam may be obtained by squaring the beam divergence angle.

d. Temporal and Spatial Coherence. The coherency of a laser beam relates to the constancy or predictability of the spatial and temporal variations in the wavefronts of the radiation. A high degree of coherence implies a constant phase difference between two points on a series of equal-amplitude wavefronts (spatial coherence), and a correlation in time between the same points on different wavefronts (temporal coherence). The two coherence terms are a part of the overall four-dimensional coherence function which completely describes the degree of coherency of the beam.[36]

In the laser beam is considered as a plane wave traveling in one direction, ti will be spatially coherent as a result of the perpendicularity of the wavefronts in the direction of propagation. Also, due to the monochromatic nature of the laser light, the beam will be temporally coherent; that is, it will display a fixed-phase relation between a part of the beam emitted at one time and a portion emitted at another. Should the wavelength (or frequency) change, then the temporal coherency would degrade. (Figure 10)

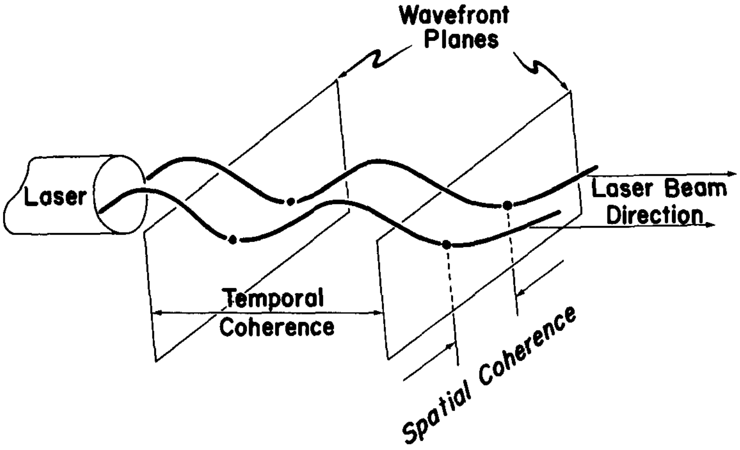


Figure 10.

Even in the beam from an "ideal" laser, there will be random fluctuations in the phase difference of the electromagnetic fields at two separate points on a wavefront. The distance between points on the wavefront for which the average of this phase difference is $\pi/2$ radians is generally defined as the lateral coherence distance. Recombination of the light samples from points separated by a distance equal to, or less than, this amount can produce interference fringes. This distance is a classical measure of the spatial coherence of a light beam as observed in the famous "double slit" experiment of Young.

The temporal coherence is a measure of the length of time that the beam is truly monochromatic. That is, as previously mentioned, since most lasers have a finite frequency spectrum width ($\Delta\nu$), the "coherence time" is defined as

$$\Delta\tau = \frac{1}{\Delta\nu}.$$

This may be considered as the time during which the amplitude of the electromagnetic field will remain constant at a given point in space while the phase varies linearly with time. During this time the beam will travel a length $\Delta L = c\Delta T$ defined as the coherence length (where $C = 3 \times 10^8$ m/sec. the velocity of light). Thus the coherence time is the time required for light to travel the coherence length in the direction of travel of the beam.

By virtue of this argument it is seen that the frequency bandwidth is actually a measure of temporal coherence. Thus a frequency stabilized He-Ne gas laser ($\Delta\nu$ = 3-5 cps) will have a coherence time of several hundred milliseconds and a corresponding coherence length of 10^5 km. In contrast to the high spectral purity of gas lasers, the coherence lengths of pulsed ruby lasers are in the order of 15 meters with corresponding coherence times in the order of only 100 nanoseconds (ie, one ruby laser "spike").

e. Polarization of the Laser Output. The polarization of the most lasers is directly related by the nature of the resonator. For example, most gas lasers made today are built with Brewster's angle windows on both ends of the gas discharge tube. Such windows present virtually no losses to a beam which has a linear polarization component lying in the plane of incidence. Hence, the output will be linearly polarized in this plane.

In some solid-state crystal lasers, for example, the ruby laser, the output will be linearly polarized. This is a result of the birefringent nature of the crystal in which the slower "ordinary" polarized photons will have a longer time to interact with the excited chromium ions, thus favoring a polarized output in this plane.[37] This is generally only true for ruby crystals operating near lasing threshold unless Brewster's angles are fabricated on the ends of the crystal. This latter practice is often necessary for very high power ("Q-spoiled") laser systems.

In diode lasers, linear polarized light is also observed. This may be attributed to the linear symmetry of the region of the junction.

f. Electrical Field Strength. The electromagnetic theory of light depicts a light wave as having instantaneous electric and magnetic fields which oscillate at the same frequency. The electrical (E) and magnetic (H) fields are fixed at right angles and are mutually perpendicular to the direction of propagation of the wave. Of particular importance in the description of laser beam interactions is the magnitude of the electric field associated with the beam. From classical considerations (using Maxwell's equations) the electric field (E) in volts per centimeter associated with a light beam in a vacuum (or air) of average power (P) in watts, spread over a cross-sectional area (A) in square centimeters is given by [38]

$$E = 27.4 \left(\frac{P}{A}\right)^{1/2}$$

Prior to lasers, the electric fields associated with commonly occurring light sources were most nominal. For example, the electric field of sunlight occurring at the earth's surface is about 10 v/cm. This constitutes an average field spread over all the wavelengths present in the "white light" of the sun. In contrast, the instantaneous electric field associated with an unfocused "Q-Switched" ruby laser burst operating at a level of 125 megawatts and confined to 3/8 inch beam diameter will approach 4×10^5 v/cm. Should this beam be focused to 1.5 mm spot, the field at the focal plane would reach 1.2×10^7 v/cm.

Such strong fields are also found elsewhere in nature, as they are at the magnitude of the electrostatic cohesive forces which bind together atomic structures. Such binding forces are in a range from 10^6 to 10^9 v/cm. Consequently, when a laser beam with a field of comparable magnitude enters even a transparent structure, an instantaneous massive redistribution of the electric system of the material can occur due to the interaction of the fields. At the present, the interaction of these enormous electromagnetic fields is not fully understood, to be sure. The production of free electrons, ionized atoms, and rays have been detected in the reaction association with the interaction of high power laser beams.[39]

Summary

This discussion has reviewed the unique properties of the electromagnetic radiation generated by the most common types of laser sources. Emphasis has been placed upon the wide variations possible in the levels of power and the degree of spectral purity possible in the beams produced by these devices.

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LASER INSTRUMENTATION AND DOSIMETRY

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✓

I INTRODUCTION

The objectives of this presentation will be to familiarize you with the problems you may be faced with in making safety measurements on existing laser systems and to introduce you to some of the instruments commonly used to measure energy and power in the laser field.

It almost goes without saying that radiometric units,[1] such as power and energy, and particularly their MKS versions, such as watts and joules, should be used, and that photometric units, such as lumens and candles, serve no useful purpose in this field. This follows for several reasons:

(1) Many lasers exist with wavelengths outside the visible spectrum, and the output of all lasers is normally specified either as power or energy, or both.

(2) The power and energy are fundamentally more important factors in determining the safety of a given laser than its visibility, even in the eye.

(3) All proposed safety criteria have, and probably always will be, specified in terms of power or energy, or their densities, and the wavelength--a wavelength variation that bears no relation to the visibility of the laser wavelength.

It is also apparent that almost all cases requiring a decision about whether or not a given laser or laser installation meets safety requirements can be resolved by reference to the laser manufacturer's specifications. In this day of keen competition among the manufacturers, the output from most systems seldom exceeds the specifications by very much, and then only when new.

However, if one is forced to measure the output of a laser system for one reason or another, and if the facilities of a well-equipped laser laboratory are not available, then one must resort to the use of one of the number of commercially available instruments. Unfortunately, none of these instruments has been designed specifically to satisfy the needs of the health physicist; hence we will discuss later some of the ways in which such instruments may be adapted for such use, and the rationale behind these adaptations.

It is here that one must pay particular attention to the safety criteria that the system must meet--particularly whether these criteria specify a safe energy or power density in the beam[2,3] or a safe total energy or power entering the eye.[4,5] The first form, namely, energy or power densities, are used in the current Army/Navy criteria[2] and will probably be used in the forthcoming recommendation of the American National Standards Institute, Z-136 Standards Committee on Safe Use of Lasers and Masers. Therefore, it will be assumed here that energy or power densities will be the parameter that must be measured.

II MEASURING INSTRUMENTS

A great variety of instruments has been developed for the measurement of optical radiation, including ultraviolet and infrared, and many of these have been adapted for use with lasers. Such instruments, including a number that are available commercially, are treated in detail in several readily available references.[6-13] Most of the commercially available laser measuring instruments* in wide use today[14] can be divided into the following categories:

(1) Measurement of power (watts)

  (a) Thermal--such as thermocouples and thermopiles, thermistors and bolometers, calorimeters, and Golay cells.

  (b) Photoelectric

  Photoemissive--such as vacuum photodiodes and photomultipliers.

  Photoconductive--such as many solid-state detectors in the infrared.

  Photovoltaic--such as solar cells.

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* See Table 1 at the end of this paper for a representative list of such instruments.

(2) Measurement of total energy (joules)

  (a) Thermal--such as hollow-cone and liquid calorimeters and rats' nest bolometers--often used ballistically; i.e., the laser pulse length is much shorter than the thermal relaxation time of the instruments.

  (b) Photoelectric--by integration of the output signal from an adequately fast photoelectric detector.

Note that some of the same instruments can be used to measure either energy or power. For instance, although most photoelectric detectors and radiation thermopiles are designed to measure instantaneous power as a function of time, they can also be used to measure the total energy in a pulse by integration (usually electrical or graphical) as long as the important instrumental time constants are much shorter than the laser pulse. Conversely, devices that measure total energy such as ballistic thermopiles, rats' nest bolometers, or photographic film can be used to calibrate instantaneous power-measuring devices that give pulse versus time.

Photoelectric devices, in general, have much more limited spectral response than thermal devices, although some photoconductors are useful well out into the infrared. They are, however, generally very much faster than thermal devices and hence can faithfully reproduce the shape of most laser pulses. These pulses are normally displayed on an oscilloscope--an instrument often used to make good pulse-length and pulse-shape measurements.

Fortunately, the energy and power density measurements that are required to determine the safety of a given laser installation do not require extremely low-level or extremely high-level measurements--i.e., they can often be made with conventional, relatively inexpensive instrumentation. Furthermore, high accuracy is seldom required for these measurements--except, perhaps, for borderline cases. Most of the common commercially available instruments do not claim high accuracy--± 5 percent is sometimes claimed but seldom achieved. Since none of these instruments, however, has been designed for safety measurements, they must be used with intelligence and with careful attention to the manufacturer's instructions. It is anticipated that specially designed instruments will become available once reasonably designed safety standards become widely accepted. Such instruments will undoubtedly be much simpler and more foolproof than current instruments, and with reasonably wide distribution they need not cost more than a good photographic exposure meter.

III MEASURING TECHNIQUES

There are two distinct cases of practical importance that must be treated: (1) the beam incident directly on the eye or skin, and (2) the beam incident first on a diffusely reflecting surface or target that may be visible to the eye or skin.

A. Direct Irradiation of Eye by Collimated Beam

To evaluate the potential eye hazard from a laser system in which an individual may be exposed by looking directly into the collimated beam, or toward a distant, unresolved laser, we have assumed that it will be necessary to measure the average energy or power density in the beam over an area comparable to that of the pupil of the eye that may be exposed (a maximum range of about 2 to 8 mm in young eyes; 3.5 to 4 mm under average lighting conditions[15]). In order to measure approximately the worst case,* an iris diameter of about 3.5 to 4 mm should be used with the instrument. The instrument is then placed in the beam from the laser such that all the beam enters the iris if the beam diameter is less than the iris diameter, or a maximum reading is obtained by probing over the cross section of the beam if the beam diameter is greater than the iris diameter. This reading, expressed as joules/cm^2 or watts/cm^2, is then used to compare with the prescribed safety criteria. Methods to facilitate this probing will be discussed in Section III-D.

If the laser system is safe for direct viewing as measured above, then it is also safe when the beam is reflected from diffuse surfaces or flat or convex specular surfaces. As always, one can visualize special circumstances in which this might not be true. For instance, if the laser system has a large-diameter beam that is safe for all direct viewing, portions or all of the beam could be concentrated and then recollimated using suitable optics, with a resultant increase in density across the output beam that may not be safe. This is exactly what

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*An instrument such as visualized here will average the power or energy entering its entrance pupil. If this entrance pupil is 3.5 to 4 mm in diameter and the beam is smaller than this, then the local densities within the cross section of the beam will be higher, but the reduction in "optical gain" of the eye (see Ref. 3 or the paper by Sliney in this volume) will keep the retinal densities from increasing. Similarly, if the pupil of the eye is larger than 3.5 to 4mm and the incident beam is larger, the increased aberrations, etc., will also reduce the gain and keep the retinal densities from increasing appreciably.

happens if an observer uses a telescope or a pair of binoculars to look into the laser beam. In this case, the increase in density of the output beam over the input (neglecting instrumental losses) is equal to the square of the magnification or "power" of the instrument.

B. Extended-Source Viewing

In this case, the source of laser radiation can be resolved by the eye; i.e., it appears much larger than a distant point source, and the illumination from this source on the retina covers a much larger area than that covered by the image of a point source. The most frequently encountered example of this type of source is a laser beam incident on a diffusely scattering surface, such as a painted wall or piece of clothing. In this case, it is also simplest to measure the maximum energy or power density in the incident beam and then to calculate the energy scattered per steradian when the beam is incident on a diffuse target. This value, the "brightness," radiance, or radiant exitance of the scattering source, is then compared with the appropriate safety criteria. It should be remembered that the irradiance on the retina is independent of the distance that the viewer is from the target as long as it can be easily resolved. Some targets may not be perfectly diffuse (or "Lambertian"), there being some absorption, some specular reflection, and/or some scattering that does not fall off in angle as the projected area. In these cases, it may be necessary to assume a "worst-case" target.

In case of a relatively large illuminated area, however, it is important to measure the highest density that occurs in the cross section of the beam. . Some laser systems, especially those with imperfections in the lasing material, such as ruby, produce highly irregular beams with some portions much more intense than others--called "hot-spots"--that may shift around within the beam at ranges within the near field of the laser system (i.e., at ranges less than a^2/λ, where a is the diameter of the laser beam as it leaves the system, and λ is the wavelength). In addition, turbulence in the atmosphere can produce very nonuniform beam distributions at longer ranges from the laser.

Hence an instrument with an iris comparable to or smaller than the hot-spot size, or comparable to the size that can be easily resolved by any potential observer, should be used to measure the maximum flux density in the beam in the vicinity of the target.

C. Skin Exposures

The measurement problem here is essentially identical to that above where the laser beam is incident on an extended target; i.e., it is necessary to know the energy or power density incident on the skin.

In this case, however, the spatial resolution required to determine the densities in the "hot-spots" in the beam may be higher; i.e., smaller iris diameters may be required in front of the detector. (It is perhaps fortunate that very many lasers and laser systems have been developed to the point where "hot-spots" are not a problem.)

D. Beam Cross-Section Imaging

For visible-wavelength lasers, it is a simple matter to observe the beam if it is incident on a diffuse target (taking suitable precautions to protect one's self, of course). In the spectral region in which film is sensitive (ultraviolet to near infrared), the distribution of energy or power over the cross section of the beam can be determined by taking a picture of the beam incident on a diffuse white target. In fact, if care is taken to control exposure and development, reasonably quantitative density data can be recorded. These are the problems common to all photometry. Such a camera may provide a useful and rapid survey tool to uncover potentially dangerous situations that could then be measured more carefully. A recent special issue of Applied Optics reviews the entire field of photographic films as radiation detectors.[16]

In addition, several infrared imaging devices, analogous to the familiar "snooper-scope," are available commercially[17] to aid in locating and examining the cross-sectional densities of near-infrared laser beams incident on diffuse surfaces. Specially prepared phosphor screens[18] are also available that are useful with near-infrared lasers to visually display the beam cross section.

E. Extrapolation

If one is faced with the problem of measuring the laser at one range (for instance, close to the laser) and then extrapolating this to other ranges (to determine safe or unsafe ranges), several methods of making such extrapolations are readily available[1,3,4] and depend on such factors as:

(1) Divergence of the laser beam

(2) Focusing (if any) of final optics of the system

(3) Absorption, scattering, and turbulence in the atmosphere.

Table 1

REPRESENTATIVE LIST OF COMMERCIALLY AVAILABLE LASER MEASURING INSTRUMENTS

Manufacturer	Description	Pulse	Power	Energy	Type	Spectral Response (nm)	Sensitivity	Power Rating (Watts)	Energy Rating (Joules)	Rise Time	Fall Time	Band Width	Active Area or Aperture (Sq cm)	Additional Equipment Need	Price
Abtronics	Model 1401 Photon detector	X			Biplanar Photodiode	S11 S1 UV	30μA/lumen	50μA dc	5A-1μs	<5x10^{-10}s		1GHz	7 0	Scope not Calibrated	\$ 450
Barnes Engg	Model 30-140 Laser energy meter		X	X	Wedge-Pyroelectric	300-40 000	5x10 V/W	10^{-4}-10^{-3}	10^{-3}-100	40ms sampling		-	up to 5 05	-	\$1 750
Cintra Physics	Model 101 Quantum radiometer		X		Photo Detectors	400-1 200	-	10^{-10}-10^{-1} ~40W/cm^{2}	-	30-60ms	sampled twice/s	-	1 6	-	\$2 490+
	Model 202 Infrared radiometer		X		Thermopile Thermistor	UV-FAR IR	-	10^{-7}-10^{-1}W/cm^{2}	-	30-200ms	sampled twice/s	-	-	-	\$2 690+
Coherent Radiation	Model 201 laser power meter (Battery Powered)		X		Cone-Thermopile	300-30 000	40μV/W	10^{-3}-100 200W/cm^{2}	-	<1s	-	-	5 25	-	\$ 925
	Model 212 Optical power meter (Battery Powered)		X		Silicon Cell	450-1 100	-	10^{-7}-0 3	-	0 1ms	-	-	0 5	-	\$1 250
	Model 213 Power meter (Battery Powered)		X		Cone-Thermopile	up to 10 600	10 4mV/W	1500 200W/cm^{2}	-	<1s	-	-	11 8	-	\$1 250
Control Data (TRG)	Model TRG 100			X	Cone-Thermopile	300-5 000	150μV/J	Max 1 5x10^{8}	Max 150	7s	30s	-	0 785	Microvoltmeter or TRG 102 energy meter	\$ 385
	Model TRG 101	X		X	Cone-Thermopile + Photodiode	300-5 000	150μV/J	Max 1 5x10^{8}	Max 150	7s	-	-	0 785	Microvoltmeter or TRG 102 energy meter + scope	\$ 525
	Model TRG 107			X	Cone-Thermopile	300-5 000	35μV/J	Max 5x10^{8}	Max 300	20s	2 min	-	3 15	Microvoltmeter or TRG 113 energy meter	\$ 550
	Model TRG 108	X		X	Cone-Thermopile + Photodiode	300-5 000	35μV/J	Max 5x10^{8}	Max 300	20s	2 min	-	3 15	Microvoltmeter or TRG 113 energy meter	\$ 690
	Model TRG 117			X	Cone-Thermopile	300-5 000	22μV/J	Max 10^{9}	Max 1000	90s	2 5 min	-	12 6	Microvoltmeter or TRG 113 energy meter	\$1 875
	Model TRG 118	X		X	Cone-Thermopile + Photodiode	300-5,000	22μV/J	Max 10^{9}	Max 1000	90s	2 5 min	-	12 6	Microvoltmeter or TRG 113 energy meter	\$2 000
	Model TRG 127			X	Cone-Thermopile	300-5 000	-	-	-	-	-	-	-	-	
	Model TRG 128	X		X	Cone-Thermopile + Photodiode	300-5,000	-	-	-	-	-	-	-	-	-
EG & G	Model 560 B Lite mike	X	X	X	Silicon Photodiode	350-1 130	0 25μA/μW	0 5 peak 3x10^{-3}avg	<10^{-6}	5ns	20ns	-	0 087	-	\$ 450
	Model 580A Radiometer	X		X	Biplanar Photodiode	(S4) 350-775	0 13A/W	-	-	<1ns	-	-	12 97	-	\$2 995
	Model 580B Radiometer	X		X	Biplanar Photodiode	(S20) 350-850	-	7 1x10^{-9}-2 1W cm^{2}	7 1x10^{-9}-2 1x10^{-2}J/cm^{2}	<1ns	-	-	12 97	-	\$2 995
	Model 580C Radiometer	X		X	Biplanar Photodiode	(S1) 350-1150		2 3x10^{-7}-69W/cm^{2}	2 3x10^{-7}-0 69J/cm^{2}	<1ns	-	-	12 97	-	\$2 995
	Model 580D Radiometer	X		X	Biplanar Photodiode	(UV) 200-300	-	-	-	<1ns	-	-	12 97	-	\$2 995
						(S5) 200-775	-	1 5x10^{-8}-4 5 W/cm^{2}	1 5x10^{-8}-4 5x10^{-2}J cm^{2}	<1ns	-	-	12 97	-	\$2 995

Table 1 (concluded)

Manufacturer	Description	Pulse	Power	Energy	Type	Spectral Response (nm)	Sensitivity	Power Rating (Watts)	Energy Rating (Joules)	Rise Time	Fall Time	Band Width	Active Area or Aperture (Sq cm)	Additional Equipment Need	Price
Eppley Laboratories	Laser Thermopile		X		Thermopile	100-40 000	0 08mW/mW	250mW	-	~2s	-	-	0 1	Potentiometer	$ 525
International Light Inc	IL 600 610 Flash Integration System		X	X	Vacuum Photodiodes	-	-	200	~0 2	-	-	40kHz	-	-	$1 155
Jodon Engg Assoc	Model 450B Optical power meter		X		Silicon Detector	400-1 150	-	0 020-100mW	-	-	-	50kHz	5 05	-	$ 298
Korad	Model K-J2 Calorimeter			X	Liquid Calorimeter	530-1 060	~20μV/J	Max 10^8W/cm^2	0 05-100	-	-	-	5 05	Microvoltmeter	$ 945
	Model K-J3 Calorimeter			X	Liquid Calorimeter	530-1 060	~5μV/J	Max 5x10^8W cm^2	0 1-500	-	-	-	5 05	Microvoltmeter	$ 945
	Model K-J4 Calorimeter			X	Liquid Calorimeter	530-1 060	~2 2μV/J	Max 5 8x10^8W/cm^2	1-2000	-	-	-	10 1	Microvoltmeter	$2 500
	Model K-PM Power meter		X		Metallic Sensor	300-30,000	-	0-500W (30s) 0-300W (cont)	-	-	-	-	5 05	-	$ 950
	Model K-D1 Laser detector	X	X	X	Photodiode	(S1) 300-1,150 (S20) 300-850	- 2mA/W	1->10^{10}W using MgO diffuser	10^{-3}->1000 10^{-3}->1000	0 3ns 0 3ns	- -	1 1GHz -	3 05 -	1000-Vdc bias scope	$1 650
Light West	Model D-1 Power detector		X		-	Ruby	-	0 5-100mW	-	-	-	20kHz	2 5	-	$ 132
Optics Technology	Model 615 Power meter		X		Silicon Solar Cell	400-1 150	-	0 03-1W	-	-	-	32kHz	4 1	-	$ 295
PRD Electronics	Laser Bolometer PRD6621		X		Film Absorption-ΔR	250-4 000	-	0-100mW Max 2W/cm^2	-	15s	-	-	-	PRD 650C meter or bridge	$ 185
	Laser Bolometer PRD690		X	X	Film Absorption-ΔR	250-4,000	-	0-1000mW Peak 10MW	-	25s	-	-	-	PRD 680 meter and PRD 690-1 adapter	$ 495
Quantronix	Model 500/503 Energy receiver/control unit			X	Cone	300-10 600	5mV/J	Max 5 GW	0 0005-1000	15s	60s	-	4 35	-	$ 425
	Model 504 Energy/power meter		X	X	Cone	300-10,600	5mV/W	100mW-30W	0 1-300	4s	-	-	4 35	-	$ 875
Raytheon	Model 1A11 Output monitor (Battery Powered)	X		X	Cone-Photocell	350-1,130	-	-	0 1-1000	4ns	-	-	-	-	$ 985
	Model 1A31 Electronic calorimeter (Battery Powered)	X	X	X	Vacuum Photodiode	350-1 020	-	1μW-10GW	0 01-100	0 3ns	-	1GHz	-	-	$2 000
Resalab	XL1010 Laser power meter		X		-	300-1 200	-	10μW-10W	-	-	-	-	0 79	-	$ 795
	XL1003 Laser power meter		X		-	300-1 200	-	1mW-10W	-	-	-	-	0 79	Digital readout	$1 000
	XL1000 Laser power meter		X		-	300-30 000	-	Max 1KW	-	-	-	-	4 0	-	$1 300
Spectra Physics	Model 401C Power meter		X		Photovoltaic cell	450-1,050	-	0 02-100mW higher with adapter	-	-	-	20kHz	3 1	-	$ 355
Tropel	Model 330 Light detector	X			Photodiode	350-1 150	-	Max 6mW	-	0 1ns	-	1GHz	0 1	Scope not Calibrated	$ 289
Westinghouse	Model D-1 Power detector			X	Rat s Nest	-	625μV/J	-	0 1-5J/cm^2	10^{-4}s	20s	-	5 0	Microvoltmeter	$ 350

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BIOLOGICAL EFFECTS OF LASER ENERGY ON THE EYE

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ABSTRACT

In the spectral range 400 - 1400 nm the eye is the most sensitive organ of the body to laser radiation. The ocular media of the human eye transmit and refract wavelengths within this bandwidth, focussing an image of the radiation source on the retina. Thus, ocular damage is confined primarily to the tissues of the retina and adjacent choroid, the principal hazard being the production of an irreparable burn resulting in a permanent blind area or scotoma of the visual field. Overexposure of the retina to intense sources of light at power densities well below the burn threshold produces flashblindness, a reversible phenomenon caused by excessive bleaching of the visual photopignments. There is also evidence to suggest that long term overexposure to optical sources can produce irreversible changes in the retina.

Anatomical and physico-chemical features of the eye pertinent to radiation damage will be presented, followed by experimental procedures employed to obtain threshold burn data on rabbits, monkeys, and humans. These threhold data are evaluated as a function of power density on the retina, exposure time, and retinal image size. A discussion of heat conduction in the retina and choroid in terms of simple mathematical models which predict time-temperature histories will be given.

LASER HAZARD CONTROL PROCEDURES

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The development and maintenance of an effective laser hazard control program depends first of all upon a sustained conviction that laser safety requires more than casual attention. The extent and depth of the program are then molded by individual philosophy and perspective as to the hazard of lasers relative to other forms of radiation. And finally, the credibility of the functioning program depends upon the expertise of those who implement it.

I. GENERAL CONSIDERATIONS

Assuming that the need for a control program is recognized and a qualified staff is available for its implementation, some attention should be given to the relative hazards of laser radiation. Health physicists have traditionally been concerned with ionizing rather than non-ionizing radiations such as those produced by most lasers. For this reason a simple comparison of certain features of ionizing versus laser radiation, as given in Table I, might be useful.

TABLE I

Ionizing vs. Laser Radiation*

Ionizing Radiation	Laser Radiation
Quantum energy high	Quantum energy relatively low
Established genetic effects	Little evidence of genetic effects
Body receptors relatively insensitive	Body receptors more sensitive
May be highly penetrating	Usually absorbed near body surfaces, except eye
Potential internal emitter problems	No internal emitter problem
Cumulative	Noncumulative
Nonthermal dissipation of energy	Thermal dissipation of energy

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*Extending from near ultraviolet through infrared.

Analogies are always imperfect and the comparisons in Table I must be qualified by imcomplete knowledge: No studies have been conducted on the chronic or cumulative effects of laser radiation or the bioeffects of very fast processes, e.g., picosecond pulses; nor has a comprehensive study been made of biological effects as a function of frequency. Also, overlaps between the "ionizing" and nonionizing can occur, e.g., an electrical field in a convergent laser beam increases (light intensity increases) to a point where it causes an electrical breakdown in the surrounding gas (ionized plasma). The sum of our present knowledge of bioeffects indicates that ionizing radiation will have a more significant effect on the human genetic pool than laser radiation, the effect of the latter being primarily confined to the potential production of acute injuries.

A knowledge of certain additional factors is necessary in deciding on the kind of control measures required for lasers. First, most lasers are still in the hands of scientists and technicians who have been trained in the physical sciences. While this fact does not guarantee safety in the use of laser equipment, it is fair to say that such persons have a greater awareness of hazard potentials than the average lay person. Second, all lasers do not represent a significant potential hazard to people. The devices range from high power giant pulse or continuous wave (cw) systems to tiny semiconductor materials with power outputs a fraction of that of a small flashlight bulb. The number of these fractional milliwatt semiconductor devices far exceeds that of the more traditional systems such as ruby, argon, helium-neon and carbon dioxide. Several thousand of the semiconductor "chips" may be held in the palm of one's hand.

The control procedures for research and development personnel, manufacturing plant people, students and members of the public are different in design but not objective. Persons engaged in laser research must rely on individual knowledge and judgment in dealing with the hazard; such judgment must operate in place of inflexible procedural requirements. Persons working in manufacturing plants where procedures can be routinized to a greater extent may properly rely on established procedures and systems with "inherently safe" designs such as closed systems equipped with interlock mechanisms. The most stringent types of controls should be exercised for members of the public and students. Low power continous wave devices should be handled with particular care since greater numbers of such devices will find their way into public use. Since these devices are relatively low powered there may be a tendency to regard the laser radiation as nonhazardous thereby promoting a willingness to place the eye in the primary beam.

In defining the general characteristics of a laser control program the needs of industry and academic institutions will be given primary attention; however the recommendation may be scaled down appropriately to meet individual or small group needs.

First of all, someone should be given the responsibility for the control of laser hazards. This may be a health physicist, industrial hygienist, safety engineer, environmentalist or other specialist. Secondly, those who have the greatest stake in laser hazard control should be brought together and formed into a committee. Such a committee should establish company policy with regard to lasers. The membership should consist of technical personnel, general counsel, medical director, hygienist and other specialists. Third, the posture of the company with regard to the control of laser hazards must be clearly defined as a policy matter. The front office must go on record. The policy must then reach and be understood by those using laser devices. Fourth, a written manual or guide on Policies and Practices for Personnel Using Laser Devices should be developed.

A. PROGRAM GUIDELINES

The guide should contain certain basic provisions.

1. The responsibility for laser safety must rest primarily with supervision and the employee engaged in laser work. Each supervisor should

    a) make certain that all persons reporting to him are fully informed as to the potential hazards and that control measures are instituted for the protection of all persons who have occasion to visit or use the laser installations under his jurisdiction.

b) give priority consideration to the engineering control of laser radiation such as interlocks, shielding and equipment isolation, especially to high power systems. Greater emphasis should be placed on equipment design than on procedural dictum.

c) make certain that employees have available to them, are familiar with, and follow the provisions contained in the company policies and practices and any supplementary instructions either oral or written received from the organization in charge of implementing the program.

2. Provision must be made for the education and training of people in the safe use of laser equipment. Orientation seminars should be established for persons expected to use lasers for the first time. Such education and training should be carried out on a periodic basis.

3. The safety of visitors who are unfamiliar with the potential hazards of lasers is of paramount importance. Each person and his immediate supervisor who intends to bring visitors or members of the public on to the premises must make certain that all safeguards are utilized to ensure the safety of such people.

4. Personnel who plan to demonstrate laser equipment to nonemployees or members of the public at locations off the company premises should be asked to use laser equipment which has been certified by the organization responsible for laser safety.

5. A copy of all purchase requisitions for laser devices, laser protective equipment, or laser irradiation services should be sent to the responsible hazard control organization. The person initiating a requisition for the purchase of laser equipment should indicate clearly on

the requisition that laser equipment is involved, especially in those cases where the manufacturer's designation does not make such a fact readily apparent. The purchasing department should make the safe design of equipment a competitive item in the purchase of laser equipment.

6. Close communication and cooperation must exist between the hazard control organization and the engineering services when laser equipment is being installed.

7. Loans of laser equipment should be effected only by letter agreement with the recipients of such equipment. If possible loans should be limited to educational institutions, hospitals, scientific organizations, and research institutes rather than individuals.

8. Arrangements should be made for periodic eye and skin examinations of all employees engaged in laser work.

B. RESPONSIBILITIES OF LASER PROTECTION ORGANIZATION

The organization which has the responsibility for the control program should:

1. Provide consultative services to supervision.

2. Conduct orientation seminars.

3. Initiate new guidance or requirements as knowledge is gained in laser technology and biological effects.

4. Review and advise as to control measures when lasers are demonstrated to the public.

5. Compile and maintain performance data on laser protective equipment.

6. Investigate unusual circumstances involving laser radiation, such as overexposure.

7. Submit for medical examination the names of persons who are assigned to work with laser equipment for the first time, and periodically thereafter.

8. Develop a special appreciation for the interplay of environmental factors associated with laser operations. For example, the electrical hazard associated with energized circuits, e.g., condenser banks for pulsed systems may be a greater potential hazard than exposure of the eye to laser radiation. Special attention must be given to the possibility of accidental discharge of the condensers. Also, certain flammable, toxic, corrosive, and possibly carcinogenic chemicals are being introduced into laser technology, e.g., chemicals in dye lasers, and in Q switching components. A recent speculation is the possible use of lasers for controlled fusion.

Laser systems must not be treated alike in the control program, otherwise equal attention would be given to semiconductor devices, carbon dioxide, ruby, and YAG-Nd systems. Attention must be given to the separation or classification of laser systems according to relative hazard. One method of classification is to identify as "high power lasers" those devices capable of producing hazardous diffuse reflections or igniting flammable materials. The justification for giving special consideration to such laser systems is that persons in the vicinity of a hazardous diffuse reflection cannot escape ocular injuries merely by changing position: the diffuse reflection is hazardous at all viewing angles. The flammability criterion is self-explanatory. Needless to say, the radiations from high powered laser systems must be rigidly controlled. Less stringent controls may be used for visible wavelength laser systems having insufficient output levels to meet the "high power" criteria. Lasers operating in the ultraviolet and infrared can be hazardous and will be treated separately.

II. SPECIFIC CONTROL MEASURES

A. CONTROL FACTORS

The following factors help determine the type and degree of engineering and procedural control necessary for any given situation.

1. Power or energy output of laser
2. Pulse length
3. Pulse repetition rate
4. Wavelength
5. Beam path
6. Beam shape (divergence, hot spots, atmospheric effects)
7. Number of laser systems at particular location
8. Position of windows, doors, layout of areas
9. Degree of isolation of location
10. Type of population (informed staff in control, local knowledgeable personnel, uninformed transients)

B. PRECAUTIONS FOR LOW-POWER LASERS OPERATING AT VISIBLE WAVELENGTHS

It is desirable to orient the laser equipment so that the laser beam and potential specular reflections are aimed away from doors, desks, and work bench areas despite the fact that these beams have been carefully terminated. If it is possible for the main beam or reflection from a specular surface to be directed toward a doorway to a hallway, such doorway should be kept closed during laser operations. All glass portions of doors which would allow people to view such beams or reflections should be covered or replaced with opaque materials. Similar precautions should be considered for windows. All unnecessary specularly reflecting materials should be removed from the area of the beam path. Misaligned lenses may cause hazardous unexpected specular reflections and should be treated with caution.

Personnel should not be exposed to the direct beam or specular reflections. Control measures should rely on positive safeguards, such as curtains, and backstops rather than procedural protocols. If a laser continues to operate with no one in attendance, controls must be provided to prevent accidental exposure. In the absence of such controls, the doors leading to the laser area must be locked. A warning note should be affixed to such doors.

Special emphasis should be placed on proper termination of all laser beams with diffuse low-reflectance materials. All rear exit ports which are not used in the experiment should be covered. Auto-collimators which remain within the optical system should have the eyepiece covered when not in use.

Since the probability of an accidental exposure is greatly increased as the eye approaches the beam axis, alignment procedures should be performed with care so that the beam will not enter the eye. Direct viewing of the beam is to be avoided. A high level of ambient illumination will serve to constrict the pupils to some extent, thus limiting the laser energy entering the eye.

C. PRECAUTIONS FOR HIGH-POWER LASERS OPERATING AT VISIBLE WAVELENGTHS

High-power lasers require more rigid control measures not only because there is a greater chance that specular reflections will be of sufficient magnitude to cause injury, but because of the greater risk of injury from potentially hazardous diffuse reflections. The entire beam path capable of producing hazardous diffuse reflections must be controlled. Controls must not depend on procedural safeguards but must rely on more positive methods such as enclosures and interlocks.

For very high energy pulsed laser systems, it may be necessary to isolate the laser system completely and accomplish all monitoring with TV monitors. If the beam path is enclosed, the enclosure should be interlocked.

For pulsed systems, interlocks should be designed so as to prevent firing of the laser by dumping the stored energy into a dummy load. For cw lasers, the interlocks should turn off the power supply or interrupt the beam by means of shutters. Interlocks should not allow automatic reenergizing of the power supply, but should be designed so that after tripping the interlock, the power supply or shutter must be manually reset.

For high energy pulsed laser systems, great care must be used to prevent accidental firing of the laser. When the laser is not intentionally being fired, some positive means of preventing exposure to an accidental firing must be utilized, such as blocking the exit port. If visual inspection of the target area is routinely required prior to and after firing, some method of viewing by means of movable mirrors or baffles which are interlocked to the power supply should be used to prevent accidental exposure. If possible an alarm system and a countdown are advisable when the capacitor banks begin to charge.

Since it is normal policy not to lock doors to laser areas, the frequent interruption of interlocks may cause serious damage to the laser system or ruin an experiment. For such cases, use may be made of a doorknob cover; the cover may be easily removed in event of an emergency but will prevent people from unknowingly opening the door and tripping the interlock. Warning lights which automatically flash when the laser power supply is energized may be mounted in the hallway. The warning sign shall contain the standard caution symbol and appropriate instructions.

Diffusely-reflecting matte surfaces should be employed on walls, ceilings and objects near the primary beam.

D. PRECAUTIONS FOR INFRARED WAVELENGTH LASERS

Laser radiation at wavelengths greater than 1.4 micrometers may produce burns of the skin and cornea. Firebrick or asbestos are not always adequate for long periods when used to terminate high-power density beams; therefore, the proper choice of material and periodic inspection by the user are essential for these cases. The backstop and laser should be arranged so that the beam cannot be inadvertently diverted to unprotected flammable materials. Many materials, particularly composite firebrick used for backstops, can be heated to incandescence with moderate power densities. This creates a potential hazard from the heating and evaporation of toxic materials. Also, the radiance of the heated spot may be sufficiently great to cause retinal burns. Viewing such spots should be avoided unless protective eyewear is worn.

Areas which might be exposed to reflections should be protected by enclosing the beam or target area with suitable impervious fire-resistant materials. Plexiglas and similar materials should be used with caution since they melt and burn at relatively low beam intensities. Since the beam is not visible to the eye, one is not always aware of the location of the main beam and reflections. These areas should be planned and isolated with these factors in mind. Equipment for personal protection against possible eye and skin burns from the main beam or reflections is readily available, however ordinary safety glasses should not be used for eye protection.

E. PRECAUTIONS FOR ULTRAVIOLET WAVELENGTH LASERS

Exposure to ultraviolet radiation can be easily prevented by means of shielding; sometimes the greater subtlety is in being aware of the presence of UV radiation. Quartz laser tubes are transparent to ultraviolet thus shielding is required. Protective goggles, face shields and body protection are required for work near unshielded UV sources.

F. EXEMPT LASERS

An exempt laser is any laser system which is incapable of producing radiation which will result in exposures in excess of maximum permissible values for direct viewing of laser beams or extended sources. Once a system is so designated it is exempt from any control requirements.

G. LASER SAFETY EYEWEAR

Engineering controls rather than personal protection devices are first lines of defense against laser injury. However laser eyewear has a definite place in the control program.

Laser safety eyewear is available for most laser systems. Table II is a listing of available commercial eye protection devices compiled by Schreibeis(1). Ordinary sunglasses should never be confused with laser safety eyewear since the former only reduces the light transmitted to the eye by factors typically less than 10, whereas laser safety eyewear may be required to reduce the light reaching the eye by factors of as great at 10^8. The following must be considered when choosing the appropriate eyewear:

1. Wavelength of laser output
2. Intensity of laser output
3. Eye damage criteria
4. Visible light transmission requirement
5. Radiation intensity at which laser safety eyewear damage occurs
6. Need for prescription glasses
7. Comfort

Commercially available protective eyewear is designed for protection against specific wavelengths. No single device protects against all laser wavelengths. Most devices completely attenuate the primary wavelength, a condition which may be undesirable under given circumstances. Rather than a complete, or almost complete, attenuation of the primary beam wavelength perhaps some intermediate degree of protection should be afforded against diffusely reflected or scattered radiation. It is extremely important to label all protective devices in order to avoid an incorrect selection. Manufacturers have generally taken insufficient action with regard to proper labeling. Labeling should include optical density as a function of wavelength, information on the type of device; i.e., whether absorptive, reflective or a combination of both, as well as data on the effect of angle of incidence of attenuation properties.

Many lasers radiate at more than one wavelength; eyewear designed for a given absorption characteristic

Table II. Laser eye protection goggles (based on manufacturer's information)

$$\text{OPTICAL DENSITY} = \log_{10} \frac{1}{\text{Transmittance}}$$

Manufacturer or Supplier	Catalogue Number	Argon 4880 Å	HeNe 6328 Å	Ruby 6943 Å	GaAs 8400 Å	Nd 10600 Å	CO$_2$ 10.6 µ	UV < 4000 Å > 3000 Å	Coated Filter	Approx. Cost $	No. of glass filters & thickness of each	Visible light trans-mission	Useful Range Å
American Optical Co.	SCS--437,*	0.15	0.20	0.36	1	5	High	No	No	55	1, 3.5 mm	90 %	10600
	SCS--440												10600
	580, 586*	0.2	2	3.5	4	2.7	-	> 0.2	No	35, 25*	1, 3.5 mm	27.5%	-
	581, 587*	0.6	4.1	6.1	5.5	3	-	> 1.6	No	35, 25*	1, 3.5 mm	9.6%	6328
	584	0	1	5	13	11	High	> 0.6	No	55	2, 2 mm	46 %	10600
	585	0.3	2	8	21	17	High	> 0.6	No	55	2, 2 mm	35 %	6943-10600
	598*	13	0	0	0	-	-	>14	No	25*	1, 3 mm	23.7%	4550-5150
	599	11	0	0	0	-	-	>14	No	35	1, 2.5 mm	24.7%	4550-5150
	680	0	0	0	0	0	50	No	No	35	1, 2.75mm	92 %	10600
	698	13	1	4	11	8.5	High	>14	No	55	2, 2&3 mm	5 %	10600 and 5300
Bausch & Lomb	5W3754	15	0.2	0	0	0	≥ 35	20	Yes	39	1, 7.9 mm	4.3%	3300-5300
	5W3755	4	0	0	0	0.1	≥ 35	10	Yes	39	1, 7.9 mm	57 %	4000-4600
	5W3756	0.8	12	15	5.6	4.8	≥ 35	3	Yes	39	1, 6.4 mm	6.2%	6000-8000
	5W3757	0.9	4.5	7.7	12	5.7	≥ 35	2	Yes	39	1, 7.1 mm	4.7%	7000-10000
	5W3758	1.9	1.8	2.2	4.8	7.5	≥ 35	2	Yes	39	1, 7.6 mm	3 %	10000-11500
Control Data Corp.	TRG-112-1	-	5	12	30	30	-	No	No	50	1, 6 mm	22 %	6943
	TRG-112-2	10	0	0	0	0	-	No	No	50	1, 6 mm	31 %	4880
	TRG-112-3	5	2	6	15	15	-	No	No	50	2, 3 mm	5 %	6943-4880
	TRG-112-4	-	-	-	-	-	High	No	No	50	1, 5 mm	92 %	10600
Fish-Schurman Corp.	FS650AL/18	0.34	3.8	10	>10	>10	-	No	No	30	1, 6 mm	30 %	6943,8400,10600
Glendale Optical Co.	NDGA**	1	0.5	2	16	16	High	>20	No	25	Plastic	60 %	8400,10600
	R**	0.4	2.2	6.3	0.4	0.0	High	5	No	25	Plastic	19 %	6943
	NH**	0.4	5	2.5	0.6	0.5	High	>10	No	25	Plastic	19 %	6328
	A**	15	0	0	0	0	High	>12	No	25	Plastic	59 %	4880,5143
	NN**	0	0	0	0	0	High	>12	No	25	Plastic	70 %	3320,3370
Spectrolab	-	8	5	9	13	12	0	8	Yes	115	2, 3.2 mm	<15 %	Broadband

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* Spectacle Type

** Available in goggles or spectacle type

CAUTION

1. Goggles are not to be used for viewing of laser beam. The eye protective device must be designed for the specific laser in use.
2. Few reliable data are available on the energy densities required to cause physical failure of the eye protective devices.
3. The establishment of engineering controls and appropriate operating procedures should take precedence over the use of eye protective devices.
4. The hazard associated with each laser depends upon many factors, such as output power, beam divergence, wavelength, pupil diameter, specular or diffuse reflection from surfaces, etc.

at a particular wavelength could have a much lower absorption characteristic at another wavelength. A particular problem exists when lasers are tuned through a band of frequencies for which the eyewear is no longer protective. Under such circumstances, other control measures must be utilized. Laser safety eyewear requirements are normally calculated on a worst possible case basis; i.e. the assumption is made that the total beam just fills the pupil of the eye. The eyewear of choice is one with an optical density sufficient to attenuate this calculated value to the acceptable level.

In selecting laser safety eyewear, the visible transmission properties of the eyewear and the level of the ambient lighting must be considered. If the eyewear has very low visible transmission (approximately 20 percent or lower), and if room illumination level is low, the increased hazards of poor visibility can outweigh the benefits of the eyewear in protecting the wearer from laser radiation. Every attempt should be made to use eyewear with the greatest visible transmission obtainable and to keep the level of room lighting high. However, adequate optical density at the laser wavelengths of interest should not be sacrificed for improved visible transmission.

When laser safety eyewear is used to protect against very high beam intensities, damage to the eyewear may result. Tests have shown that serious damage to absorbing glass from pulsed laser systems may occur between 10 and 1000 j/cm^2, and between 1 and 10 j/cm^2 for plastics and dielectric coatings. More recently available plastic eyewear seems to offer adequate protection even with energy densities up to 50 j/cm^2. Laser safety eyewear which has been exposed to high beam intensities should be carefully inspected for damage.

H. LASER WARNING SIGNS AND SYMBOLS

Laser warning signs should be posted in all laser areas, except where "exempt" lasers are used. All portable lasers should have warning signs affixed to them in a conspicuous location.

A warning sign such as the one shown in Figure 1 should be displayed on the outside of all doors

Figure 1. Laser warning signs and symbols.

leading to a laser area. The sign should be placed at approximately eye level and should contain specific information as to the action required of the individual who reads the sign.

I. WARNING LIGHTS, DOORKNOB COVERS

Warning lights may be used to indicate the operation of high power laser systems. Such lights should be positively interlocked with the operation of the laser system. Doorknob covers may be used to prevent unnecessary interruption of a functioning laser system.

J. MISCELLANEOUS CONSIDERATIONS

1. High-voltage sources and wiring on all laser systems should be shielded.

2. High-voltage equipment may produce x-radiation and require shielding.

3. High-voltage equipment and intense beams of UV light may produce hazardous concentrations of ozone and may require additional ventilation.

4. All electrical equipment should be properly grounded.

5. Materials used with laser systems may be toxic or combustible. Procedures for handling such materials should be developed.

6. Cryogenic fluids can be extremely hazardous if allowed to come in contact with the skin or eyes. Protective gloves, masks and clothing should be available and used as needed. Failure of materials at extremely low temperatures and high pressure explosions resulting from plugged relief valves or trapped liquid are of constant concern. Asphyxiation due to displacement of oxygen by inert gases, explosion, or fire due to oxygen enrichment must be considered. Ventilation must be provided to remove gases.

7. Flashlamps may explode and should be shielded. Also, the radiation from these lamps may constitute an ocular hazard.

8. Certain laser tubes produce ultraviolet radiation. If such a laser tube is constructed of materials transparent to this ultraviolet radiation, a shield should be placed around the tube. Suitable protection for eyes and skin should be worn if a shield is not feasible.

9. Intense beams may vaporize toxic materials; an exhaust system may be required.

10. The possible fragmentation of high-speed, rotating devices used for Q-switches and choppers may require special mechanical shielding.

It is difficult to interpret the fact that very few laser injuries have been reported in the literature. It may hopefully reflect a high degree of conscientiousness by laser users. It is possible that an indeterminate number of people has experienced small laser-induced lesions without their knowledge. Continuing attempts are being made to establish a laser injury bank, however, such a venture is bound to be plagued with the usual difficulties of cooperation and accurate reporting.

In assessing all the factors that go into control procedures there is little doubt that the single most important factor is the education, training or at the very least the conveying of information to persons who will use lasers. Increasing numbers of people are using lasers in increasingly sophisticated ways. One continuing hope is that all such people will consider it just as sophisticated and fashionable to use them in a safe manner.

Since the available data on the biological effects of laser radiation are far from complete research must continue to resolve unanswered questions and to refine permissible exposure levels. In the meantime one must continue to use his best conservative judgment as to what constitutes reasonable and effective control measures.

REFERENCE

(1) Schreibeis, private communication, Bell Telephone Laboratories, Murray Hill, N. J.

SESSION IV: LASER AND ULTRAVIOLET, CONTRIBUTED PAPERS

Chairman: S. Fine

Some Recent Developments in Laser Interaction with the Skin of Man
L. Goldman, N. Abraham, W. Rutti

Ocular Hazards of Q-Switched Erbium Laser
G. H. Bresnick, D. J. Lund, M. B. Landers, J. O. Powell, J. E. Chester, C. Carver

Chronic Effects of Low Level Helium-Neon Laser Irradiation
A. I. Goldman, R. L. Carpenter, G. J. Karches

Laser Radiation Viewed as a Point Source or a Diffuse Source
D. H. Sliney

Laser Hazard Evaluation and Calculations
O. D. T. Lynch, Jr.

Army Laser RAnge Controls
B. C. Freasier

A Low Power CW Laser Evaluation Kit
R. W. Peterson, H. F. Stewart, W. F. Van Pelt

A Safety Oriented Laser Manual for Science Teachers
W. F. Van Pelt, H. F. Stewart, R. W. Peterson

A General Consideration of the Biological Hazards of Occupational Exposure to Ultraviolet Radiation
J. R. Prince

The Detection of Ultraviolet Radiation Using the Thermoluminescence of Sapphire
W. G. Buckman, D. C. Sutherland, D. W. Cooke

SOME RECENT DEVELOPMENTS IN LASER INTERACTION WITH THE SKIN OF MAN

Leon Goldman, M.D., Nazem Abraham, M.D., and William Rutti, M.D.

Laser Laboratory, Children's Hospital Research Foundation,
established by the John A. Hartford Foundation at the
Medical Center of the University of Cincinnati, and the
Department of Dermatology, College of Medicine at the
University of Cincinnati.

Next in importance to the eye for laser safety is that vast organ, the skin. In all fields of laser research, development and application there is significant exposure on the face about the safety glasses and the hands and arms. Little is known about the effect of chronic exposure.

Health physicists are interested in current figures of maximum permissible exposure levels for so-called worst case conditions. The following recommendations relative to the skin of the Z-136 Standards Committee on "Safe Use of Lasers and Masers" of the American National Standards Institute have been made recently. The Skin Committee was under the chairmanship of Wordie Parr.[2] (Table No. 1)

For pulsed laser devices operating in the 0.4 - 1.4 micrometer spectral region (visible and near infrared), the maximum intensity incident on the skin should not exceed 0.10 J/cm^2 per pulse for exposure times greater than 0.1 millisecond and should not exceed 0.01 J/cm^2 for pulses of shorter durations. For continuous wave lasers with exposure times greater than one second, the power output shall not be in excess of 0.1 W/cm^2, and with exposure times of one second or less the power output shall not exceed 1.0 W/cm^2. For laser devices operating in the 1.4 - 1,000 micrometer spectral region (infrared) the permissible exposure levels are the same as stated before.[11] Ultraviolet is harmful to the skin but there is no data available as yet for man with regard to ultraviolet lasers. Peacock[3] has reviewed some of older data on ultraviolet erythema from 296.7 nm. (Table No. 2) and in 1948, the American Medical Association Council on Physical Therapy recommended that exposures at .2537 micrometers should not exceed 0.5 uW/cm^2 for exposures less than 7 hours and for continuous

TABLE NO. 1

AMERICAN NATIONAL STANDARDS INSTITUTE Z-136 STANDARDS COMMITTEE

SKIN BIOLOGY - CHAIRMAN, WORDIE PARR

MAXIMUM PERMISSIBLE EXPOSURE SKIN

1. Pulsed Lasers - Visible and Infrared 0.4-1.4 micrometer 0.01 joules/cm^2 per pulse - exposure time more than 0.1 millisecond - 0.01 joules/cm^2 - shorter pulses.

2. CW Lasers - 0.1 w/cm^2 exposure times more than 1.0 second
   1.0 w/cm^2 exposure times 1 second or less

3. 1.4 - 1000 micrometer - same as 1 and 2

TABLE NO. 2

Ultraviolet erythema - 296.7 nm. (R. Peacock)
Threshold Dose - Power Density - 20 microwatts/cm^2 - 15 minutes
Peak Sensitivity - Energy Density - 1.8 X 10^{-2} joules/cm^2

exposure (24 hours a day), the power density should not exceed 0.1 uW/cm^2. Such exposures referred to ultraviolet lights used especially for prevention of droplet infection in air and for exposure of personnel using ultraviolet light sources. With the increasing development of ultraviolet laser systems, it is necessary to have more information than speculation. Current studies on ultraviolet lasers will shortly give much needed data not only for the skin but also for the eye. Ultraviolet can produce changes in DNA with formation of pyrimidine dimers. In the skin, this irradiation can produce elastotic changes in the dermis and malignancy. In recent studies on animal skin by Klein, Laor and Fine[4], "minimal changes produced by laser radiation in the ultraviolet region were confined to the surface epidermis, microscopic changes did not extend to the melanocytes."

Many phases of skin reaction with the laser have been reported by our laboratory and other investigators over a period of years.[5,6,7,8,9] This presentation will review only briefly, by request, some of our current studies. We have used many different laser systems. The skin of man has been exposed to ruby, normal mode, Q-switched, and picosecond pulses, neodymium normal mode, argon, YAG, and CO_2 lasers. For transillumination studies, that is, the passage of light through the skin to look for areas of different density, HeNe, Krypton, and He-Cadmium lasers have been used. (Table No. 3).

Over the past seven years, more than 600 patients have had investigative laser treatment done for skin lesions with these various laser systems. (Table No. 4). This investigation has provided data for follow-up studies on the acute, often severe, reactions and its healing, since many of these treatments have been for significant disfiguring and cancerous lesions. One patient with a squamous cancer of the leg had normal mode ruby laser impacts of 20,000 joules/cm^2. In addition, there has been the opportunity to do follow-up studies on many of these patients. Recent investigations have included operative surgery on skin cancers of two patients by the CO_2 laser alone, without the use of other surgical instruments.

Controls for laser surgery in these laser investigative studies have included the knife, high-frequency electrosurgical equipment, the special plasma torch of Brayshaw, cryosurgery with liquid nitrogen, and X-ray radiation, both conventional and Grenz x-ray.

The Department of Dermatology has a phototesting center for the testing of patients sensitive to light. Such reactions are increasing with the introduction of new drugs, soaps and cosmetics. This center makes it possible also to test patients for sensitivity to laser irradiation.

TABLE NO. 3

LASER SYSTEMS USED ON SKIN OF MAN

FROM THE LASER LABORATORY

MEDICAL CENTER - UNIVERSITY OF CINCINNATI

RUBY - Skin testing and treatment

Normal Mode
Q-switched
Picoseconds

NEODYMIUM - Skin testing and treatment

Normal Mode

ARGON - Skin testing and treatment

YAG - Skin testing and treatment

CO_2 - Skin testing and treatment

KRYPTON - Transillumination

HELIUM-NEON - Transillumination

HELIUM-CADMIUM - Transillumination

TABLE NO. 4

PATIENTS WITH SKIN DISORDERS TREATED AT LASER LABORATORY

1962 - 1969

TATTOOS - 400

VASCULAR BIRTHMARKS - 129

CANCERS - 54 (Lesions - 303)

MISCELLANEOUS - 30

TOTAL PATIENTS - 613

In addition, patients have been tested to attempt to develop minimal reactive dose thresholds. These programs are being developed in connection with cooperative studies with Dr. Wordie Parr[10] and Dr. Arnold S. Brownell.[11] Preliminary studies have indicated that these tests should be done on the flexor surface of the forearm. Already, more than a thousand impacts of this type have been done on Negro and Caucasian volunteers. (Table No. 5). One individual in this series (L.G.) has received more than 900 impacts of laser for such specific testing purposes over a period of seven years. The first report on this subject was made in 1964.[12] For the skin, at least, the minimal reactive dose (MRD), appearance of an erythema or redness without swelling or edema, may not be the same as "maximum permissible exposure" (MPE) or "maximum safe exposure" (MSE) for eye safety. Current studies in MRD of the skin are concerned with the relation of reactions which do not show redness but do show functional disturbances without evident structural change, even with transmission electron microscopy.

In brief, clinical studies of the laser reaction with the skin have shown that the skin reaction is a non-specific coagulation necrosis, similar to that produced by an electrical burn or by the high-frequency electrosurgical apparatus. The differences relate to color absorption by the laser systems, precision of the cutting, and relatively bloodless feature of this laser surgical technique. At present, our current surgical research program is on the basic fundamentals in connection with critical analysis of laser surgery both as relates to the skin and other viscera, especially, such hemorrhagic organs such as heart, lung, and liver.

Follow-up studies in patients have shown no evidence of carcinogenesis produced in any of the patients; some observed for more than six years. It is important to note that many of these patients have had high output laser treatments. Microscopic sections show non-specific scarring and none of the characteristics of post x-ray radiation. Such x-ray changes are, in brief, the absence of abnormal fibroblasts, endarteritis, and telangiectasia.

In addition to CO_2 laser surgery on patients, recent studies with Q-switched ruby laser impacts on normal skin and tattoos have included energy densities to 8 joules/cm^2 of energy density, 150 nanosecond pulses, target sizes 0.33 cm^2. Biopsy studies of these also show types of coagulation necrosis.

1. More superficial necrosis by Q-switched impacts, in some areas absence of marked epidermal change.
2. Intercellular dispersion of tattoo pigments by Q-switched
3. Less fibrosis by Q-switched

Our studies on Q-switch impacts on tattoos are similar to those of Laub and his associates.[13]

TABLE NO. 5

SKIN TESTING IMPACTS

Subjects - 9

Caucasian - 7

Negro - 2

TOTAL IMPACTS - More than 1000

So these laser scars are not x-ray scars. Whether such burn scars have any more predisposition than any other thermal burn scars for future slow carcinogenesis, is not evident at the present time. Many parameters of cancerization of ordinary burn scars are unknown at the present time, other than possiblities of continued tension and irritation due to location of the scar.

So, in brief, exposure to high output laser systems with laser that have been used on patients, show benign, nonspecific reactions in the skin. The future role of the value of laser surgery as relates to the skin will await more significant development in flexible high output systems and well-controlled clinical studies.

For the health physicist, the question is how valuable is our series of patients for determination of minimal reactive dose, the effects of severe laser burns, and the effects of chronic exposure. It has been pointed out by many investigators the problem of proper calibration of instrumentation is the real deterrent in determining the actual exposure of individuals. Our laboratory is fortunate in having as Directing Physicist, R. James Rockwell, Jr., who is an expert in the field of laser instrumentation and calibration. With the individual case records available, the actual dose delivered and received by the patient has been recorded in detail.

The determination of exposure of the skin outside the target areas and eye and general skin exposure of laser personnel throughout the years are not known at the present time. As indicated for laser personnel, there has been continued exposure during many thousands impacts of high output laser systems of the face, hands, and arms of many, over a period of seven years. At the present time, none of the personnel at the Laser Laboratory have had any detectable results of chronic laser exposure as judged by examination of the eyes by Dr. Kenneth Rowe, the Directing Ophthalmologist of the Laser Laboratory, or by clinical examination of skin and examination under Wood's light. As yet, there has been no evidence of carcinogenic effect on the skin of any of the laboratory personnel. Chronic actinic exposure is significant as regards chronic laser exposure since the areas of the face, hands and arms are exposed in both. True, there are differences in wavelengths but with the development of high output ultraviolet lasers it may be difficult, if not impossible, to separate out ultraviolet laser and solar exposure. In laser medical surveillance programs, this information is required on skin record forms of patients exposed to lasers.

The health physicist should be interested also in our experiments with laser epilation. With this technique it is possible to deliver a measured output to a single hair bulb area. So, it is possible to study hair cycle and pigment changes following irradiation to a single hair follicle. We are studying also the bleaching effect of Q-switched lasers on the hair shaft.

We have attempted to develop a model for chronic exposure with the use of pathologic skin to "diminish" long time requirement for chronic exposure. The so-called common, mysterious senile freckle was selected as the test target. Admittedly, this term is a confusing one since it means many things to many people. This basic brown spot starts as a nonspecific area and has the potential to change into a variety of reactions, some benign, chiefly of cosmetic interest, such as the seborrheic keratosis, some pre-cancerous, such as the actinic keratosis, and some definitely cancerous, such as squamous carcinoma (and the melanotic freckle?). The early recognition and the early developments and mechanisms of change of this spot is a current major research project of the Department of Dermatology. This lesion has been studied in its dynamic morphology with skin microscopy of the living skin at 20 - 40X magnification, replica microscopy, electron microscopy, both transmission and scanning (SEM). In addition, the immunobiological features of certain of these lesions have been examined with current immunologic techniques including immunofluorescence and also genetic studies to determine family patterns. This material will be reported elsewhere.

For the laser phase of this study, a senile freckle on the dorsum of the hand (L.G.) Caucasian, age 64, has been exposed weekly for a period of one year with impacts by normal mode pulsed ruby laser with the following characteristics: Laser #500, Maser Optics, 3.9 KV, 20-90 microseconds, lens fl. 38 mm., target size $2.4X10^{-3}$ - $3.4x10^{-3}$ cms^2, 14-20 $joules/cm^2$ energy density. Output readings were done with VOD-POD calibration instrument of Epstein of the Laser Laboratory. A total of 109 impacts were given. (Table No. 6). Reactions were characterized by pruritus followed by a small 3-4 mm. reddened papule in five to six hours. The redness persisted for 48 hours and then subsided completely. Controls included a similar senile freckle on another area of the same hand. Controls also included normal skin of the flexor surface of the right arm of this individual. This control was used to determine the reaction on normal non-pigmented skin. Impacts on this area showed no reaction. The chronic exposure area and the control were excised five days after the last impact. Histological, histochemical, replica microscopy, scanning electron microscopy studies were done both of the chronic exposure area and the control. The microscopic studies were viewed in detail by the consulting pathologist to the Laser Laboratory, Dr. Daniel Richfield,[14] who reported typical senile freckles both of the chronic exposure area and the control. There was no evidence of any cellular dysplasia suggestive even of precancerous change in the chronic exposure area.

TABLE NO. 6

CHRONIC EXPOSURE STUDY

Subject L. G. - Caucasian - Age 64 - Senile Freckle Dorsum
Left Hand

Laser - Ruby 6943 A° - Normal Mode - Maser Optics - Series 500
Pulse - 20 - 90 microseconds
Transmission - fl 38 mm. lens
Target Area - 2.4×10^{-3} - 3.4×10^{-3} cm^2
Energy Density - 14-20 joules/cm^2 (VODPOT)

Reaction - 3-4 mm. red pruritic papule

Total Impacts - 109   11/29/68 - 1/6/70

Results - Clinical - No change
Biopsy - No significant difference
between irradiated and control
senile freckle on dorsum-same hand

In brief, then, there was no significant changes between the chronic exposure and the control senile freckle. The same individual[12] had had numerous impacts on seborrheic keratoses, freckle areas and hundreds on the flexor surface of the forearm with Q-switched ruby picosecond, Nd, YAG, CO_2 and He-Cadmium laser. Recently, he received 4 impacts Q-switched ruby 150 nanoseconds, 8 joules/cm^2, target area 0.33 to a senile freckle on the hand. There was complete disappearance of the lesion and no perceptible scarring observed.

DISCUSSION

Studies, then, over a period of years of the acute and chronic skin exposure of man establishes within the limits of these investigations, that there is no evidence of a carcinogenic effect of the Laser irradiation. The specific differences between the normal mode, Q-switched mode, and the CW laser systems may be listed as follows:

1. selective pigment effect of ruby and neodymium and YAG
2. relative follicular apparatus sparing by ruby and neodymium lasers
3. more superficial reaction of Q-switched ruby lasers and less scarring
4. Absence of dissemination of lesion material with pulsed systems
5. CW lasers have precise, thermo-coagulation induced necrosis whose effects vary with the parameters of CW laser surgery and the organ involved.
6. no laser post-irradiation carcinogenesis has been observed in the tissues of man.

CONCLUSIONS

Our investigations, then, show that for the study of laser interactions in living tissues in man the skin may be used as an accurate, easily available, well-controlled test model system. With planned programs, this testing technique is safe and valuable. Much data is incomplete as yet for the health physicist in spite of the easy availability of this large organ. This lack of information concerns especially chronic laser irradiation effects, specific details of the skin reaction of ultra-short pulses and the effect of ultraviolet lasers.

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OCULAR HAZARDS OF Q-SWITCHED ERBIUM LASER

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Because of the serious ocular threat posed by laser devices operating in the visible and near-visible portions of the spectrum, less hazardous laser systems are being sought by both the civilian and military communities. One approach is to utilize lasers that operate in spectral regions where the ocular media are relatively opaque to the incident radiation. In this respect the erbium laser offers a theoretical advantage based upon its emission spectrum in the infrared[1].

Depending upon the host material employed, the emission wavelength of erbium varies from 1.53μ in glass to 1.64μ in Yttrium-Aluminum-Garnet (YAG). The transmittance of the eye at the erbium wavelengths is quite low as shown in Figure 1. This is a composite curve showing the transmittance of the ocular media as a function of wavelength. The visible and near-visible portion of the curve is based upon published experimental data from several laboratories and shows that the transmittance of the ocular media from 0.4 - 1.3μ approaches unity. That is, attenuation of incident light by the eye in this region is minimal until absorption sites in the pigmented retinal epithelium and choroid are reached. The portion of the curve beyond 1.3μ represents the transmittance of a 2.2 cm layer of pure water and can be considered a theoretical approximation to ocular tissues. At the erbium-glass wavelength (1.54μ) one can estimate 10-orders of magnitude decrease in ocular transmittance. One would anticipate a considerable attenuation of the erbium beam in the anterior segment of the eye and one would expect the cornea to be the primary absorption site and the primary locus of damage.

Based upon these considerations a series of experiments were conducted to study the ocular effects of the Q-switched erbium laser.

METHODS

An erbium laser was constructed in this laboratory to deliver Q-switched laser pulses at 1.54μ. The dearth of erbium laser rods of even moderately good quality seriously restricted the design technique. The resulting erbium-glass laser consistently delivered up to 100 millijoules Q-switched energy in a single 50 nanosecond pulse. Between 100 and 200 millijoules output double pulsing occasionally occurred yielding

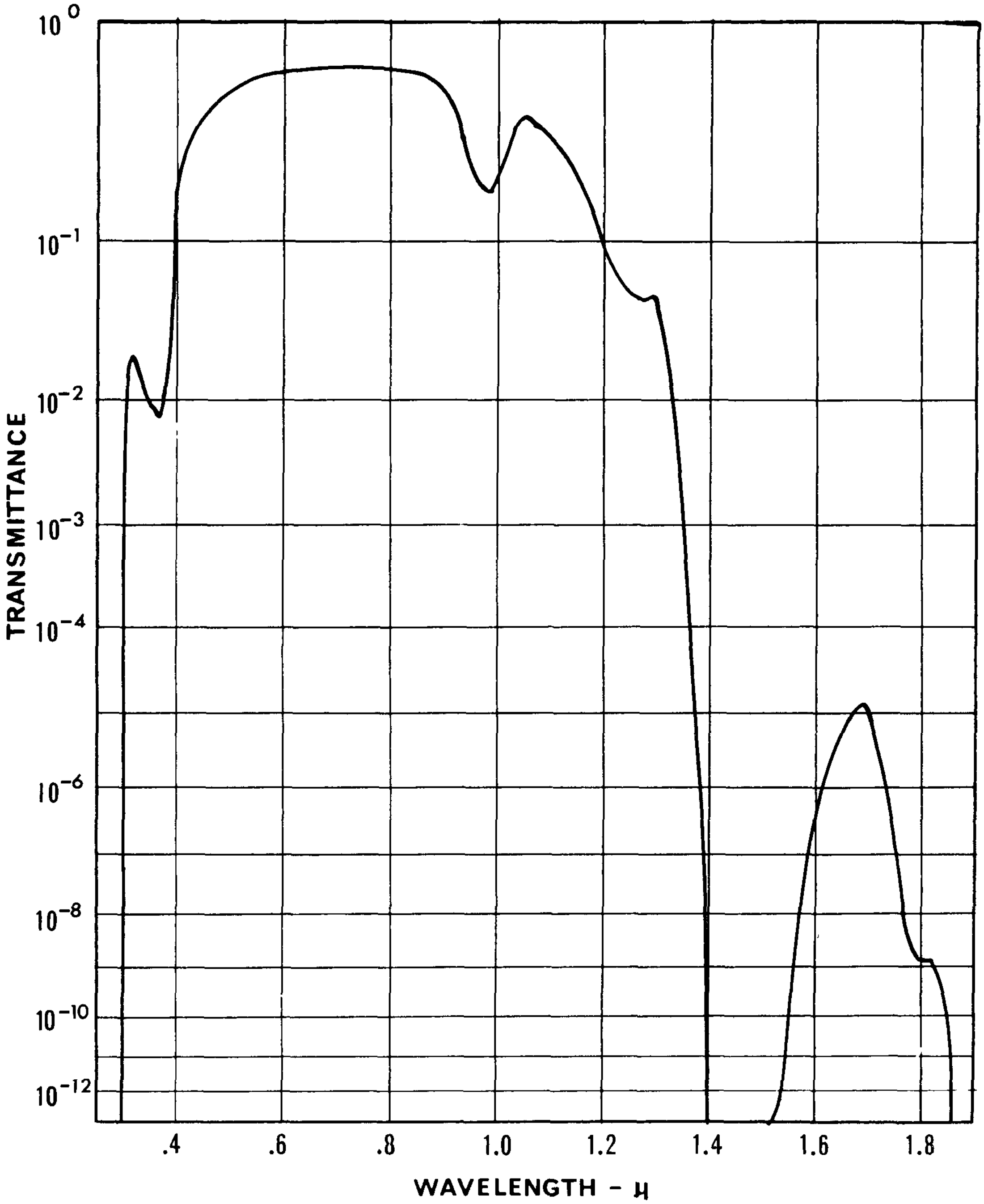

Figure 1. Spectral transmittance through human eye. Between 0.3 and 1.3μ, the curve is based on measurement of human ocular tissues[2]. Beyond 1.3μ the transmittance is that of 2.2 cm layer of pure H_2O.

two 50 nanosecond pulses separated by 200 nanoseconds. Due to the quality of the laser rod, the beam cross section was quite irregular.

An elliptical cavity was used to couple the linear flash lamp to the laser rod. Q-switching was accomplished by a rotating prism driven at 20,000 rpm and electronically synchronized to the flash lamp. A three-element quartz resonant reflector with a reflectivity of 65% was used as the output mirror. A sapphire optical flat inserted in the resonant cavity at the Brewster angle polarized the laser output. This was required because polarization dependent beam splitters were used in the delivery-detection system. The separate components were mounted on an optical bench yielding a total resonator length of 50 centimeters. A pulse forming network consisting of 1300μf capacitance in series with 850μh inductance provided a 3.5 msec pulse through the flash lamp. Triggering was accomplished through an in-line trigger transformer.

A detection system and a delivery system to couple the laser energy into the eye of the experimental animal were constructed as shown in Figure 2. A low power helium-neon laser beam was coupled into the delivery system through a beam splitter and carefully aligned to be co-linear with the erbium laser beam, thus facilitating aiming and alignment of the system. After passing through attenuating and focusing optics, the erbium laser beam was limited by a 2 mm diameter aperture. Immediately beyond this aperture, a beam splitter directed a portion of the energy to a diffuse reflecting surface where it was monitored by calibrated detectors. An indium-arsenide photodiode measured the duration and number of output pulses and a germanium photodiode with an integrating network measured the energy. The portion of the beam passing through the beam splitter was incident upon the cornea of the experimental animal. Calibration of the detection system was accomplished by placing a TRG 100 Ballistic Thermopile in the eye-exposure position and comparing the photodiode output to the thermopile output. This technique compensated for the peculiarities of the aperture, beam splitters and detectors by utilizing them in calibration exactly as they were used in measurement. The calibration was checked immediately before and after each animal experiment, giving results reproducible to ± 10% over the experimental period.

The animals used in these experiments were owl monkeys (Aotus Trivirgatus). Pre-anesthetic medication consisted of a sedative dose of phencyclidine hydrochloride (0.25 mg per kg) I.M. and atropine sulfate (0.2 mg) subcutaneously. Anesthesia was induced with sodium pentobarbital (approximately 5 mg per kg) via the saphenous vein. The pupils were dilated with phenylephrine hydrochloride (10%) combined with cyclopentolate hydrochloride (1%). Sutures of 3-0 silk were placed in the upper eyelids to facilitate their manipulation. Physiological saline was used to prevent drying of the cornea.

Immediately before exposure, the eyes were carefully examined by slit-lamp biomicroscopy and ophthalmoscopy, and any abnormal eye was rejected. The animal was placed in position in the delivery system and

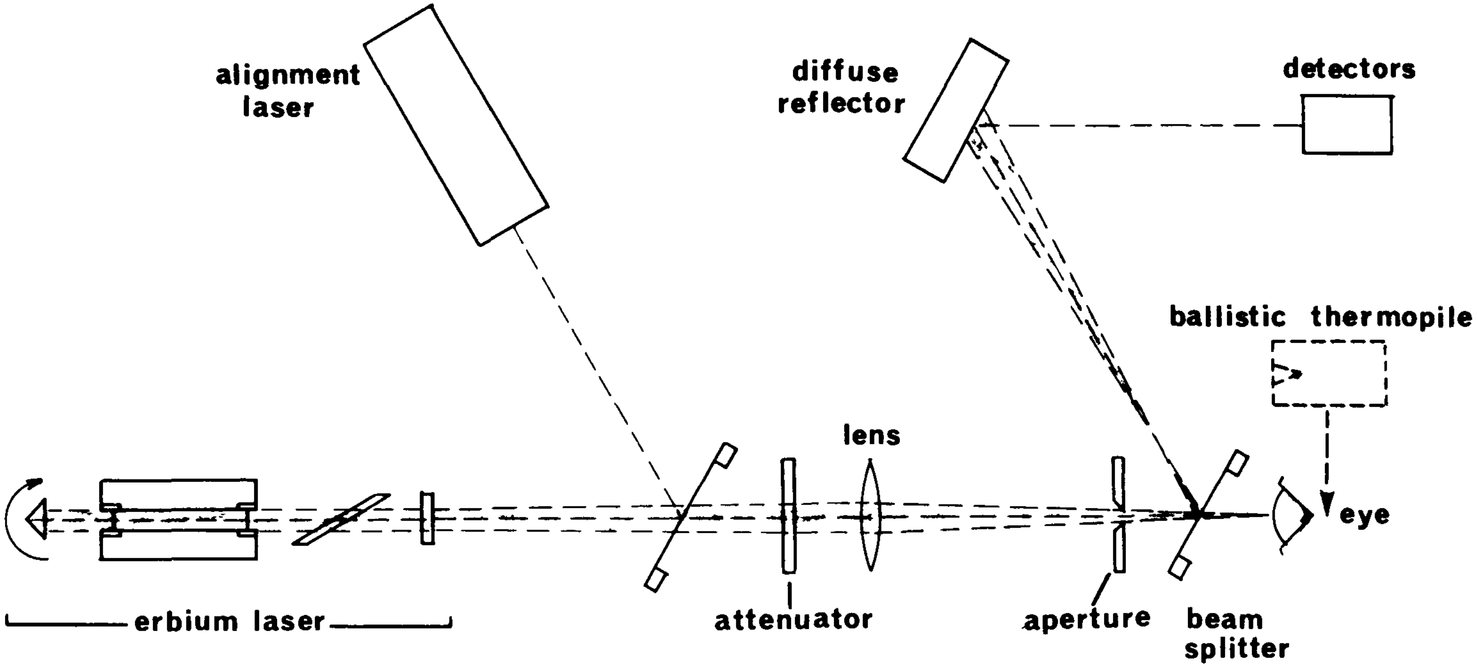

Figure 2. Schematic diagram of the erbium experimental configuration.

irradiated. Each corneal exposure site was examined immediately, and detailed biomicroscopy and ophthalmoscopy were performed at thirty to sixty minutes following exposure. Several eyes were observed at one day, seven days and three weeks following exposure.

Pathological examination was performed on all eyes. The eyes were enucleated either immediately or from one to fourteen days following exposure and fixed for twenty-four hours in 10% formaldehyde. Serial sections of paraffin embedded specimens were stained with hematoxylin and eosin and examined by light microscopy.

Two techniques of exposure were utilized. In the first series of experiments the direct output beam of the laser was employed without intervening optical lenses. In the second series of experiments a lens was used to focus the beam onto the cornea of the experimental animal. In order to define the threshold level for damage, it was necessary to determine the peak energy density within the focused beam. This posed the problem of measuring the characteristics of the beam cross section at the focus of the lens. A technique employing exposed polaroid film was used for this purpose. When impacted by laser radiation, the emulsion was burned from the film where the laser energy density exceeded a certain value. The film was subjected to a series of exposures with the laser at constant output, but with the beam attenuated in step-wise fashion by calibrated neutral density filters. Measurement of the diameter of the progressively decreasing spot size, allowed the relative energy density profile to be plotted (Figure 3). The beam at the focus was found to be approximately Gaussian. If the beam is assumed to be Gaussian, it is possible to calculate the peak energy density. For the purpose of computation the diameter of the beam spot is taken to be that diameter at which the relative energy density falls to a value 1/e of the peak value. The peak energy density is then the total measured energy divided by the area of the spot so defined.

RESULTS

In the first series of exposures using the direct output beam of the laser, corneal energy densities up to 1 j/cm^2 were achieved. No evidence of corneal, lenticular or chorioretinal injury could be detected at these energy levels. In the subsequent series of exposures with the laser beam focused at the cornea, ocular damage occurred and was limited to the cornea. The probability of corneal damage as a function of incident corneal energy density is plotted in Figure 4. All exposures to energy densities greater than 30 j/cm^2 produced injury. The median level for damage occurred at 21 j/cm^2 and no injury could be detected below 17 j/cm^2.

Minimal corneal lesions detectable by slit-lamp biomicroscopy were characterized by a shallow depression of the epithelial surface with localized epithelial edema and mild fluorescein staining. Discrete

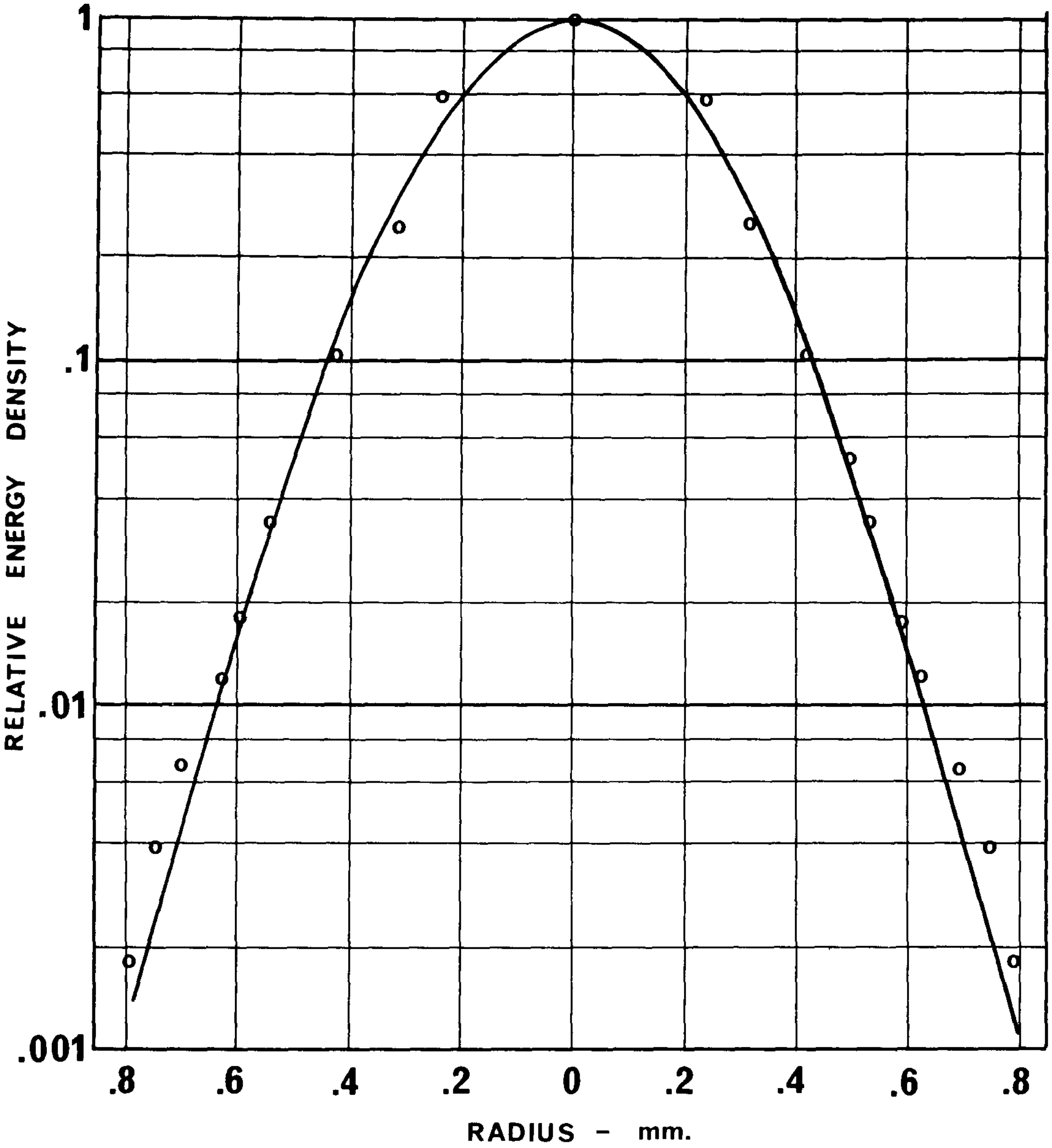

Figure 3. Profile of the focused erbium laser beam showing experimental data points and a theoretical Gaussian curve. (Erbium beam profile.)

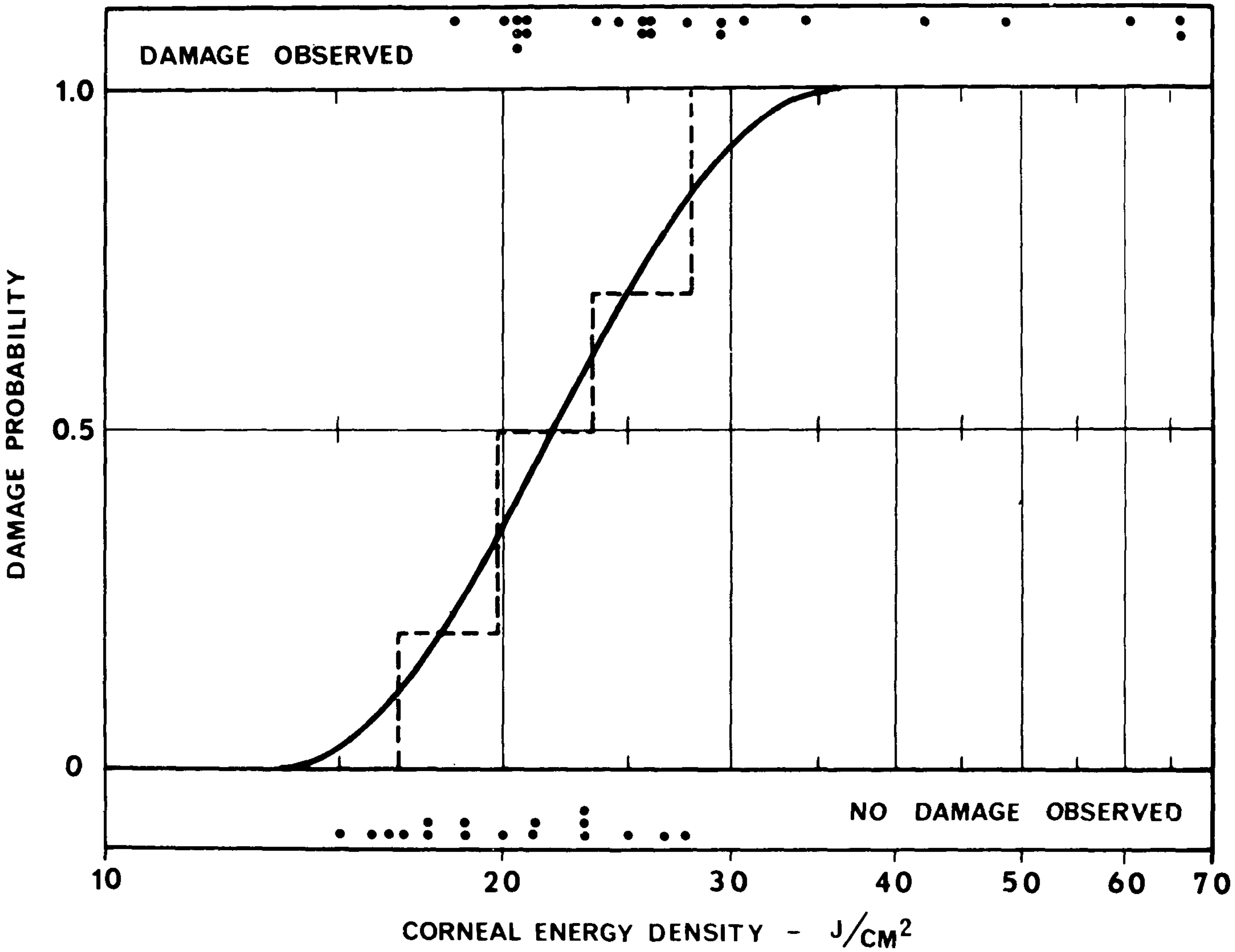

Figure 4. Hostogram of corneal damage probability as a function of corneal energy density for Q-switched erbium laser.

grayish opacifications of Bowman's membrane and the anterior corneal lamellae occurred at the impact site. More severe lesions showed a whiter opacification down to the deeper stromal layers and, in some cases, wrinkling of Descemet's membrane (Figure 5). No lens or fundus changes were noted, and anterior chamber reaction was absent. The epithelial defects healed in the course of 1-3 days, while the stromal opacification remained essentially unchanged at the end of three weeks.

In fresh corneal lesions the pathological changes were characterized by localized coagulation necrosis of the epithelium, Bowman's membrane and anterior stromal layers. Healed lesions showed proliferation of the corneal epithelium and the formation of collagenous scar tissue in the anterior stroma (Figure 6). No evidence of lenticular or retinal damage was found on careful examination of serial sections.

DISCUSSION

This report represents the first published data on the ocular effects of the erbium laser. In order to produce any ocular injury with the erbium laser at energy outputs currently achievable, it is necessary to increase the energy density at the cornea by focusing the beam onto the cornea. Under these conditions observable ocular damage is restricted to the cornea.

The threshold energy for ocular damage by the Q-switched erbium laser is 5-8 orders of magnitude higher than the threshold energy for ocular damage by Q-switched ruby or neodymium lasers as reported by a number of different laboratories. In addition, the implications of injury are seen to be vastly different when one contrasts the localized erbium-induced corneal opacity (Figure 6) with the massive and devastating retinal hemorrhage produced by a Q-switched ruby laser at a considerably lower energy level (Figure 7).

The feasibility of utilizing erbium lasers in such military items as laser range finders are currently being investigated by the Army Materiel Command. Feasibility studies to date have been favorable and perhaps we can look forward to the efficient application of this relatively safe laser.

Figure 5. Photograph of a fresh corneal lesion produced with the Q-switched erbium laser at 45 j/cm^2. Note the localized opacification of the epithelium, Bowman's membrane and stroma with radiating folds in Descemet's membrane.

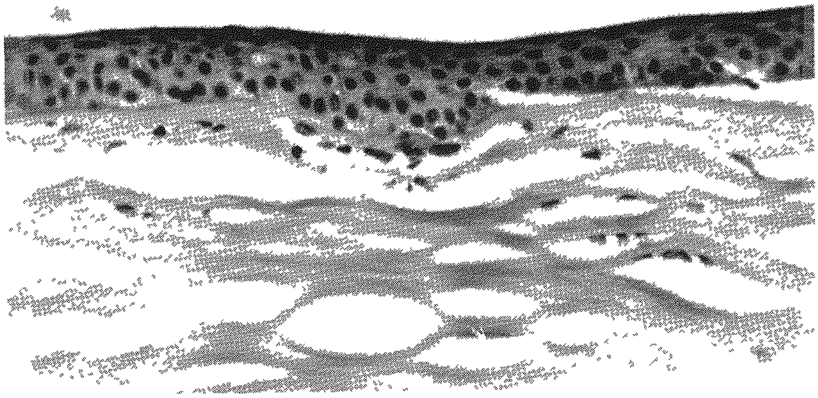

Figure 6. Epithelial facet at the site of a healed 10-day-old corneal lesion. The anterior stroma contains fibroblasts and inflammatory cells. Separation of stromal lamellae is artifactitious (H&E X500).

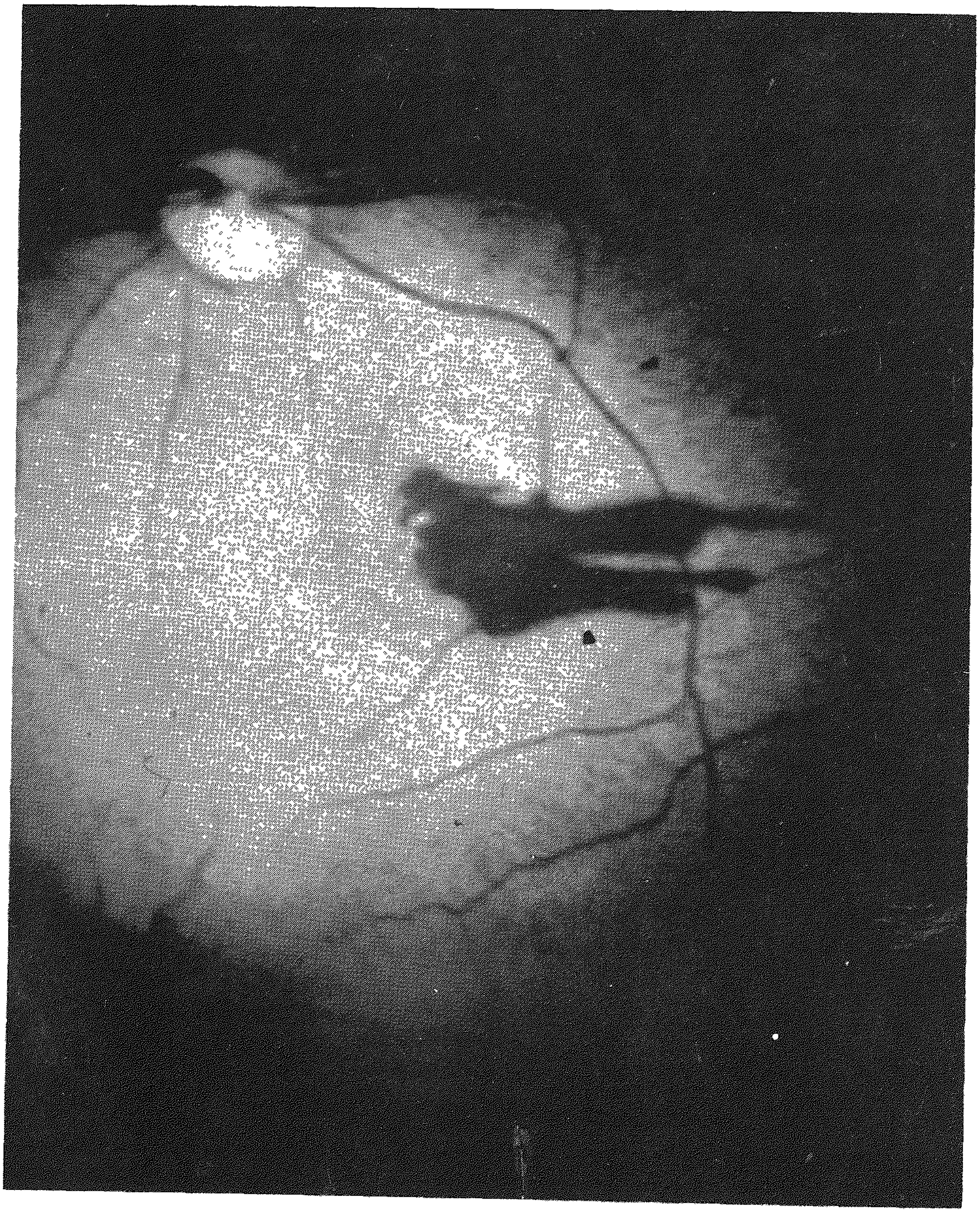

Figure 7. Massive retinal and vitreous hemorrhage produced in the eye of an owl monkey by a Q-switched ruby laser. Total intraocular energy 300 microjoules.

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CHRONIC EFFECTS OF LOW LEVEL HELIUM-NEON LASER IRRADIATION

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Although many workers are investigating the ocular hazards of lasers, relatively few of the experimental studies employ the He-Ne CW laser. Furthermore, the experiments which have been reported deal only with single exposures. Ham et al(1), propose that lesion formation is the result of thermal effects causing primary damage to protein structure in the retinal. Kohtiao et al(2), state that "the lesion is produced by a mechanism which is based on other than pure thermal effects". Based on pure thermal considerations, it would be expected that if a sub-threshold exposure gives no effect, a series of sub-threshold exposures separated by adequate cooling periods would also produce no effect.

The experiments are being conducted in two parts, the same equipment and procedures being used in both. The first part is concerned with determining the threshold for a single exposure. In the second part, these results will be used to establish suitable sub-threshold exposures for a series of chronic irradiations separated by intervals of at least one day.

The experimental animals were rabbits. Their eyes are sufficiently large and the threshold for chorioretinal burns is about the same for rabbit and man(3). Chinchilla rabbits were first tested but were unsatisfactory because the pigment of the retinal pigment epithelium was not uniformly distributed. Marshall et al(4), found that the amount of energy required to produce a threshold lesion varies according to the density of the pigment; accordingly, we chose to use the Satin variety of rabbits, in which the retinal pigment is fairly dense and its distribution is quite uniform. The animals were prepared for irradiation by dilating the pupils with Murocoll #2 (a solution of 10% phenylephrine hydrochloride and 0.3% scopolamine hydrobromide) and tranquilizing them with approximately 50 mg. of Sparine (promazine hydrochloride) injected intramuscularly.

Exposure was made with a Jodon HN-1576 He-Ne laser having a measured output of 22 mW and was controlled by the use of attenuation filters and an electric shutter regulated by a digital photo-timer. Actual exposure times were verified by a Hewlett-Packard Model 5202L Scaler-Timer and a BNC Model PB-2 Pulse Generator gated by a fast (15 ns rise time) photodiode. This combination is accurate to four significant digits. The power delivered to the eye was measured by a Spectra-Physics Model 401C Power Meter placed in the plane of the cornea.

The retinal target site was viewed through a Zeiss Model A Slit Lamp Biomicroscope with a Hruby Lens attachment (Figure 1). The illuminator of the slit lamp was modified to accept the laser beam through the side of the tube leading to the prism. A lens and a dichroic mirror, passing frequencies below 600 nm and 95% reflective at 632.8 nm, were incorporated to place the laser beam confocally along the axis of the slit lamp beam. A strong filter was placed in the beam to protect the eye of the rabbit during the procedure of aiming the laser beam. Aiming was done by manipulating the slit lamp illuminator to place the laser beam on target. This arrangement produced a spot on the retina of approximately 100µ diameter. With his own eyes protected by a suitable filter, the experimenter could monitor the target area during exposure and thus observe whether any movement of the eye occurred.

The retina was photographed before and after each exposure with a Kowa RC-II fundus camera. A green filter with a strong absorption between 580 and 600 nm placed before the lens heightened contrast and made the lesion more easily visible.

Histological studies have not yet been made, but are planned for the future. The primary criterion of damage has therefore been the identification of a visible lesion on a fundus photograph (Figures 2 -4). Lesions detectable photographically after 24 hours were accepted as lesions for this study, as distinguished from those visible within two minutes post exposure, which is the accepted criterion for threshold lesions. It has been reported in the literature that intensities of 1(2), 3(5), and 8(6) mW have not produced lesions for any duration tested, but that a 24 mW exposure for 2.5 sec.(2) was successful in producing lesions.

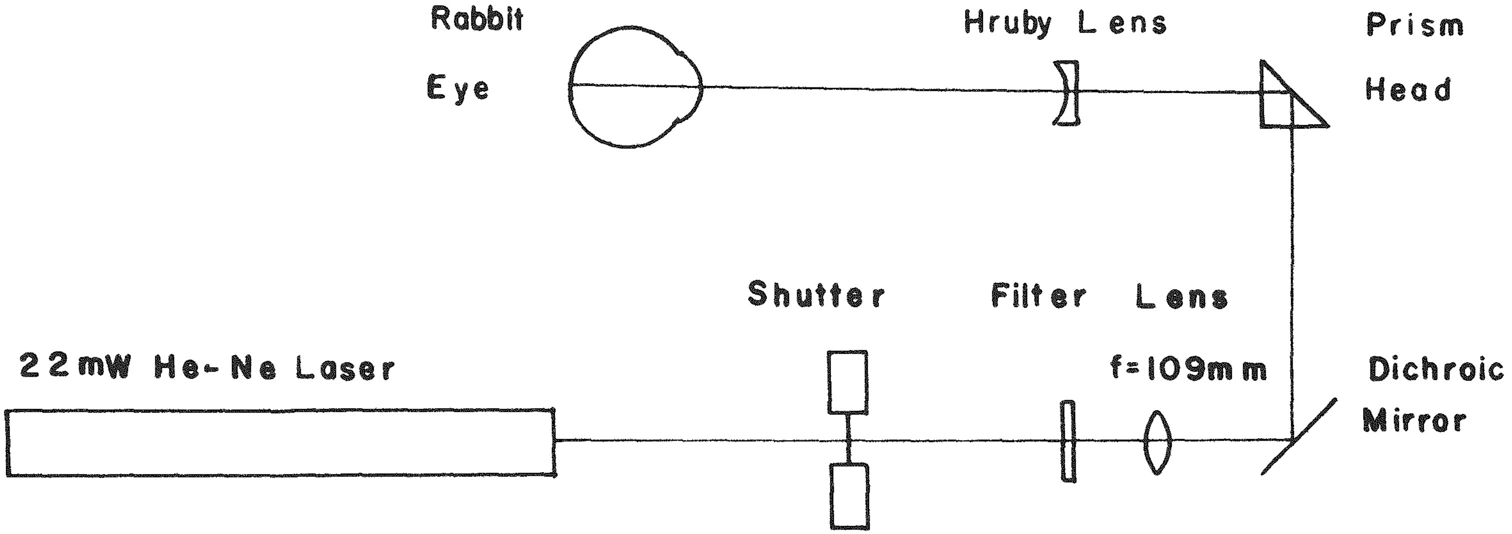

Figure 1. Equipment for laser irradiation of rabbits.

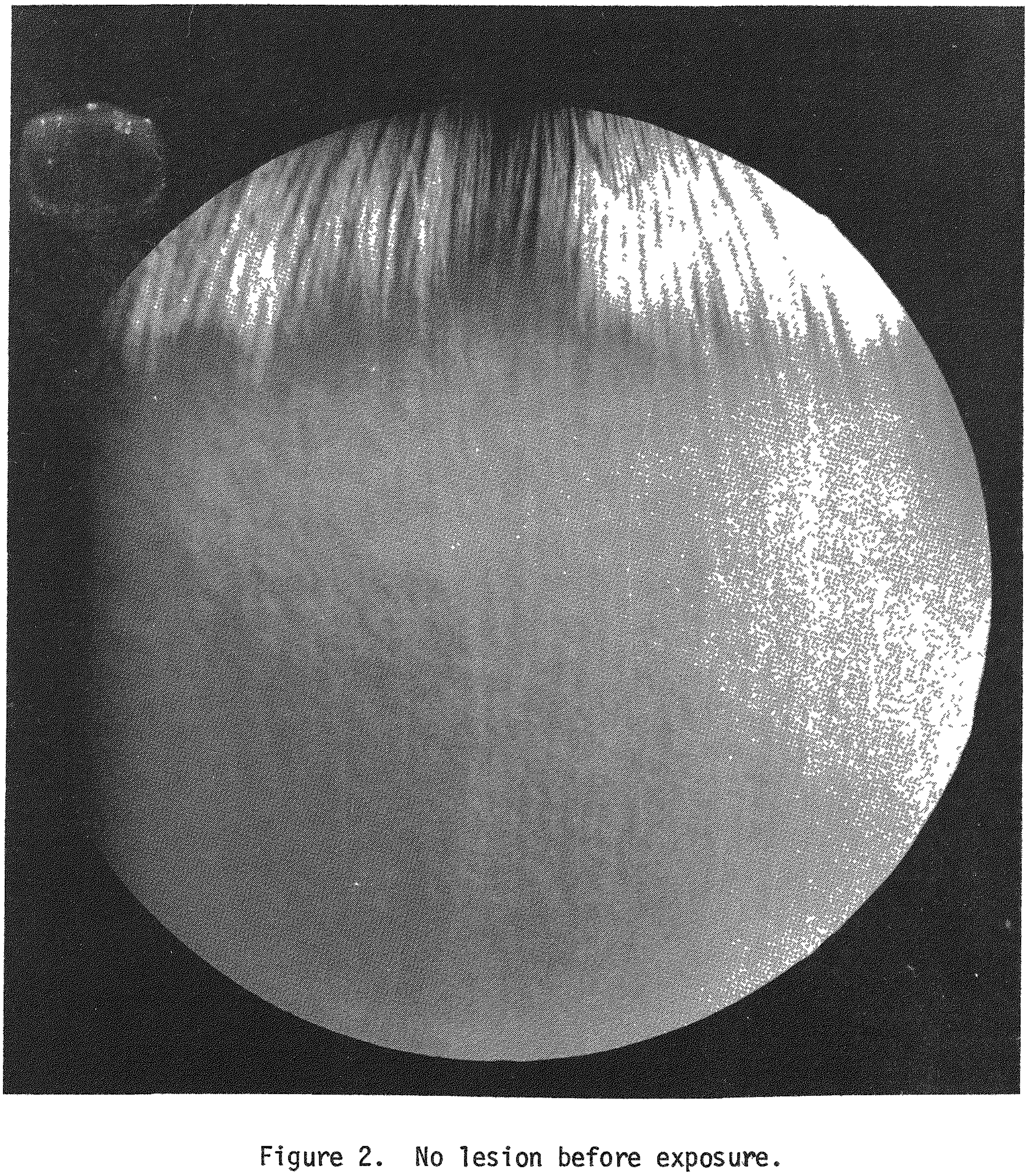

Figure 2. No lesion before exposure.

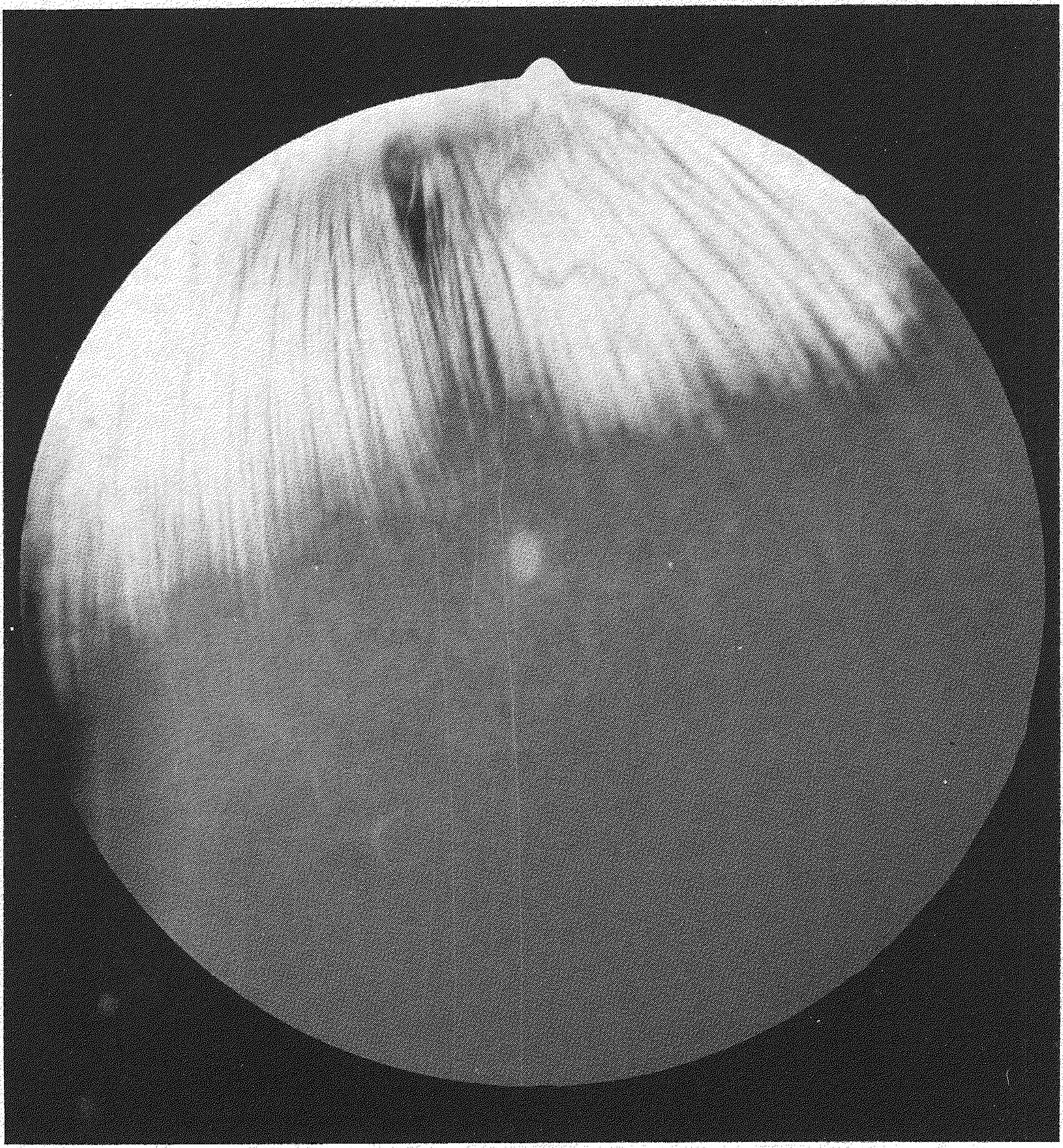

Figure 3. After exposure to 15 mW for 1.5 seconds.

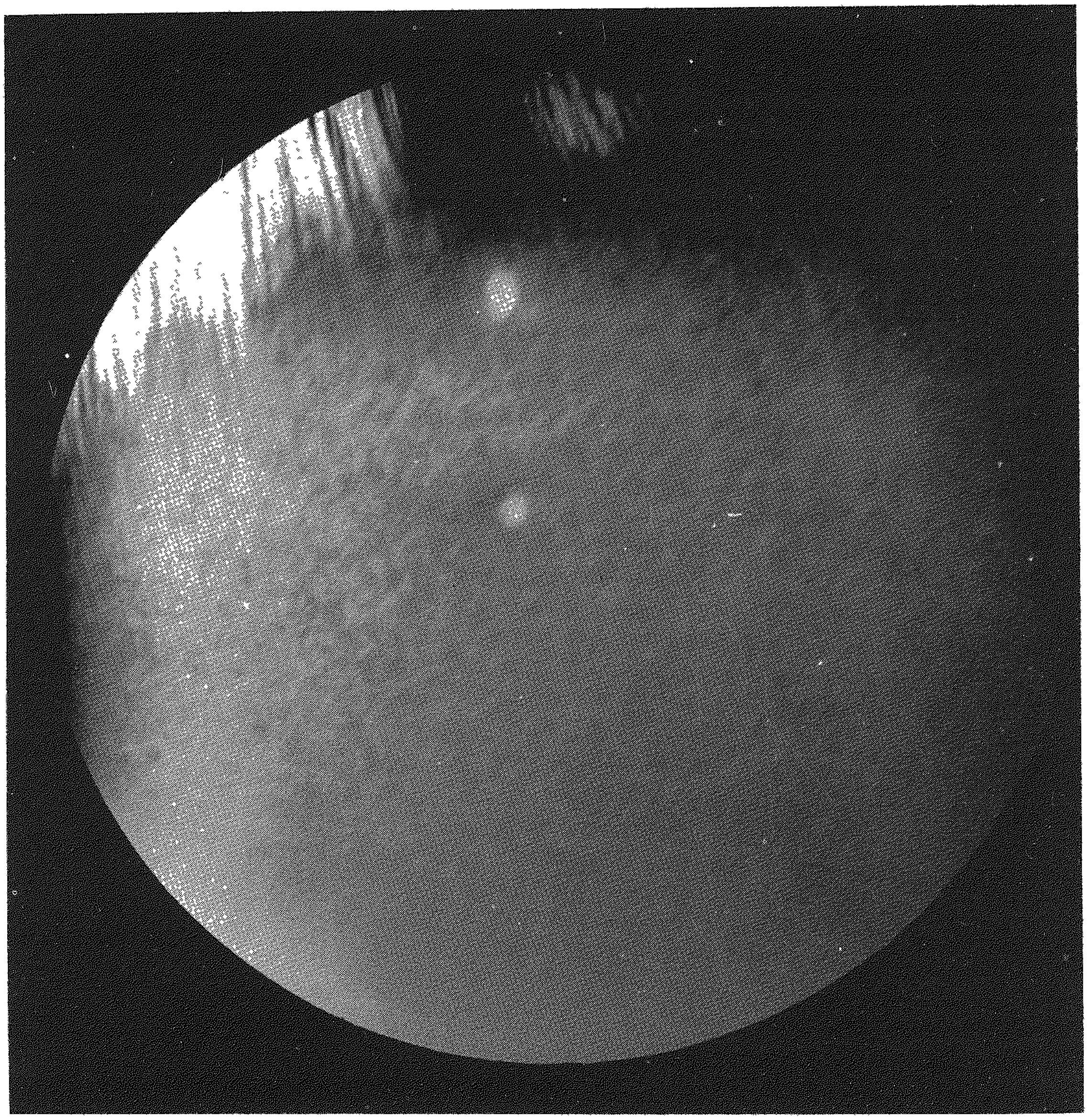

Figure 4. Second exposure after exposure to 13.5 mW for 0.725 seconds.

Preliminary results from these experiments include the following findings: For a series of 31 exposures of more than one second in duration, the threshold for causing a lesion was 9.5 mW (Figures 5 and 6). Between 0.5 and 1.0 sec., 5 of 11 exposures above 9.5 mW failed to produce lesions: The decrease in reliability for producing lesions for these short times suggests that at times less than one second, lesion production is a function of both duration and intensity. Investigation of this possibility is planned for shorter exposure times.

To estimate the power density upon the retina, a 10% reflective loss can be postulated upon entering the cornea; 90 - 93% transmission through the ocular media has been reported(1,7), as well as a 40% maximum absorption in the pigment epithelium(1,7), the target layer in this case. This means that for the worst case, approximately one third of the light incident upon the cornea reaches the target area, and the experimentally determined threshold level becomes approximately 30 watts/cm^2 upon the pigment epithelium or 75 watts/cm^2 upon the retina.

Chronic exposures of between 4 and 6 mW having durations of 60 seconds each have been initiated, but results are inconclusive at this time. Here the target site is identified by the use of two to three marker lesions, each produced by a single exposure to 13-15 mW for 5-6 sec. (Figure 7).

It was discovered that the lesions occasionally faded after a little less than a week, although sites exposed to greater than 13 mW for durations of more than 30 sec. tended to fade slowly or not at all. This is perhaps an indication that the extent of damage is dependent upon duration of exposure even for long exposure times. It is significant that after the lesion had faded and was no longer detectable with the fundus camera, a change in the appearance of the retina was still visible at the lesion site through the superior optics of the slit lamp. Histological studies are planned to determine whether this is an anomaly or permanent damage has indeed taken place at these sites.

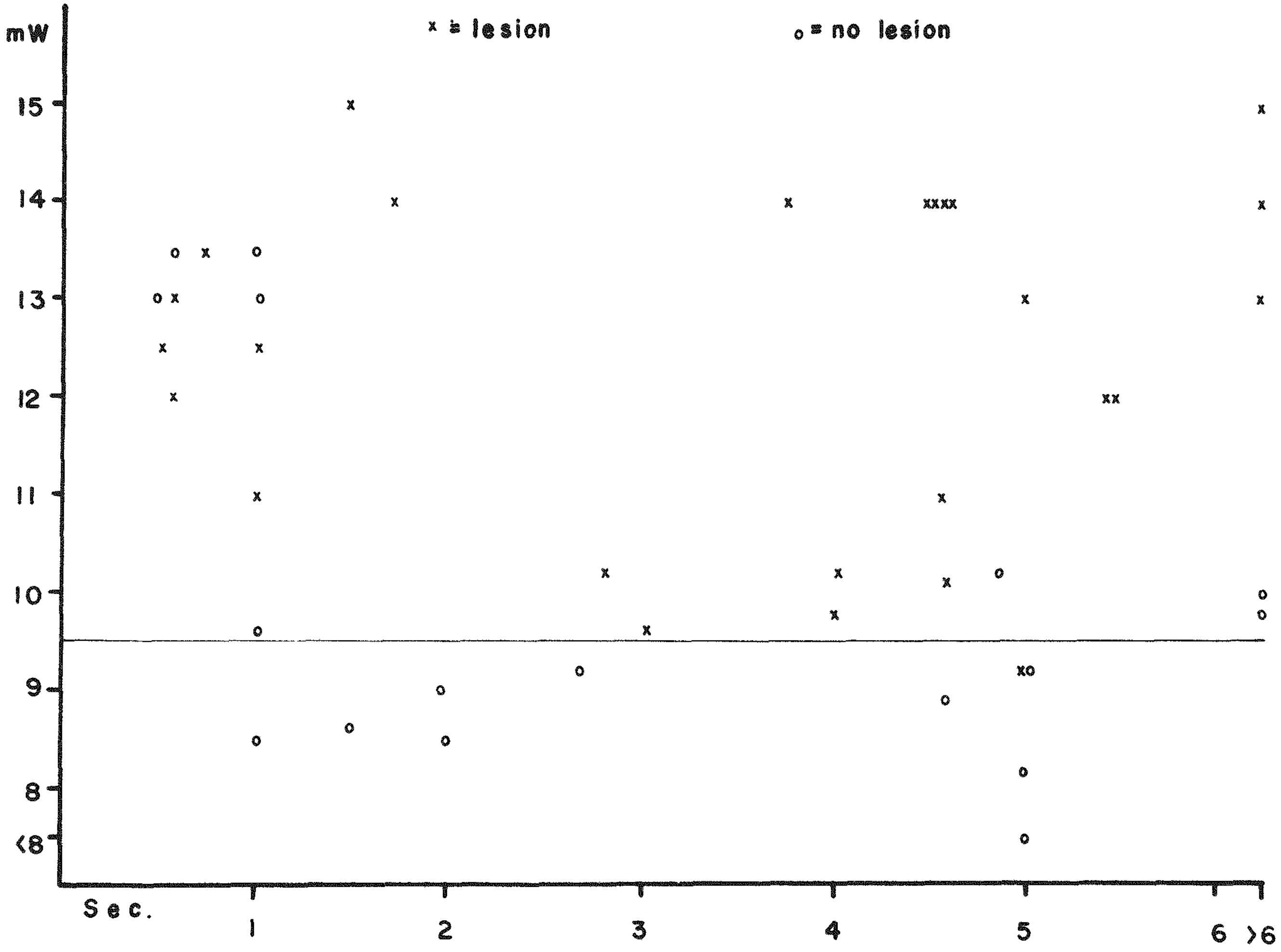

Figure 5. Retinal lesion production after one shot.

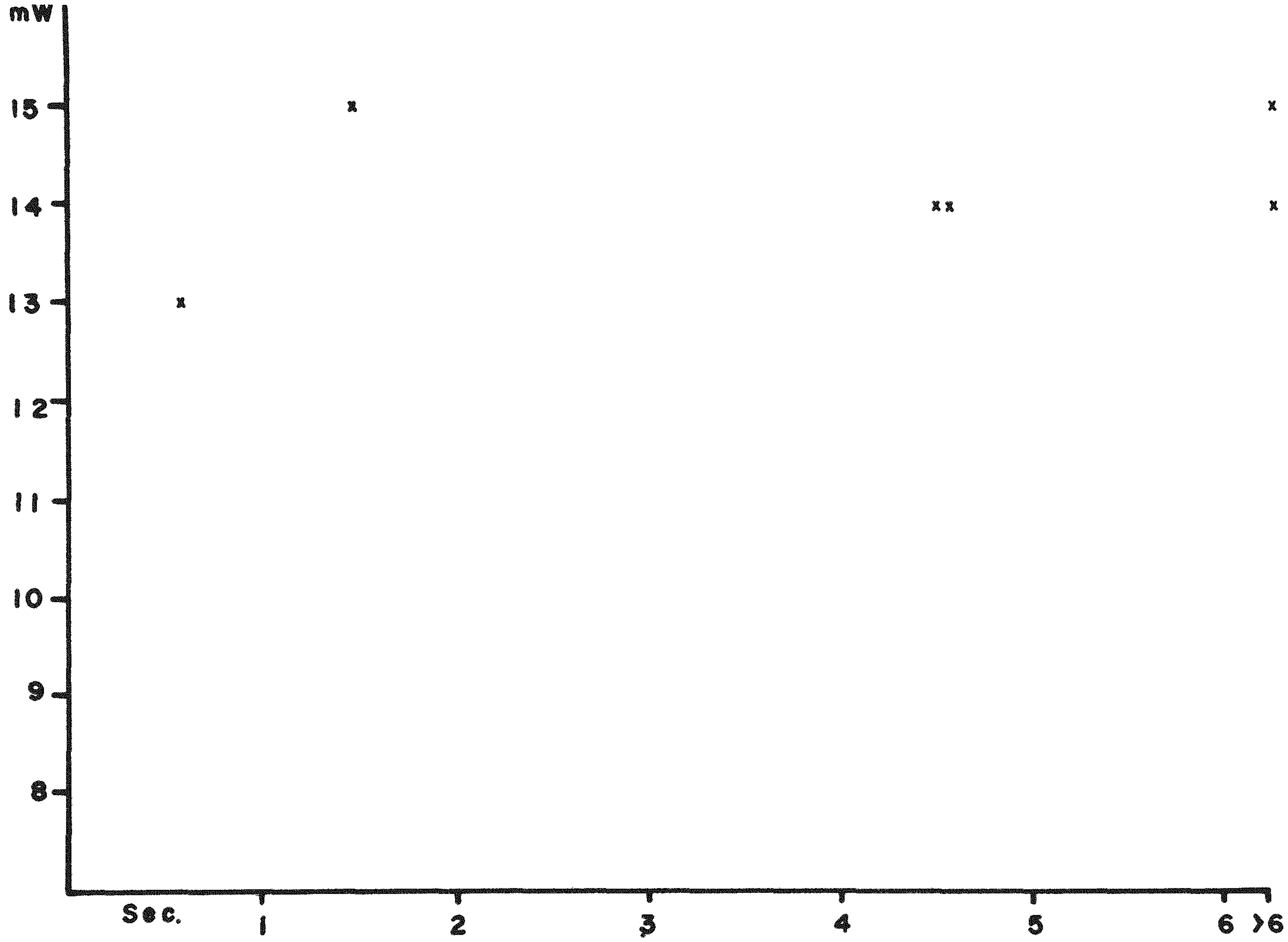

Figure 6. Lesions visible within 2 minutes of exposure for one shot.

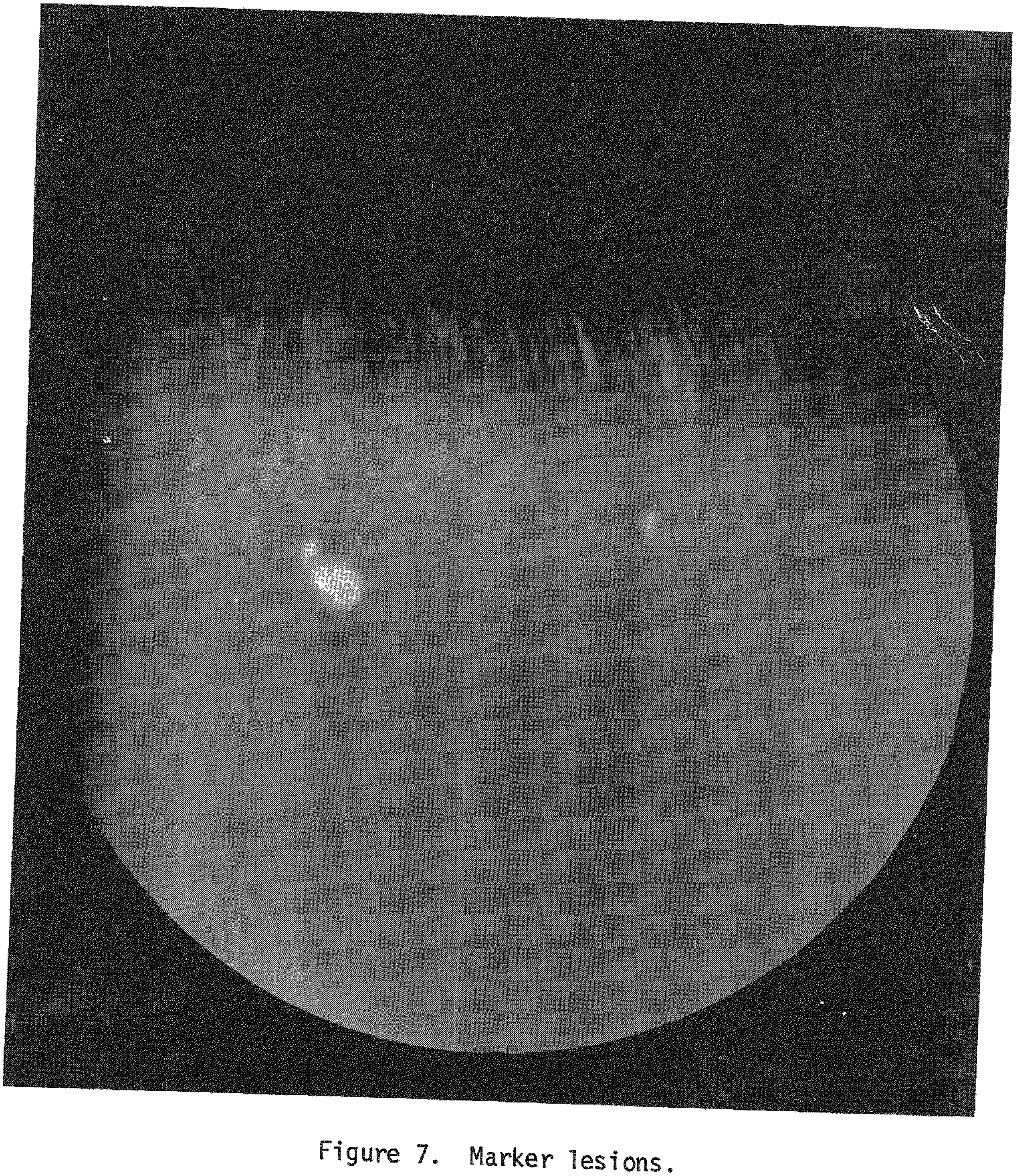

Figure 7. Marker lesions.

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LASER RADIATION VIEWED AS A POINT SOURCE OR A DIFFUSE SOURCE

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ABSTRACT

The evaluation of the potential ocular hazard resulting from an individual looking directly into the beam (intra-beam viewing) or observing a specular reflection of the direct beam requires the knowledge of several optical characteristics of the eye, which will be presented. The interpretation of thresholds of termal injury of the retina and the determination of the corresponding thresholds measured at the cornea require a knowledge of the optical gain of the human eye. The methods of deriving safe exposure levels are explained.

Whereas the greatest consideration of laser hazards has concentrated on evaluating the hazard resulting from viewing the direct beam, potential hazards from viewing the diffuse reflections of high powered laser beams are often overlooked. Several radiometric relationships permit the evaluation of diffuse reflection hazards in a very straightforward manner. The methods of developing a second set of safe levels for viewing diffuse reflections are presented. The practicality of two sets of safe levels is illustrated by evaluating a typical laboratory laser arrangement and pointing out the potential hazardous viewing conditions with the requirement that only the output irradiance of the laser be known.

LASER RADIATION VIEWED AS A POINT SOURCE OR A DIFFUSE SOURCE

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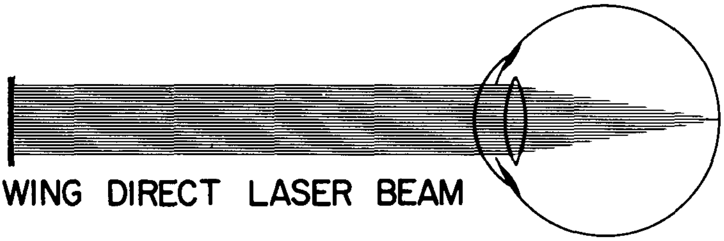
The evaluation of the potential hazards to the eye resulting from an individual looking directly into a laser beam (intra-beam viewing) or from observing a reflection of the direct beam requires an understanding of the optical performance of the human eye and thresholds of injury. In the visible and near-infrared region of the spectrum from approximately 400 nanometers to 1400 nanometers, the ocular media transmits much of the incident radiation to the retina.[1] When the eye directly observes the direct beam of a collimated laser, it is possible if the eye is relaxed to focus the incident energy into an extremely small "point" image on the retina (see top of figure 1). On the other hand, if the eye observes an extended light source, such as a lightbulb or a diffuse reflection of a laser beam, the eye focuses the incident energy into a considerably larger image as shown at the bottom of figure 1. Clearly, in evaluating the hazard of viewing laser radiation, or radiation from any other intense light source, one must know how the energy incident upon the front of the eye (the cornea) is transmitted to and focused at the retina.

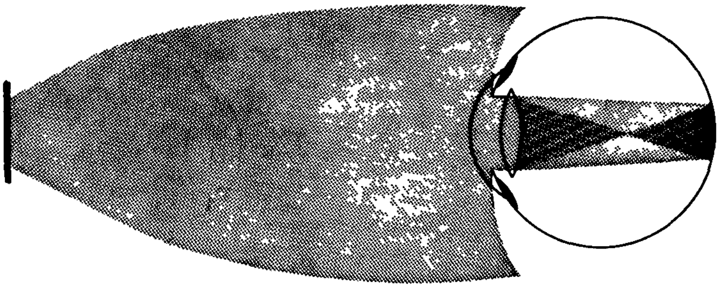
DEFINING THE OCULAR HAZARD FROM INTRA-BEAM VIEWING

Those lasers which produce a beam of radiant energy in the visible and near-infrared regions of the spectrum, which are capable of delivering very high concentrations of energy to a very small area of the retina, can do so even at considerable distances from the laser. This capability results from one of the characteristics which distinguishes the laser from other conventional sources of radiant energy such as a lightbulb or a flame. This characteristic is its beam collimation (or capability of collimation in the case of Ga-As laser diodes). This means that the beam has a plane wavefront, i.e., the light rays in the beam are parallel. The relaxed eye focuses such parallel rays of light to a very small "point" image on the retina, just as it focuses the parallel rays from a star to such a "point", as was shown at the top of figure 1.

This"point" image on the retina, however, it not truly a geometrical point, but a very small disc of approximately 10 to 20 microns in diameter. This spot size is determined by the physical phenomenon of diffraction and the optical aberrations introduced by the cornea of the eye. Since the amount of laser light entering the eye is a function of the pupil size, the gain in light intensity from the cornea to the retina is approximately the ratio of the area of the pupil to the area of the image. This ratio, or "optical gain" of the eye, is typically 100,000 to 200,000 (figure 2). Considering this magnification factor, it is easy to see



(a) VIEWING DIRECT LASER BEAM



(b) VIEWING DIFFUSE REFLECTION

Figure 1. A diffuse reflection of a laser beam normally can be viewed, because the concentration of light on the retina is not as great as in the case of the direct beam. However, some lasers can produce hazardous reflections even from diffuse surfaces.

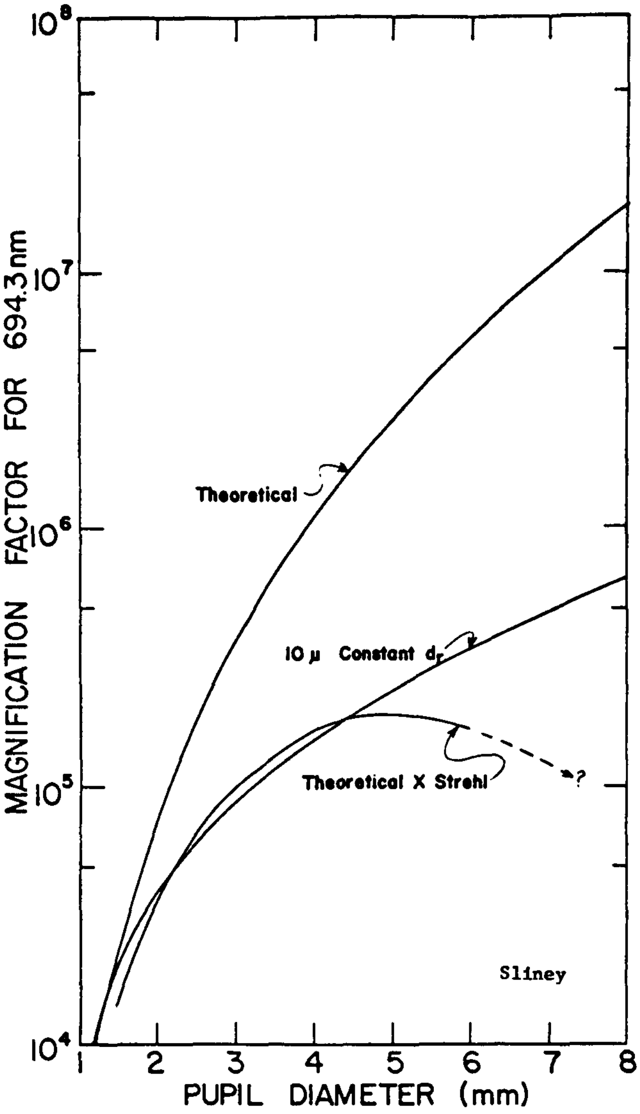


Figure 2. Influence of pupil size on magnification factor of corneal to retinal irradiance. Theoretical curve was obtained using Airy formula for peak retinal intensity. A second curve shows the magnification factor if a constant value of 10 μ were used for the retinal image diameter. Final curve is believed to accurately represent the magnification factor and was derived by multiplying the theoretical limit by the Strehl ratio, reported by Gubisch (1967).

why the eye is the most vulnerable organ of the body to laser injury. As an example, consider a beam irradiance of 5 mW/cm^2 incident upon the cornea (pupil size 5 mm), the retinal irradiance would be approximately 1 kW/cm^2! This cornealirradiance would be simple to achieve with a small 2 mW helium-neon laser.

It should be noted, however, that laser radiation in the ultraviolet and far-infrared regions of the spectrum does not penetrate the cornea. Thresholds for injury of the skin are comparable to those for the eye at these wavelengths. The principal laser which operates in the far-infrared spectrum is the carbon-dioxide, nitrogen laser which emits at 10.6 microns.

The foregoing discussion of intra-beam viewing applies to only the worst-case-condition of viewing laser light and does not apply to the viewing of extended sources such as diffuse reflections which are most often encountered in practice. The criteria for safe exposure to diffuse reflections of laser radiation -- or of any extended source of high intensity -- may best be defined in terms of an acceptable "brightness" or radiance (W/cm^2·sr), since a given source radiance will produce the same retinal irradiance, I_r, independent of distance, as shown by the following:

$$I_r = 0.27\ RTD_e{}^2$$

where R is the source radiance in W/cm^2·sr (j/cm^2·sr may be used for pulsed lasers, giving I_r in j/cm^2), T is the transmission of the ocular media (dimensionless), and D_e is the pupil size in centimeters. To further clarify this concept, consider the following example: A man views a diffuse reflection of 1 centimeter diameter laser beam at a distance of 1 meter and receives a retinal irradiance of I_r. If he steps back to a viewing distance of 2 meters, the irradiance (W/cm^2), which could be measured by an instrument in front of his eye, drops inversely as the square of the viewing distance to one-fourth the level measured at 1 meter. However, the diameter of the retinal image decreases to one-half its original size; hence the image area is decreased by one-fourth. Thus, we conclude that although less radiant power entered the eye, it was concentrated into a smaller image, such that I_r remained constant. For a perfectly diffuse Lambertian source, the retinal irradiance is also independent of viewing angle.

Limitations to the formula apply if: (1) the source is unresolved (a "point source"); or (2) if the radiant energy is attenuated between the source and the observer, as by the atmosphere or protective eyewear; or (3) if the source subtends a large angle (more than a few degrees).

BIOLOGICAL DATA

Several research laboratories in this country and overseas have performed investigations to determine the threshold for retinal injury resulting from exposure to intense light sources such as lasers and have found that thresholds vary with wavelength, exposure time, and retinal image size.[2,3,4,5,6] Differing criteria for injury based upon ophthalmic observation, histological techniques, and physiological techniques provide differing retinal injury thresholds. A detailed discussion of the research data available is beyond the scope of this talk.[7] Nevertheless, it has been customary in establishing safe exposure levels to insert a safety factor based upon an understanding of the limitations of the biological experimental techniques.

DEVELOPMENT OF STANDARDS

Present exposure standards for intra-beam viewing specify safe irradiances incident at the cornea since these values may be measured. The ocular exposure criteria are derived generally by extrapolating a retinal damage threshold productive of a large ophthalmoscopically-visible lesion, to the minimum possible retinal lesion which is typically 10 to 20 microns in diameter (approximately the diffraction-limited Airy disc). The corresponding dose at the cornea is then less by a factor on the order of magnitude of 10^5 (see figure 2 for the estimated optical gain of the human eye). Exposure standards used by the Army and Navy[8] are given below.

Ocular exposure for the wavelength region 0.4 to 1.4 microns:

10^{-7} j/cm^2 - q-switched pulse

10^{-6} j/cm^2 - non-q-switched pulse

10^{-6} W/cm^2 - continuous wave

Skin exposure for wavelength region 0.4 to 1.4 microns:

Multiply the foregoing values by 10^5

Ocular and skin exposure at 10.6 microns (CO_2 laser):

0.1 W/cm^2

Developing such standards requires assumptions relating to the minimal possible lesion size, the mechanism of damage, dose variations, wavelength variations, significance of forward scattering in the ocular media, and other questions which require resolution before more accurate determinations can be made. Despite the shortcomings, the computed levels are considered to be reasonable at present. At first glance, it may seem that the establishment of only four ocular exposure values is an oversimplification; however, our experience would indicate that they are adequate, in view of the available biological data and the uncertainties often associated with how they must be applied.

The method of expressing the foregoing ocular exposure levels is based upon many considerations. First, although the retina is the site of injury for visible and near-infrared laser radiation, retinal exposure criteria are not used. Past experience with safe retinal exposure levels created problems for many users who were not familiar enough with physiological optics to extrapolate retinal doses to the exterior of the eye. Second, these levels disregard any consideration of "near-field" viewing conditions (as first explained by Solon, Aronson and Gould in 1961[2]), since the near-field condition has little applicability in practice and furthermore has caused much confusion owing to lack of distinction between intrinsic beam divergence (divergence between two adjacent rays within a collimated beam) and divergence defined by the outer envelope of the beam or by some averging methods. Third, no distinction is made between different pupil sizes associated with night and day, since there is every indication that the optical gain of the eye remains largely unchanged(figure 2). As explained previously, safe exposure levels for viewing diffuse reflections are specified at the diffuse surface and not as an irradiance at the cornea of the eye.

Unfortunately, there exists some question whether the dependence of dose rate for threshold of injury with spot size, which is known to exist with continuous wave sources, may also exist for pulsed sources (even q-switched). Until this dependence is better understood, the use of a single set of safe radiances, based upon biological data for large retinal image sizes, must be used and may provide a conservative analysis of the hazard when source sizes are very small. The safe radiances from diffuse reflections are not expressed as radiances, but as radiant exitances* which are more easily applied in practice. The radiant exitance for a Lambertian source is the product of π and the radiance. The safe radiant exitances used by the Army and Navy are:

0.07 j/cm^2 - for q-switched pulse

0.9 j/cm^2 - for non-q-switched pulse

2.5 W/cm^2 - for continuous wave

THE EVALUATION OF HAZARDS

In any practical problem, one must first distinguish between hazards resulting from viewing the primary beam and viewing reflections. Perhaps the simplest procedure is to first determine whether it is safe to view a diffuse reflection of the primary beam, since hazards from diffuse reflections occur only with high power lasers. The great practicality of the safe levels for diffuse reflections may be illustrated by considering a typical laboratory situation (figure 3), where a q-switched laser beam is directed along an optical bench through a beam splitter and toward a white diffuse target. If the beam irradiance upon the target is

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*The radiometric terms used in this paper follow the definitions of Systeme Internationale.[9]

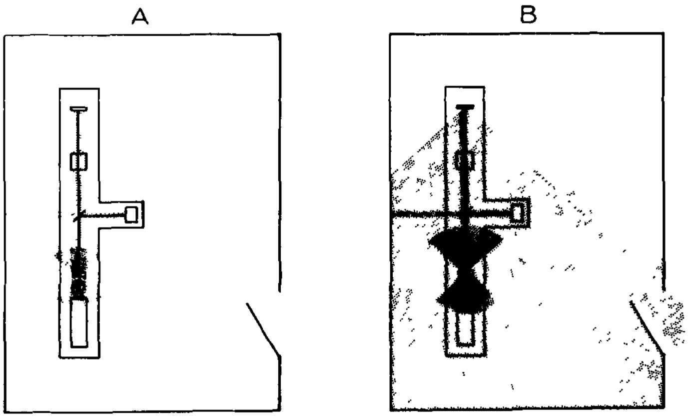

Figure 3. Potentially hazardous areas (shaded) within a laboratory may vary greatly, depending on whether the laser can (B) or cannot (A) produce a hazardous diffuse reflection.

below 0.07 j/cm^2, the potentially hazardous area is limited to the beam path; however, if it is above 0.07 j/cm^2 (for a 100 percent reflecting target or 0.14 j/cm^2 for 50 percent target, etc.), the potentially hazardous area is essentially the entire room. Because of the significant difference, high energy or high power lasers are defined as those capable of producing hazardous diffuse reflections and have different control measures, e.g., door interlocks are required in laboratory environments.

The foregoing example also illustrates the importance of still another factor; the probability of exposure, which cannot be overlooked. Most laser accidents which have been reported occurred when the probability of exposure was very high. At least one was the result of an individual viewing a hazardous diffuse reflection.[10] In this regard, the author believes that one of the principal reasons for the low incidence of laser injury in the past has been the low probability of an individual receiving a well-collimated specular reflection. While this low accident experience has prompted some to suggest that present safe levels are overly conservative, the author believes that it is unnecessary to raise levels which are presently considered to be sufficiently below injury-producing levels to be considered truly "safe." Rather, it would seem more prudent to create a wider understanding of the probabilities involved, so that hazard controls are not unrealistically restrictive. Once ocular hazards have been analyzed, the procedures for controlling these hazards are quite straightforward.[11] [12] [13]

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LASER HAZARD EVALUATION AND CALCULATIONS

Utilized in the Review of Laser Safety Plans and Procedures

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ABSTRACT

Exposure Hazard Evaluation considerations are discussed for continuous and pulsed laser systems. Basic laser source and beam parameters are illustrated. Computations are developed for determination of energy and power densities at the laser source aperture, observation point and at the eye piece of an optical magnifier. Calculations are also presented for appropriate optical filtration to reduce beam intensities to safe levels.

PREFACE

The purpose of this paper is to assist those newly interested in lasers and laser safety in the development of their knowledge and capabilities in the field of laser hazard evaluation. The equations presented in this paper are developed from basic fundamentals with appropriate definitions and comments being made where questions may arise. The results of the calculations parallel several well known efforts; i.e., LRL-Nevada Procedure NTS-341, April 15, 1969, and Mr. W. D. Burnett's research report, SC-RR-68-174, Laser Eye and Skin Hazard Evaluations. The paper is designed to give the reader a basic understanding to better utilize Mr. Burnett's report and Mr. Grahram W. Flint's paper, Derivation of Laser Hazard Criteria, Martin Company, Orlando, May 1966.

BASIS FOR HAZARD EVALUATION

Laser systems are evaluated for eye hazards based on the criteria established in NTSO-SOP Chapter 0570, Appendix 0570-A, Maximum Permissible Exposure Levels to Laser Radiation.

Industrial Safety problems are also considered, but their detailed evaluation is not the purpose of this paper.

Each laser system utilized at the Nevada Test Site is reviewed to determine if and when it could produce laser radiation exposures in excess of Appendix 0570-A guides. If a hazard potential exists, then the degree of the hazard is evaluated by calculation of the power and/or energy density values.

LASER SAFETY PLAN

Each laser operation at the Nevada Test Site shall have an established Laser Safety Plan which should have been reviewed and approved first, by the using agency organization's management and safety personnel and second, by the Radiological Safety Branch.

The plan should include an adequate description of the proposed laser usage and any considerations given to hazard control. If the laser system is known to be hazardous by user personnel, then a thorough hazard evaluation should be prepared. Absence of such an evaluation does not necessarily mean the system is safe.

The reviewer's duty is to review the hazard evaluation if presented or make an evaluation based on the information contained in the laser safety plan, operation procedure and laser registry form. The methods for making this technical review and some of the pitfalls encountered in making the evaluation are the subject of this report.

A good laser safety plan should consider the following:

a. A complete discussion of the purpose of the laser operation.

b. A description of the proposed laser operation showing:

    1. the method of laser utilization.

    2. a description of the system including the laser and <u>all</u> associated optics (i.e., beam divergence mechanisms, collimators, filters, etc.). A sketch can be most helpful.

3. areas in which laser irradiation hazards or industrial hazards could develop and controls utilized to prevent problems.

4. nearby operations which may be adversely influenced by the laser operation.

5. non-related operations which may be affected by the laser beam.

c. Procedures by which the laser operation will be conducted.

LASER HAZARD EVALUATION

Each laser safety plan submitted must be thoroughly reviewed to determine if any hazardous conditions exist or could develop as the laser is operated. The reviewer usually has the laser safety plan and registration from which information may be drawn. This data, however, is usually insufficient and discussions must be held with the user to permit a complete review of all possible laser hazards.

Procedures must be thoroughly studied to acquaint the reviewer with what is actually proposed. In several cases, review of procedures revealed contemplated modifications of the laser system which were not evident in the laser registration form. Laser registration information usually describes only the laser source, and not necessarily the entire system that the user proproses to operate.

The primary hazard to be considered by the reviewer is that of over exposure to laser radiation to the human eye or skin. Review of the safety plan and procedures should identify all of the possible hazards present.

A hazard may be so evident that the system design precludes irradiation of personnel. In this case, review would indicate and identify controls, making an elaborate hazard evaluation unnecessary. However, the setting up and adjustment of such an enclosed system may be hazardous. This possibility should not be overlooked and the user should be cognizant of safe procedures to be followed.

In a laser system where the hazard is expected, but suitable enclosures cannot be designed or would hamper the operation, the hazards must be evaluated and all possibilities considered.

Criteria defining maximum permissible exposure to laser radiation on the Nevada Test Site have been established as indicated in Appendix 0570-A. A copy of this appendix is attached at the end of this report. The eye hazard evaluation, essentially, is a problem of determing conditions whereby the laser system produces irradiation which would exceed these criteria.

SPECIFIC HAZARD EVALUATION CONSIDERATIONS

Knowledge of the laser installation is necessary and a sketch of the system is desirable. The reviewer must study the laser source and all associated optics, reflecting surfaces, collimators, eventual beam paths, targets, optical receiving devices and magnifiers. Consideration should also be given to the beam projecting beyond the target to determine the possibility of exposure to personnel on the ground or in aircraft at locations adjacent to or beyond the target area.

Technical data on the laser will be available from the laser registration form. This data specifies the type of laser (solid state, gaseous, liquid, etc.) and whether the laser output is to be continuous (C. W.) or pulsed, (1). Average output power should be indicated for C. W. systems as well as the primary and any secondary wave lengths which could produce hazards. Peak beam energy and operating wave lengths should be indicated for pulsed systems.

Pulse duration for pulsed systems is important, as criteria have not been set for very short pulses and high repetition rates.

Beam divergence and aperture diameter are also specified, but the reviewer must be aware of pitfalls if the laser has associated optics which would change these parameters, thereby converting an essentially safe system to an extremely hazardous one.

Associated Optics

Associated optics are used in most laser systems to modify the beam characteristics to produce the desired effect. A beam collimator is a normal component of laser systems. Additional optical devices are commonly used to modify the beam divergence and effective diameter. For alignment purposes, the associated optics produce a narrow beam of extremely small divergence, even from a basic laser source not having such characteristics. Other situations may require a broad beam with considerable divergence. Hazards are somewhat reduced for the latter situation as beam power densitites decrease rapidly as distance from the source increases.

Filters are sometimes incorporated in laser systems to provide various intensities without altering laser source characteristics. These filters may be sensitive to initial or subsequent irradiation which could alter their attenuation characteristics. Neutral density (N. D.) filters have a broad transmission response to various wave lengths of laser light. The characteristics of these filters should not change when the filters are irradiated by up to 10 watts of continuous laser radiation in the visible range. Specific filters may be incorporated to eliminate undesirable characteristic wavelengths producing a more nearly monochromatic output. The possibility of change in filter characteristics due to previous irradiation should not be overlooked, especially from pulsed, high energy laser, or when such filters are being relied upon to reduce beam power levels to safe levels for direct viewing by personnel.

Mirrors and beam splitters may be incorporated to direct the beam or portions of the beam to other locations. Controls on these devices should be evaluated when the beam intensities are hazardous.

Beam Path:

The beam path is the most important item to be considered. If the beam's path is completely enclosed and not capable of personnel irradiation, the eye hazard could be considered as eliminated.

If the beam may be projected through areas where personnel exposure is possible or intended, the power density or energy density of the beam must be considered. If the potential to exceed exposure criteria is present, appropriate steps should be initiated to preclude exposure to personnel not equipped with suitable protective devices.

Interactions with other operations in the vicinity must be considered when determing beam path. Personnel should be made aware of the beam's presence and location, and be instructed to avoid direct viewing without suitable protection, or should be excluded from the immediate area of the beam path.

Target:

Most laser operations utilize a target to intercept the beam or retro-reflect it. Depending upon conditions and the beam hazard the target should intercept the entire beam. In no case, when the beam is hazardous should be beam be reflected in unknown directions.

The area around the target should be reviewed and defined. If necessary, provision should be made to exclude personnel from the immediate area.

Optical Receiving Devices:

When optical devices are used to receive the laser beam or portions thereof, beam concentration may occur. This may be particularly hazardous if the beam is viewed directly through the optical instrument. The instrument; i. e., a telescope or binoculars, receives that portion of the beam intercepted by the objective lens (considerably larger than the pupil of the human eye) and transmits this through the eyepiece, with negligible total power loss. The beam diameter is reduced to that of the exit pupil of the device, approximately equal in size to that of the human eye pupil,but the power transmitted is essentially the same that was received at the objective lens. The net result is an increase of the power density by a factor of the ratio of the square of the telescope objective lens diameter to the square of the exit pupil diameter. If the original beam power density at the receiving objective lens is so increased, a marginal exposure level by such magnification could be increased to a hazardous one.

HAZARD CALCULATIONS

Laser Parameters:

Calculations of beam hazards are based on several parameters defined for each laser source or system. Although essentially the same parameters are utilized by all laser manufacturers, definitions of these parameters may vary and must be determined by the evaluator to make a meaningful calculation.

The derivation of formulas and calculations illustrated in this report utilize specific definitions of these laser parameters as defined and discussed below. In each case, a homogeneous beam with circular cross-section is assumed.

Consider the following diagram of a simple laser system (Figure 1, Page 347). The diameter of the effective aperture of the laser source is defined as D_L, usually measured in millimeters. If the laser port is bare; i. e., includes only those optics basically designed into the laser source, then the effective aperture is that of the collimated beam as it leaves the laser port. If an external optical system is employed to alter the divergence and/or to expand or decrease the initial beam diameter, then the effective aperture will be the diameter of the beam as it leaves the associated optical device.

The divergence is the vertex angle ϕ of a cone defined by the envelope of the beam effective edge as the beam propagates into space from the source (2). The divergence is usually measured in milliradians. The effective edge of the beam is defined by the radius of the cross-section (r_e) at which the beam intensity is reduced to one-half the maximum beam intensity present at the distance in question (3). This is illustrated in Figure 2, Page 347. The absolute or physical edge of the beam would be defined when the intensity of the beam at the distance in question reaches zero. Note that this edge is not used to determine the divergence angle.

The point at which the beam or target is observed is called the observation point. The distance from the source point to the observation point is denoted by R, and is measured in meters.

The diameter of the divergent beam at a distance R from the source point is denoted as D_R and may be measured in millimeters, centimeters or meters.

The minimum output power level (P) is usually indicated by the manufacturer of the laser source and is measured in watts. Note that this value is the minimum power level guaranteed in the manufacturer's specifications. The laser output power must be measured under the normal operating conditions in order to determine the true value. For low power C.W. gas lasers, the manufacturer's specified minimum level may be utilized in hazard calculations to obtain a preliminary estimate of any problems. However, when determing the safe viewing distances of the beam from the source or the optical attenuation of filters for safe viewing, the actual value for the power should be used. If this is not available, the actual value is usually less than 10 times the minimum value specified. It may be only 2 or 3 times this guaranteed value.

The total output energy (E) for pulsed laser systems is usually indicated by the manufacturer and is measured in joules.

The pulse length (duration time, t_p) and repetition rate (offtime, t_o) should be indicated. For very short pulses and high repetition rates $t_p < 0.1 \times 10^{-6}$ sec., $t_o < 10^{-1}$ sec.), measurements are difficult to obtain and use of such data in calculations requires caution. However, a strict hazard evaluation of laser systems that incorporate very short pulses and/or high repetition rates is not necessary as criteria given in NTSO-SOP 0570, Appendix A., do not permit direct viewing

The pupilary eye diameter (D_e) of the human eye is indicated in many laser hazard calculations. Since 0570, Appendix A, specifies criteria for corneal illumination only, this parameter is not really necessary. The value commonly used for the pupilary diameter for a dark adapted human eye is 6 millimeters.

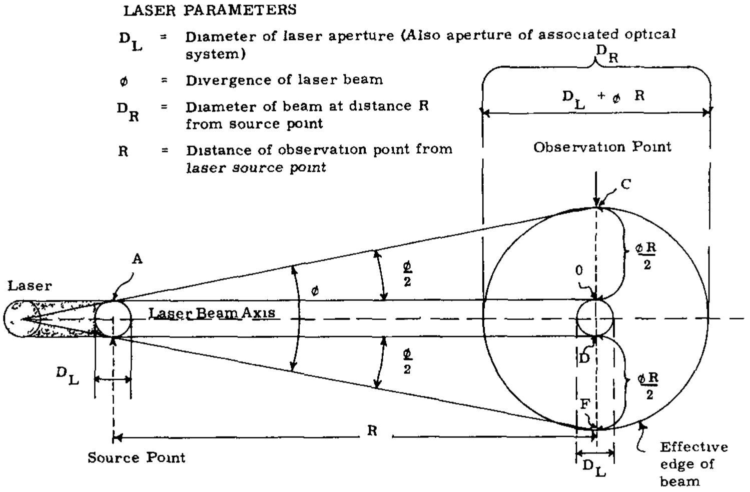
FUNDAMENTAL POWER OR ENERGY DENSITY CALCULATIONS

(Figure 1)

1. Aperture Power or Energy Density

Let P = the output power level of the laser in milliwatts, or
E = the peak energy level of the pulsed laser in joules.

The power density of the laser beam at the aperture of the laser source is the power level (P) divided by the area of the



LASER PARAMETERS

D_L = Diameter of laser aperture (Also aperture of associated optical system)

ϕ = Divergence of laser beam

D_R = Diameter of beam at distance R from source point

R = Distance of observation point from laser source point

Figure 1. Parameters defined for a simple laser system.

r_e - Distance from center to effective edge of the beam (half-power or half-intensity point)

r_o - Distance from center to absolute edge of the beam (zero intensity point)

r_e would be the same as D_R for beam cross-sections at a distance R from source point

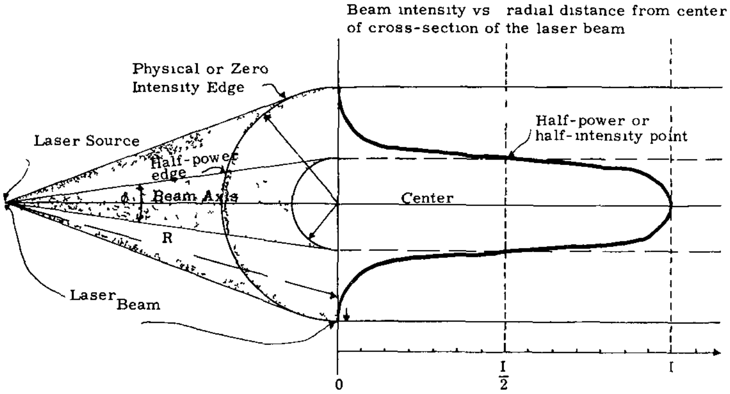


Figure 2. Determination of the divergence angle Φ from the "half-power" or half-density point.

aperture. The aperture area A_A is: $\pi\left(\frac{D_L}{2}\right)^2$. Thus the power density of the laser beam at the aperture (P_A) is:

$$P_A = \frac{P}{A_A} = \frac{P}{\pi\left(\frac{D_L}{2}\right)^2} = \frac{4P}{\pi D_L^2} \quad W/cm^2$$

where D_L is measured in cm (10^{-2} meters)

In like manner, the energy density at the aperture (E_A) is:

$$E_A = \frac{4E}{\pi D_L^2} \qquad J/cm^2$$

2. Observation Point Power or Energy Density

At the observation point, a distance R meters from the laser source, the beam will have diverged to a diameter D_R, with a cross-sectional area A_R. Thus at the observation point the power density (P_R) is:

$$P_R = \frac{P}{A_R} = \frac{P}{\pi\left(\frac{D_R}{2}\right)^2} = \frac{4P}{\pi D_R^2}$$

and the energy density would be:

$$E_R = \frac{4E}{\pi D_R^2}$$

The value of D_R may be readily determined from parameters specified in Figure 1 or by measurement. Consider the triangle formed by points AOC in Figure 1. The base AO is parallel to the laser beam axis and AC is the effective edge of the laser beam. The angle CAO of this triangle is one-half of the divergence, $\frac{\phi}{2}$. The base of the triangle is the distance R. For very small angles, the tangent of the angle is equal to the angle itself measured in radians; i. e., $\tan \phi = \phi$ rad. Also, for very small angles, the hypotenuse of the triangle is very nearly equal to the base; i. e., $AC = AO = R$.

Considering these facts we have:

$$\tan \frac{\phi}{2} = \frac{OC}{AC} = \frac{OC}{R}$$

But for ϕ very small (normal laser divergence meets this requirement), $\tan \frac{\phi}{2} = \frac{\phi}{2}$ radians and thus:

$$\frac{\phi}{2} = \frac{OC}{R} \qquad \text{or} \qquad OC = \frac{R\phi}{2}$$

At a distance R, the beam cross-section at the observation point has a diameter of $OC + D_L + DF$. Since DF is equal to OC, then:

$$\begin{aligned} D_R &= OC + D_L + OC \\ &= 2\,(OC) + D_L \\ &= 2\,\frac{R\phi}{2} + D_L \\ D_R &= R\phi + D_L \end{aligned}$$

Note that R and D_L must be in the same units and that the units for D_R would follow.

Thus, the power density at the observation point would be:

$$P_R = \frac{P}{\pi \left(\frac{D_R}{2}\right)^2} = \frac{P}{\frac{\pi\left(R\phi + D_L\right)^2}{4}} = \frac{4P}{\pi\left(R\phi + D_L\right)^2}$$

In like manner, the energy density at the observation point would be:

$$E_R = \frac{4E}{\pi(R\phi + D_L)^2}$$

Considering units:

P in watts
D_L in meters
R in meters
ϕ in radians

this will give P_R W/m^2

For energy density, E in joules would give E_R J/m^2.

These equations evaluate P_R and E_R at the point of observation and specify, after multiplying by 10^{-4}, the power density in W/cm^2 and the energy density in J/cm^2, which are the same units specified in Appendix 0570-A. Thus, in terms of corneal irradiation, the determination of whether or not the beam intensity is hazardous can be made with ease.

It should be noted that for simplification no atmospheric attenuation was considered. On the Nevada Test Site, the atmospheric attenuation is usually negligible for a considerable distance and no significant error is introduced by omitting this factor.

If atmospheric attenuation were to be considered, the beam intensity would be modified by a factor of $e^{-\mu R}$ where μ is the atmospheric attenuation coefficient per unit distance (i. e., meter $^{-1}$), and has values from 10^{-2} m $^{-1}$ for thick fog to 10^{-5} m^{-1} for clear air.

3. Filter Protection Calculation

The optical density (OD) of a laser filter is defined as:

$$OD = \log_{10} \frac{I_{incident}}{I_{transmitted}}$$

Where I is the intensity of the beam, in $\frac{W}{cm^2}$ or in $\frac{J}{cm^2}$

The optical density is dependent upon the wavelength of the laser light impinging upon it. Neutral density (ND) filters have a sufficiently broad wavelength response to be essentially "neutral" for a major portion of the visible spectrum. However, this spread should be determined to insure the suitability of the filter.

Computations to obtain the OD of a filter required to reduce the beam intensity to safe levels are accomplished in the following manner: First, determine that the filter has the proper response for the wavelength of interest (consult the manufacturer's specifications). Second, using the manufacturer's specifications, apply the following equation:

$$OD = \log_{10} \frac{P_{incident}}{P_{transmitted}} = \log_{10} \frac{E_{incident}}{E_{transmitted}}$$

P or $E_{transmitted}$ are taken as the maximum permissible exposure levels (P_{max} and E_{max}) specified in Appendix 0570-A. (Note: although levels in the appendix are in W/cm^2 and J/cm^2, these units drop out so that only numerical values are used in the above equation.) Thus:

$$OD = \log_{10} \frac{P_R}{P_{max}} = \log_{10} \frac{E_R}{E_{max}}$$

or

$$OD = \log_{10} \frac{P_A}{P_{max}} = \log_{10} \frac{E_A}{E_{max}}$$

4. Optical Recieving Apparatus Calculation

When optical receiving devices are utilized and the laser beam is viewed directly through such devices the calculation of the corneal irradiation should be made.

There are two cases:

a. Where optical device collects all of the beam,

b. Where optical device collects only a portion of the beam.

In either case, the entire beam collected by the objective lens of the optical device (telescope) will be concentrated into the area of the device's exit pupil (or less) and when transmitted through the device, would directly irradiate the cornea. In the following calculations, the assumption is made that losses in the optical system are negligible and the entire beam incident on the objective is transmitted through the system. See Figures 3 and 4, page 353.

The calculation for the optical receiving device intercepting all or part of the incident beam is one of comparison of respective areas.

The beam has diverged at the observation point distance R to an area $A_R = \frac{\pi}{4} D_R^2$. It is viewed by a telescope with an objective diameter D_T. Thus, an area $A_T = \frac{\pi}{4} D_T^2$, is intercepted from the incident beam. Although only a portion of the total power or energy would be available, note that the power <u>density</u> (P_R) or energy <u>density</u> (E_T) received by the objective lens is the same as would be observed without the telescope. Therefore:

$$P_T = P_R \quad \text{or} \quad E_T = E_R$$

This power density or energy density is transmitted to the cornea of the eye through the telescope exit pupil with a diameter of D_p

$$A_R = \pi \left(\frac{D_R}{2}\right)^2 = \frac{\pi}{4} D_R^{\ 2} = \text{Area of disc at observation point}$$

$$A_T = \pi \left(\frac{D_T}{2}\right)^2 = \frac{\pi}{4} D_T^{\ 2} = \text{Area of telescope objective}$$

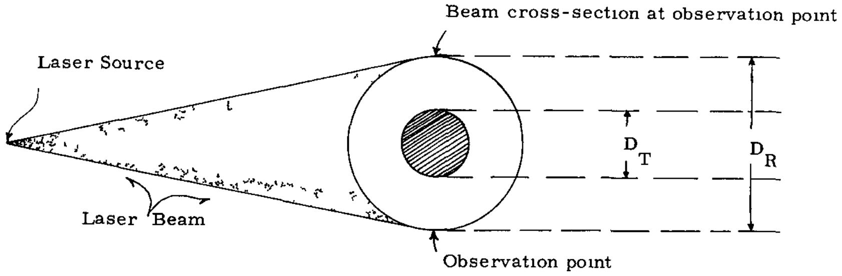


Figure 3. Optical receiving apparatus calculation illustrated.

$$A_T = \pi \left(\frac{D_T}{2}\right)^2 \qquad A_P = \pi \left(\frac{D_P}{2}\right)^2$$

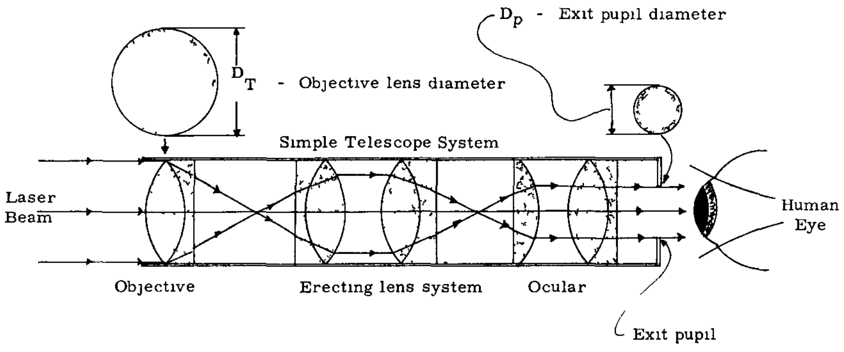


Figure 4. Illustration for optical receiving apparatus calculation using simple telescope.

(see Figure 4). Thus the total intercepted power or energy would be condensed on an area of $A_p = \frac{\pi}{4} D_P^2$. The energy density ($E_p$) transmitted through the exit pupil, and incident on the cornea as E_e, would be inversely proportionate to the areas.

$$E_p = E_T \frac{A_T}{A_p} = \frac{4\ E_T}{\pi\ D_p^2} \quad \frac{\pi\ D_T^2}{4}$$

Thus: $E_p = E_T \frac{D_T^2}{D_P^2} = E_e$

But: $E_T = E_R$

Therefore: $E_p = E_R \frac{D_T^2}{D_p^2} = E_e$

Thus showing that the energy density incident on the cornea is equal to the energy density at the point of observation E_R, multiplied by the ratio of the square of the objective lens diameter to the square of the exit pupil diameter.

$$E_e = Ep = E_R \frac{D_T^2}{D_P^2}$$

It follows, by an identical calculation, the power density is:

$$P_e = P_P = P_R \frac{D_T^2}{D_P^2}$$

Note that the quantity $\frac{D_T^2}{D_P^2}$ is equal to the square of the magnification power of the optical device.

Considering the case where the incident beam is partially captured by the objective lens, the same result is obtained. The utilization of energy densities and power densities makes it unnecessary to compute the total power or energy transmitted through the system.

MAXIMUM EXPOSURE CRITERIA FOR LASER IRRADIATION

A discussion of the basis for the criteria established in Appendix 0570-A is relevant to this paper. A copy of these criteria is attached.

The appendix specifies maximum permissible exposure levels to laser radiation in terms of corneal irradiation. Corneal irradiation was selected as a basis for the criteria because this simplifies hazard evaluation calculations. It is true that because of the nature of the human eye, there are three different ways in which radiation incident on the cornea can be projected on the retina: the near field, far field and geometric optics cases.

In establishing the exposure criteria, the limiting far field case was chosen because the Fraunhofer diffraction pattern produced by a dark-adapted pupilary diameter renders the projection of the laser beam on the retina of the eye to be the smallest possible disc, which is approximately 10^{-6} cm^2 in area.

Thus a corneal irradiation of 3×10^{-6} W/cm^2 would produce a retinal irradiation of 1 W/cm^2. This is the maximum level of continuous laser irradiation considered absolutely safe on the human retina. By basing the criteria on the minimum retinal spot size, the evaluations are automatically rendered conservative for the other two cases; near field and geometric optics. This has proven to be a satisfactory basis for the criteria for several reasons, including:

a. Calculations are considerably simplified.

b. Results are conservative.

c. Separate calculations for infrared (IR) and ultraviolet (UV) irradiation are unnecessary. These wavelengths are, of course, not transmitted by the cornea and thus do not interact with the retina unless the cornea, lens, and vitreous humor behind it are completely disrupted by an intense laser beam.

d. Skin irradiation is considered comparable to corneal irradiation and thus no special calculations are needed.

SUMMARY OF CALCULATIONS

1. Aperture power or energy density

$$P_A = \frac{4P}{\pi {D_L}^2}$$

$$E_A = \frac{4E}{\pi {D_L}^2}$$

2. Observation point power or energy density

$$P_R = \frac{4P}{\pi (R \phi + D_L)^2}$$

$$E_R = \frac{4E}{\pi (R \phi + D_L)^2}$$

3. Filter protection calculation

$$\text{O.D.} = \log_{10} \frac{P_R}{P_{max}} = \log_{10} \frac{E_R}{E_{max}}$$

or

$$\text{O.D.} = \log_{10} \frac{P_A}{P_{max}} = \log_{10} \frac{E_A}{E_{max}}$$

4. Optical receiving apparatus calculation

$$E_P = E_e = E_R \frac{D_T^{\,2}}{D_p^{\,2}}$$

$$P_p = P_e = P_R \frac{D_T^{\,2}}{D_p^{\,2}}$$

LIST OF TERMS OR ABBREVIATIONS USED IN CALCULATIONS

ϕ = divergence angle

R = distance from laser source to observation point

P = total output power

E = total output energy

P_A = power density at aperture of laser source

E_A = energy density at aperture of laser source

P_R = power density at observation point

E_R = energy density at observation point

P_T = power density received by telescope objective lens (equal to P_R)

E_T = energy density received by telescope objective lens (equal to E_R)

P_p = power density transmitted through exit pupil

E_p = energy density transmitted through exit pupil

P_e = power density incident on cornea of eye (equal to P_p)

E_e = energy density incident on cornea of eye (equal to E_p)

P_{max} = maximum permissible power density as per Appendix 0570-A

E_{max} = maximum permissible energy density as per Appendix 0570-A

D_L = diameter of laser aperture

D_R = diameter of beam cross-section at observation point

D_T = diameter of telescope objective

D_p = diameter of telescope exit pupil

D_e = diameter of pupil of eye

A_A = area of laser aperture

A_R = cross-sectional area of laser beam at observation point

A_T = area of telescope objective lens

A_p = area of telescope exit pupil

U.S. ATOMIC ENERGY COMMISSION
STANDARD OPERATING PROCEDURE

Nevada Test Site Organization

APPENDIX 0570-A MAXIMUM PERMISSIBLE EXPOSURE LEVELS TO LASER RADIATION

0570-01 The following laser exposure limits are listed in terms of incident energy/cm^2 or power/cm^2 on the body and are based upon "worst case" conditions in light of present knowledge. Any exposures that result in a persistent after-image should not be repeated.

02 Maximum Permissible Exposure Levels Incident on the Eye

a. For infrared lasers (wave lengths greater than 1.4μ) the maximum energy incident upon the cornea of the eye is 0.1 joules per square centimeter per pulse or 1.0 watts per square centimeter for continuous lasers.

b. For lasers operating in the ultraviolet ($< 0.4\mu$) portion of the spectrum, the maximum permissible energy incident on the eye is 5×10^{-7} watts/cm^2 (average power).

c. For a continuous beam laser operated in the visible or near infrared (0.4μ to 1.4μ) portion of the spectrum, a corneal irradiation 3×10^{-6} watts/cm^2 may be used.

d. For a pulsed laser operated in the visible or near infrared portion (0.4μ to 1.4μ) of the spectrum with off time between pulses of 100 milliseconds or greater and with a pulse duration of 100 nanoseconds or greater, a corneal irradiation of 10^{-8} joules per square centimeter per pulse may be used.

e. For a pulsed laser operated in the visible or near infrared portion (0.4μ to 1.4μ) of the spectrum with an off time between pulses of 100 milliseconds or greater and with a pulse duration shorter than 100 nanoseconds, a corneal irradiation of 0.1 watt per square centimeter peak power may be used.

f. Limits for repetitive pulsed lasers operated in the ultraviolet, visible or near infrared portion of the spectrum, with off time between pulses less than 100 milliseconds, cannot be determined at this time because of insufficient biological data. The limits for peak pulse power and average power output, when determined, will be more stringent than either of the limits based on the pulsed or continuous case listed above.

03 Maximum Permissible Exposure Level of Laser Radiation Incident on the Skin

For lasers operating in the visible, near infrared, and infrared portions of the spectrum, the maximum intensity incident on the skin, excluding the eye is 0.1 joules per square centimeter per pulse or 1.0 watts per square centimeter for continuous lasers.

APPENDIX 0570-B LASER REGISTRATION

NTSO SOP Manual Chapter 0570 requires the registration, with the Test Manager's Organization, of all continuous wave lasers that produce a total beam power level above two milliwatts and all pulsed lasers that are used on the NTS. Also, any laser, previously exempt, which has been modified to be able to produce a total beam level above two milliwatts must be registered at the time of such modification.

All applicable lasers will be registered with the Operations Coordination Center (OCC) at CP-1. The following information will be furnished at the time of registration:

1. Date of arrival on NTS or date of modification to applicable status.
2. Serial or other identification number of laser. (AEC or user equipment number).
3. Proposed usage.
4. Agency doing laser work.
5. Person responsible for laser.
6. Technical data concerning laser.
    a. Type
        (i) Material
        (ii) Continuous
        (iii) Pulse
    b. Peak beam power (or average power) and operational wave length(s).
    c. Pulse length (where appropriate).
        (i) Pulse rate frequency
    d. Beam divergence.
    e. Aperture diamter (effective).

LASER HAZARD EVALUATION AND CALCULATIONS

FOOTNOTES

(1) The term "C.W." refers to continuous wave, denoting a continuously operating laser and originated in the days when lasers were called "optical masers." The use of the term C.W., describing a continuously operating laser, is now standard practice.

(2) The definition for the effective edge is different for different manufacturers, depending on how they wish to represent their product. If the manufacturer's divergence is to be used for calculations, his definition of ϕ and the effective edge should be verified.

(3) Using this definition of the effective edge, the beam essentially contains all of the output power, at least for the purposes of this introduction into hazard evaluation.

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ARMY LASER RANGE CONTROLS

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ABSTRACT

Numerous factors which affect both evaluation and control of laser operational hazards in Army laser range operations are each considered under one of three categories: the laser, the environment, and potentially exposed personnel. General controls in these three areas are discussed.

Because of the long hazardous ranges of many of the Army's laser devices, such as the range finders, much of the Army's laser range hazard controls during testing center around the use of backstops and some use of protective eyewear. A general procedure for evaluating a particular laser system is outlined in a step-by-step form. This procedure includes the analysis of the following problem areas:

1. Maximum hazardous range of the laser.
2. Ocular hazards of viewing the main laser beam.
3. Potential hazards from specular reflections.
4. Potentially hazardous diffuse reflections.
5. Stability of laser platform to determine lateral constraints.
6. Administrative controls.
7. Medical surveillance.

ARMY LASER RANGE CONTROLS

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The numerous factors which affect the evaluation and control of laser operational hazards in Army laser range operations can each be considered under one of three categories: the laser, the environment, and potentially exposed personnel.[1]

Controls to be effected at the laser itself usually entail placing the entire laser system within an opaque enclosure or a closed room. Such a system is referred to as a "closed installation," and is always the most desirable procedure, when practical, (as in most laboratory and industrial applications), but enclosure of the laser beam in field applications generally defeats the purpose of the laser operation. Another approach to control at the laser itself is to reduce the power output of the laser without interfering with the laser operation. This approach should become more widespread in many applications as the state-of-the-art in detector technology advances. It might be noted that at present the lasers emitting less hazardous infrared wavelengths have fewer low-power applications than desirable due to the limitations of infrared detector technology.

Environmental control depends upon a number of factors. Backstops and shields are used to block the beam path from occupied areas. Generally, military ranges have terrain features which act as natural shields or backstops, e.g., hills, ridges, or heavily forested areas.

Naturally, the control procedure varies depending upon whether or not the laser is mounted on a fixed or moving platform. Most procedures used to limit access to direct fire ranges are readily applied to laser ranges. It should be noted, however, that the laser beam path continues in a straight line until terminated by an opaque substance. It should also be noted that the laser beam path when reflected from a flat glass surface can be reflected with a hazardous irradiance to ranges far greater than a ricocheted projectile.

Protection of personnel is centered around two concepts. First, personnel should be located outside of potential laser beam paths. In some cases, it may be advisable to forestall unsafe acts by personnel by the use of physical barriers. In any event, it is highly desirable that administrative procedures be used to educate and train personnel to stay out of the laser beam path. Second, personnel located downrange in training and testing operations must wear protective eyewear when they are in zones of potentially hazardous laser radiation.

The evaluation of a particular laser system centers around defining the extent of a number of potentially hazardous conditions. This may be done in a step-by-step manner as follows:

Step 1. Make an estimate of the hazardous range of the laser. Calculations of the average beam irradiance as a function of range can be made with the laser range equation for a circular beam:

$$I = \frac{1.27\ Ee^{-\mu r}}{(a + r\phi)^2}$$

where:

I = average radiant exposure in joules per square centimeter (j/cm^2) for pulsed lasers or average beam irradiance in watts per square centimeter (W/cm^2) for continuous wave (CW) lasers

E = laser energy output in joules (j) or power output in Watts (W)

e = base of natural logarithm

μ = atmospheric attenuation coefficient in reciprocal centimeters (cm^{-1})

r = range in centimeters (cm)

ϕ = beam divergence in radians

a = emergent beam diameter in centimeters

These calculated ranges must be considered only as estimates beyond a few hundred meters, since uncertainties arise due to atmospheric effects (scintillation due to turbulence). Typical hazardous ranges for illuminators with large beam spreads are less than 100 meters, while hazardous ranges for range finders with highly collimated beams vary from 5 to 50 kilometers. Needless to say, backstops are essential in almost all practical situations when range finders are being used.

Step 2. Consider the possibility of personnel viewing a collimated beam through optical instruments. An individual beyond the hazardous range for the unaided eye who views the main beam with an optical instrument is conceivably at risk due to the instrument's greater energy gathering capability. If this individual views a laser target area which has flat, specular (mirror-like) reflections directed back toward him, the individual would be in greater risk for the same reason. This emphasizes the need to terminate the beam at the end of its useful path to insure against such potentially dangerous circumstances beyond the controlled area.

Step 3. Evaluate potential hazards from specular reflections. Specular surfaces ordinarily encountered are oriented vertically; e.g., windows and mirrors in vehicles and windows in buildings all of which will usually reflect a horizontal beam in a horizontal plane. As much as 8 percent of the original beam's energy density can be reflected back towards the laser from a clear glass window which is oriented normal to the beam. If the beam strikes a flat, specular surface at a different angle, a much greater fraction of the beam can be reflected beyond or to the side of the target area. If the beam strikes a still pond at a low angle of incidence, the reflections are potentially hazardous. If the specular surface is curved, the hazardous reflections normally extend only a short distance from the reflector due to the wide divergence of the reflected beam. Specular reflections from raindrops, wet leaves, and most other shiny natural objects seldom reflect hazardous intensities beyond a meter from the reflector.

If flat, specular surfaces in the target area are not removed, or masked, then protective eyewear for all individuals observing the target may become necessary (depending on how far the observer is from the reflector). Then the range area subject to control must be increased, since the protective eyewear itself is a source of specular reflections. Thus, personnel located in the beam path and target area should wear protective eyewear with curved surfaces to spread the reflected beam.

Step 4. Determine whether hazardous diffuse reflections exist. If the laser has an irradiance capable of producing hazardous diffuse reflections (the threshold levels for diffuse reflections being 2.5 W/cm^2 for continuous wave lasers, 0.9 j/cm^2 for non-q-switched pulsed lasers, and 0.07 j/cm^2 for q-switched pulsed lasers), the beam path area out to a range where the laser's beam irradiance falls below the diffuse reflection levels must become a denied occupancy area, and no objects should be allowed in the beam path.[2]

Step 5. Evaluate the stability of the laser platform to determine the lateral constraints that should be placed upon the beam traverse and the lateral extent of range control. A ground based, stable laser mount requires buffer zones of only 5 mils of angle. Airborne lasers require greater buffer zones depending upon the increased degree of instability and the loss of aiming accuracy. Figures 1 and 2 indicate how azimuth and elevation limits are imposed and how they are limited by a backstop of hills.

Step 6. Insure proper administrative controls. Necessary range control measures are ordinarily implemented by the appointment of a Laser Range Safety Officer. He should also insure that proper protective eyewear is prescribed and that the eyewear be marked with optical densities at the appropriate laser wavelengths so that eyewear designed for use with one type of laser is not mistakenly used with other lasers which emit different wavelengths.

Step 7. Insure that potentially exposed personnel are under medical surveillance. In any laser operation, personnel, particularly maintenance and operator personnel, who are potentially exposed to laser radiation are included in a medical surveillance program which requires preplacement, periodic, and final eye examinations.[2,3]

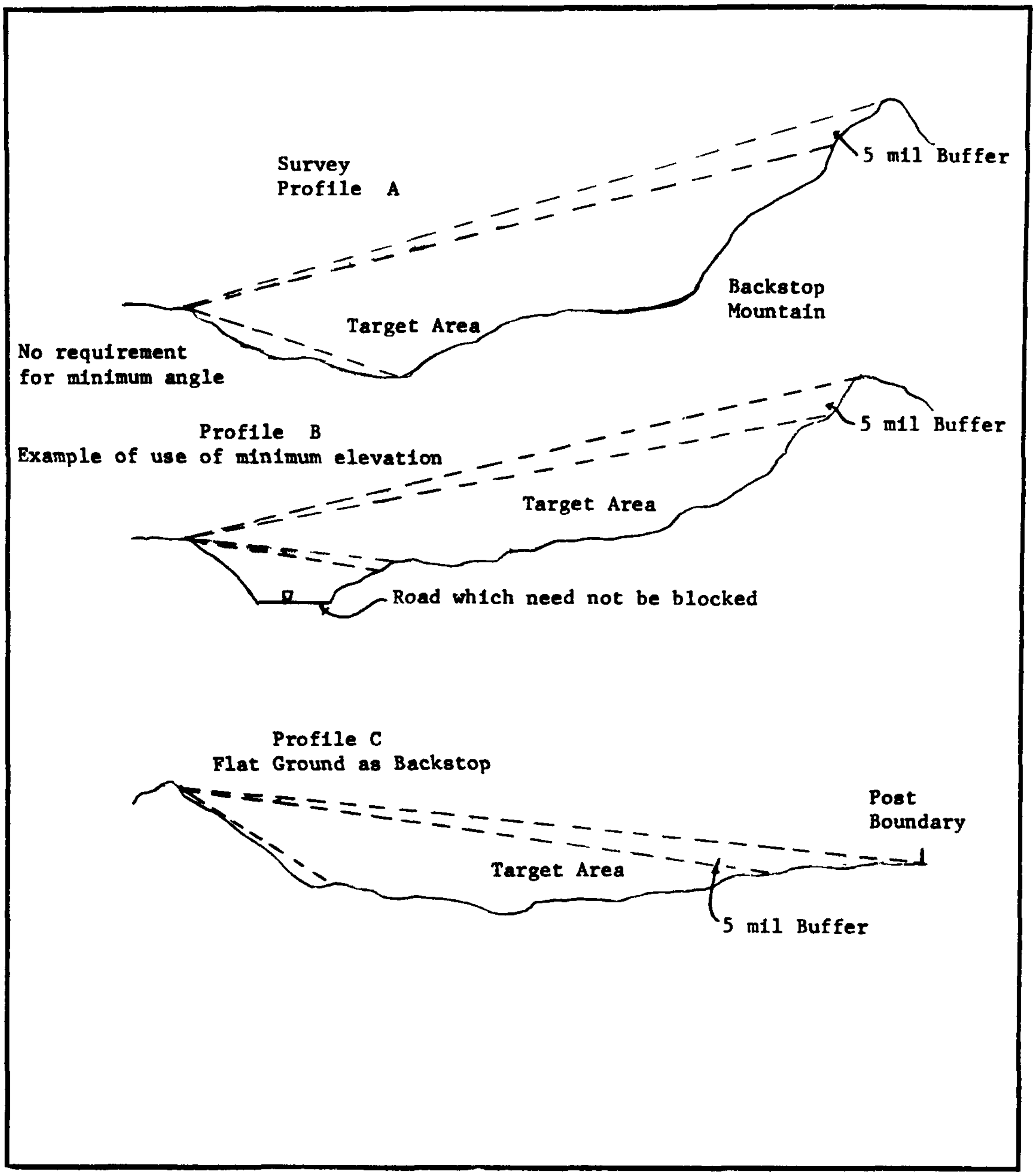

Figure 1. Elevation restrictions.

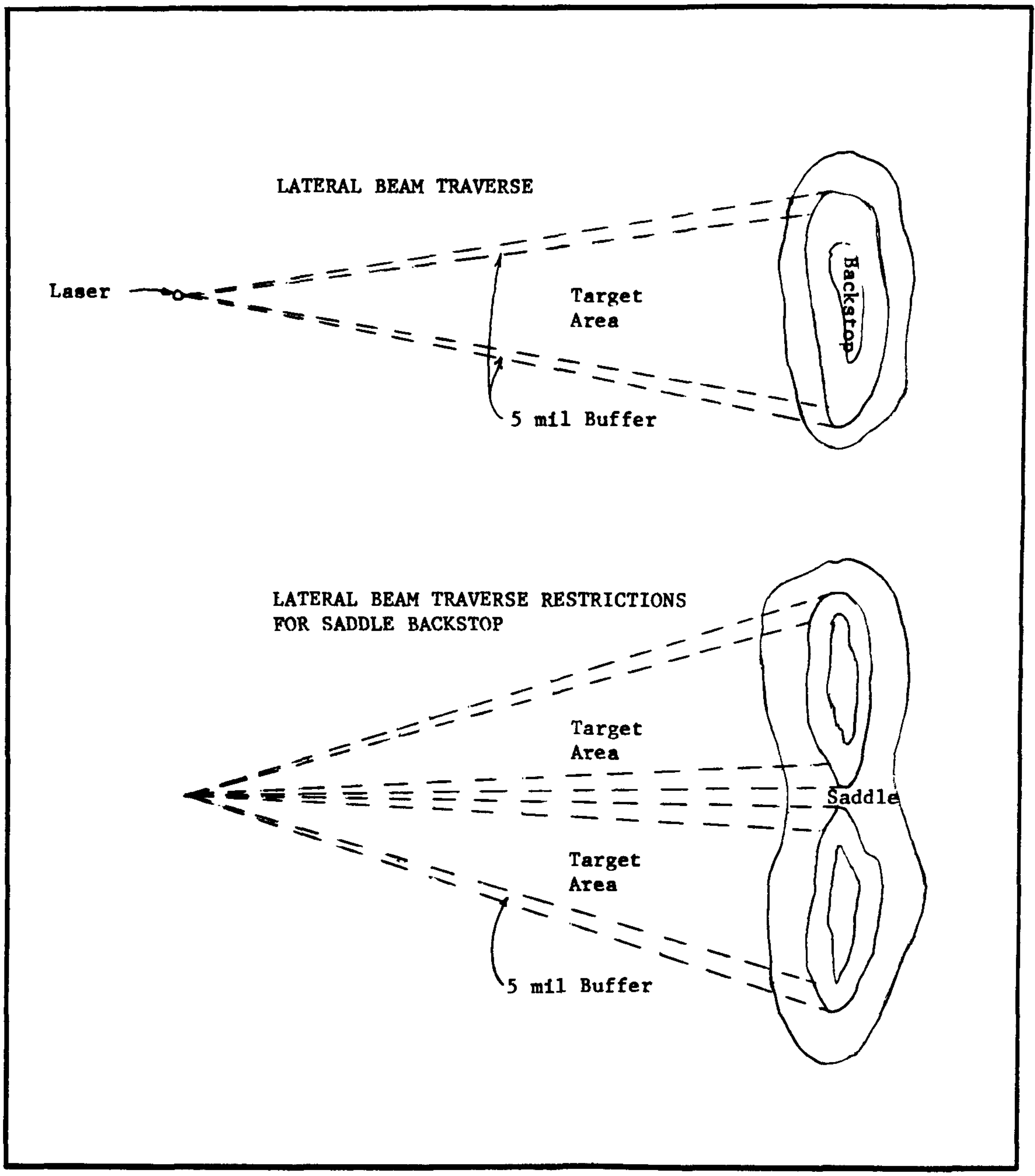

Figure 2. Azimuth restrictions.

It can be concluded that the evaluation and control of Army laser range operations are done in three different areas: the laser, the environment, and potentially exposed personnel. The U.S. Army Environmental Hygiene Agency has developed a step-by-step procedure for the analysis of a particular system's hazard potential. In the final analysis, because of the long hazardous ranges of many of the Army's laser devices (e.g., range finders), many of the Army's laser range hazard controls during testing emphasize employment of backstops and some use of protective eyewear.

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A LOW POWER CW LASER EVALUATION KIT

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The Electronic Products Studies Section of the Southwestern Radiological Health Laboratory of the Bureau of Radiological Health has been requested on several occasions to furnish a rapid analysis of laser installations which utilize relatively inexpensive low power (less than 10 mW) He-Ne gas discharge lasers. Rapid response to such requests required the development of an easily transportable set of instrumentation which would allow experimental evaluation of those laser beam parameters of interest in hazard analysis. Installations, such as art exhibits, which altered the divergence characteristics of the beam made impractical the utilization of manufacturer's specifications as even a first approximation of beam parameters.

We have developed a system which permits the evaluation of power, beam size (in the case of the direct beam, divergence and aperture size) and power distribution within the beam. Power is the most easily measured parameter and in order to expedite the acquisition of instrumentation a commercially available* power meter was utilized (figure 1). To permit the attaching of accessories to the detector head, a simple adaptor ring was fabricated which is threaded for attachment to the head and grooved, with a set screw inserted, to accept accessories (figure 2).

The measurement of beam size is accomplished through the use of either an iris or a travelling probe. Field use generally requires the use of the iris (figure 3).

Description of beam size, particularly when used to extrapolate to obtain aperture size, is dependent on the power point selected. If one wishes to compare experimental data with manufacturer's specifications it is imperative that the same power points be utilized. To reduce the number of calculations required on the part of the surveyor, we have included a graph of total beam power versus fractional power for a number of possible power point criteria. This allows the surveyor to proceed with measurements at a very rapid pace in that it is not necessary to calculate the power to which the reading must be reduced by the iris as it is closed.

The opening in the iris must be measured to obtain beam diameters. We have attempted to calibrate the opening diameter versus the position of the iris control for several available irises. We have found, however, that the backlash in the control position introduces a large uncertainty in the size of the opening. Thus an alternate method of sizing is required. The first technique utilized was the use of a drill

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Mention of specific commercial products does not constitute endorsement by the U.S. Public Health Service.

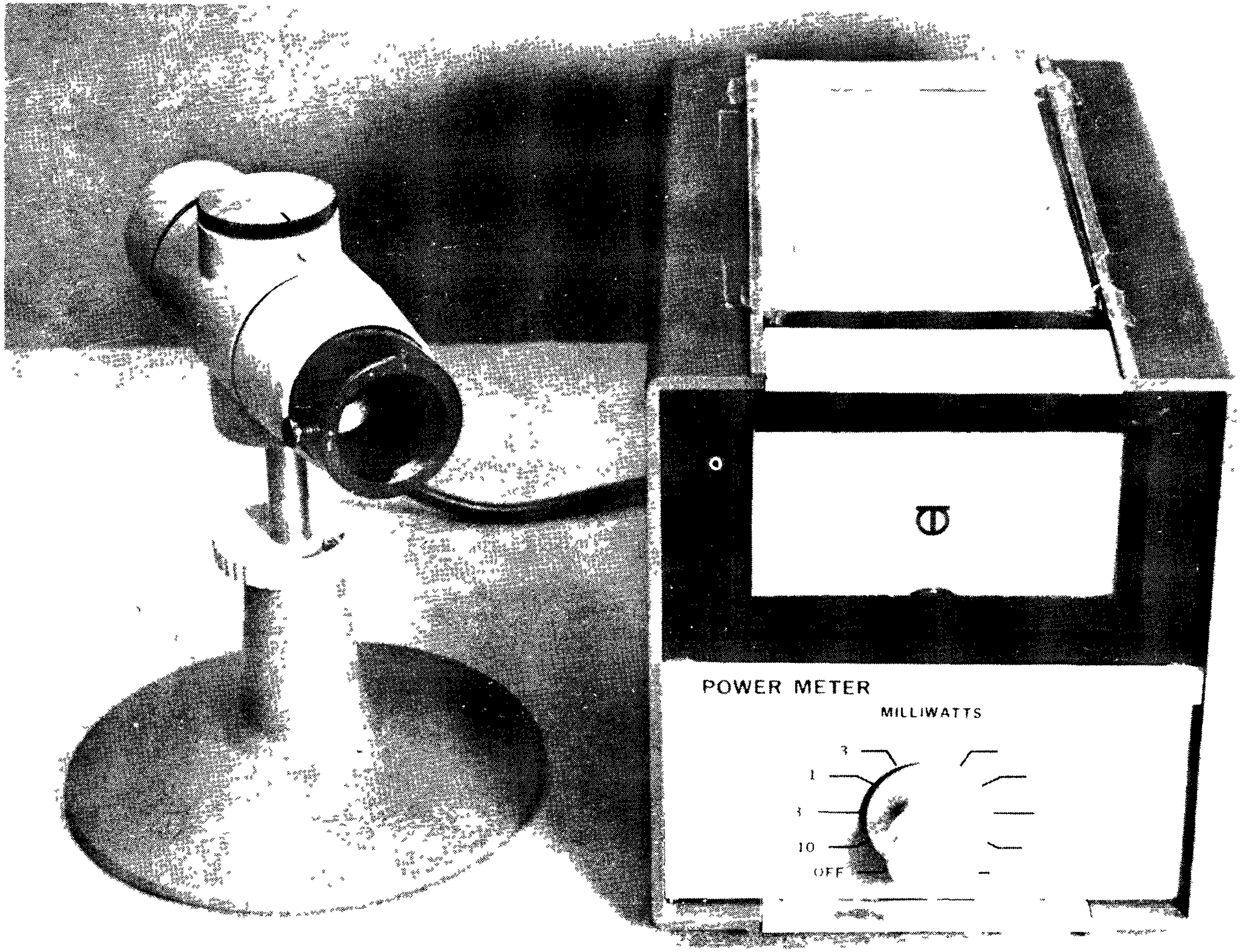

Figure 1. A commercially available power meter utilized in the kit. Note that the calibration curve has been attached to the top of the unit.

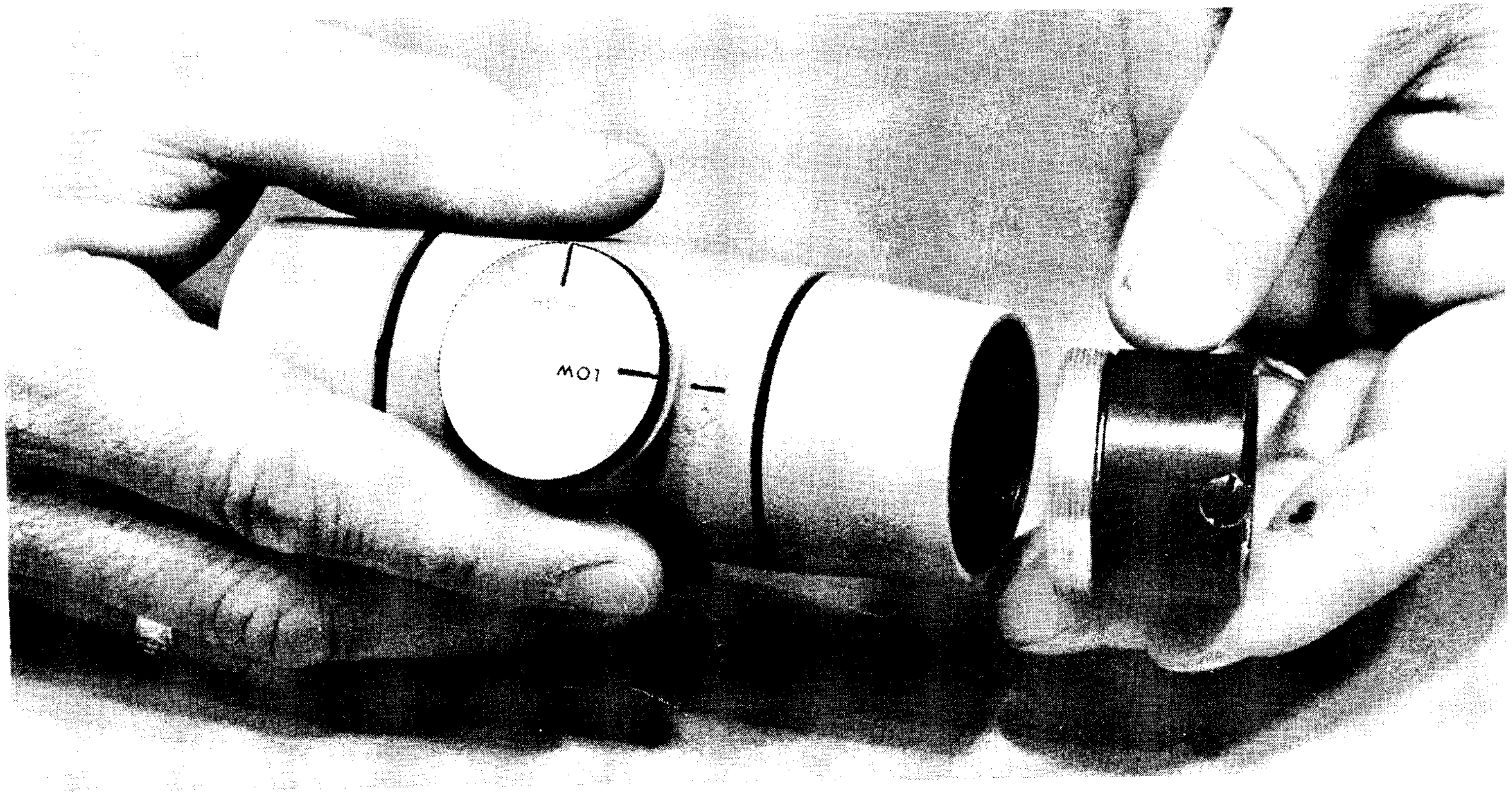

Figure 2. Threaded adapter ring with set screw used to attach accessories to the detector head.

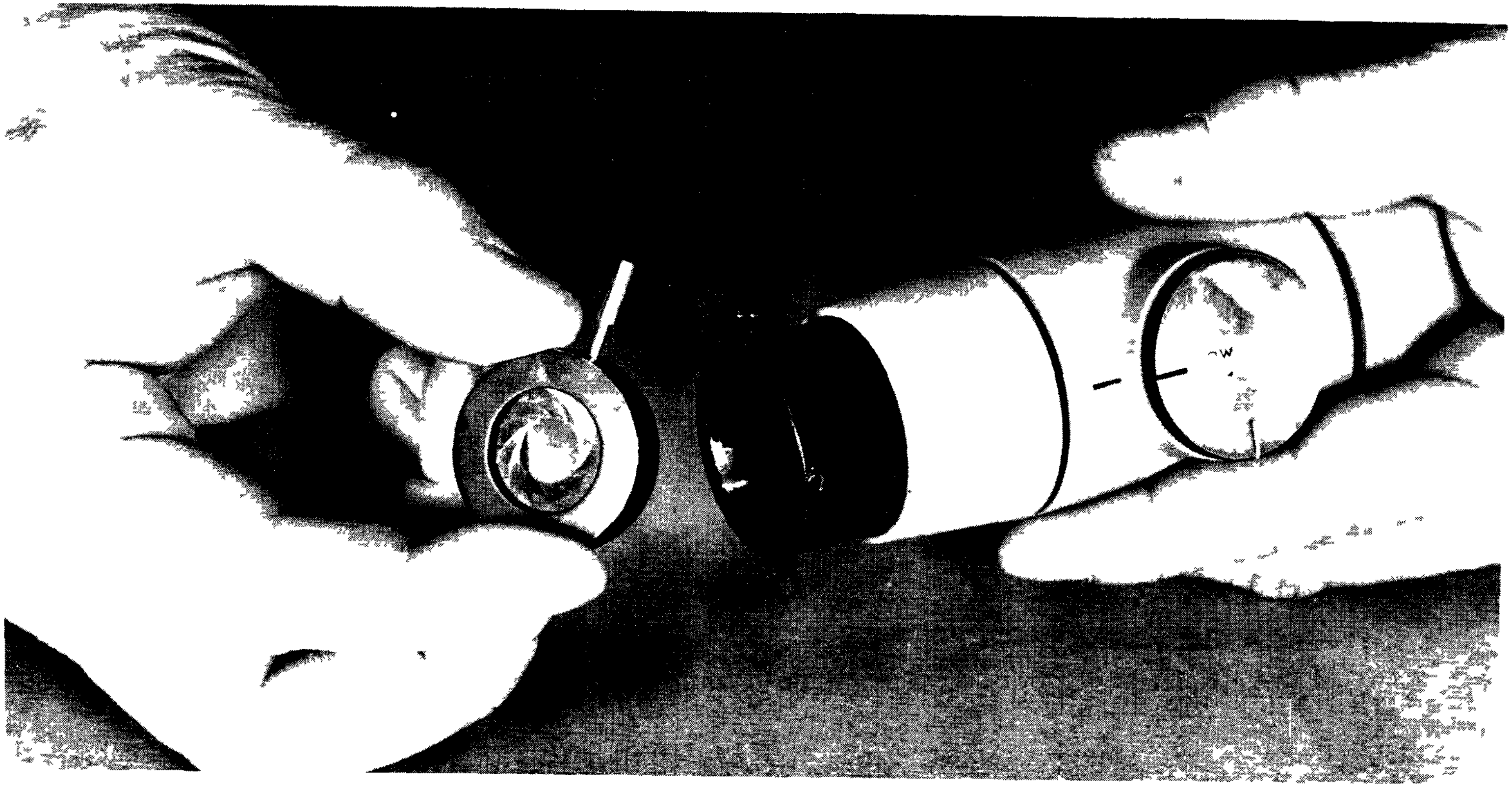

Figure 3. Iris diaphragm used in obtaining beam sizes. The iris is inserted in the adapter ring.

index. Drill bits were fitted to the iris opening until a close fit was obtained. While, with a steady hand on the part of the surveyor, this technique is workable, the cost of the drill set exceeded what we felt was reasonable. Next, a tapered steel shaft was fabricated (figure 4). The size of the iris opening is determined by inserting the shaft until the opening is filled. The depth of insertion is noted and, utilizing a graph placed in the kit, both the beam diameter and area are determined (figure 5).

In situations in which more time is available, the travelling probe may be employed. This device is an inexpensive, small diameter (.1 mm) light pipe and an inexpensive mechanical stage designed for use on microscopes. A small stand was fabricated to hold the stage and probe (figure 6). While data may be taken directly from the scales of the stage, we have also developed a readout system comprised of a potentiometer and an x-y recorder for use in the laboratory. The x-drive is derived from the potentiometer and the y signal is obtained from the power meter.

Several other items of hardware are carried in the kit. For example, if one were interested in the polarization of the output of the laser, the utilization of the polarizing filter would yield the necessary quantitative data (figure 7). A prism and variable slit attachment is included to provide divergence of wavelengths in the same fashion as a simple prism and slit spectroscope (figure 8). This enables the surveyor to determine the presence of any possible contribution of fluorescence radiations to the total beam power. If a fluorescence contribution is detected, we attempt to overcome the effect by making all measurements at large separations (greater than 2 meters) between the laser and power meter.

Two diverging lenses of known focal length at 632.8 nm are also included in the kit. We have found that some units with low divergence present measurement difficulties in obtaining a sufficiently long beam path to obtain meaningful data. This may be overcome by using an auxiliary lens which causes the beam to diverge much more rapidly (augmented divergence). The divergence of the laser may then be calculated knowing the augmented divergence and the focal length of the lens. The necessary equations are also listed in the written material in the kit. The complete set of equipment is placed in a foam-lined fiberglass case approximately 50cm x 30cm x 33cm (figure 9). The complete system, including the case, weighs 8.2 kg. Cost of the equipment, materials and labor to assemble the system is $480.00

While not all questions concerning the operation of low power CW lasers can be answered with this system (for example, mode structures, line width, and stability are not measured or recorded) we have found that information sufficient for a hazard analysis of direct beam and specular reflection can be obtained.

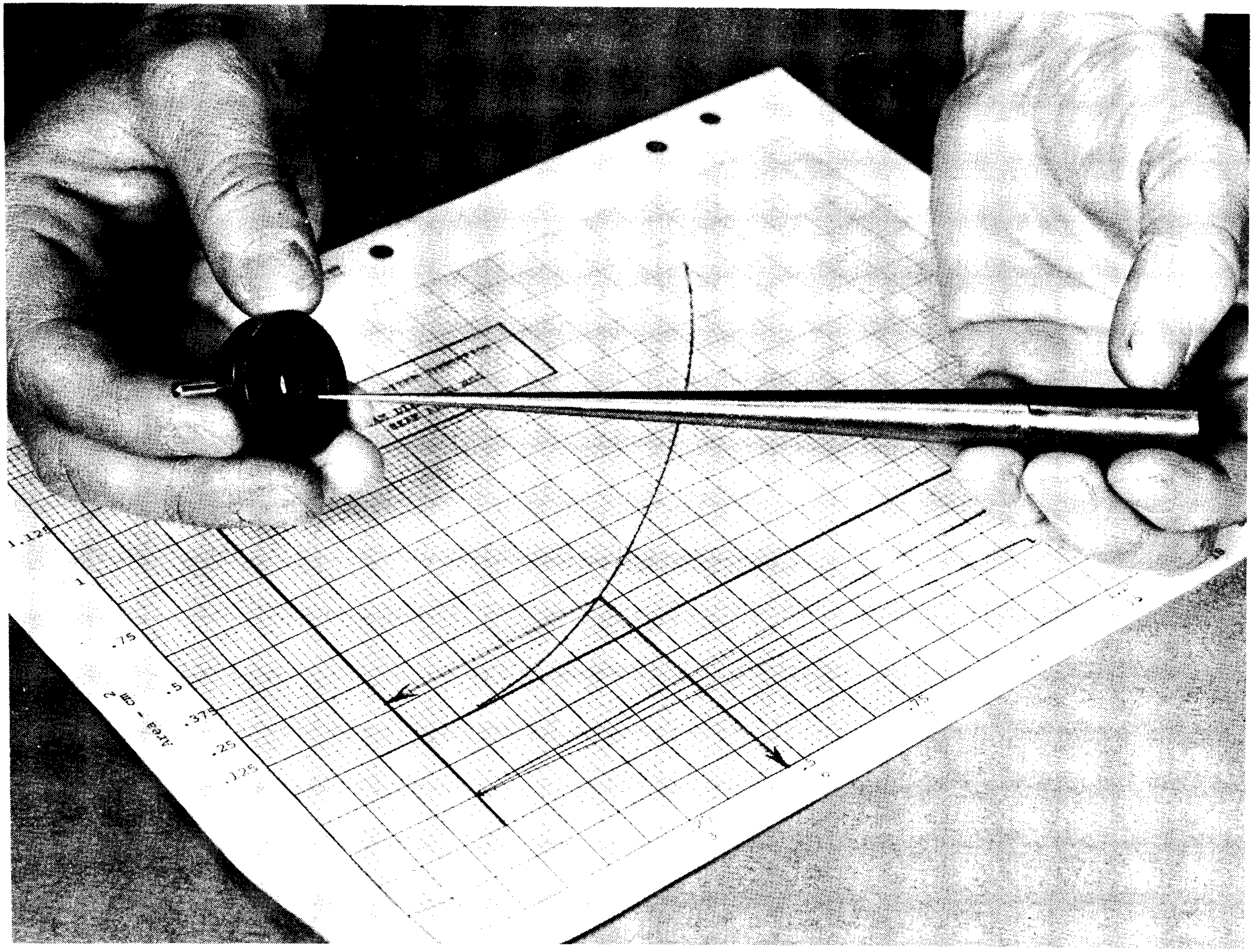

Figure 3. Tapered sizing tool used in determining the size of the iris opening.

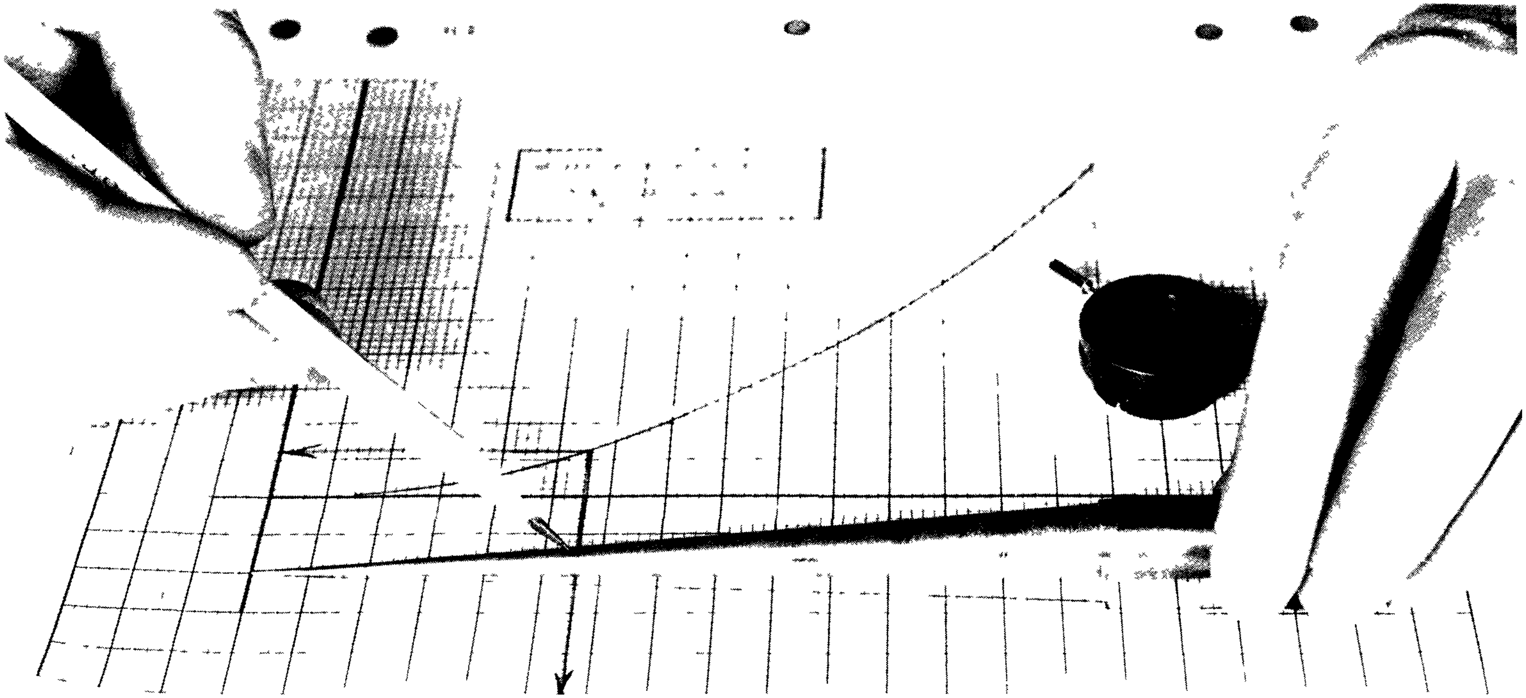

Figure 5. After the depth to which the sizing tool has been inserted is noted, the tool may be placed on the graph. The curve, placed on coordinates of beam diameter and beam area, gives both parameters from insertion depth.

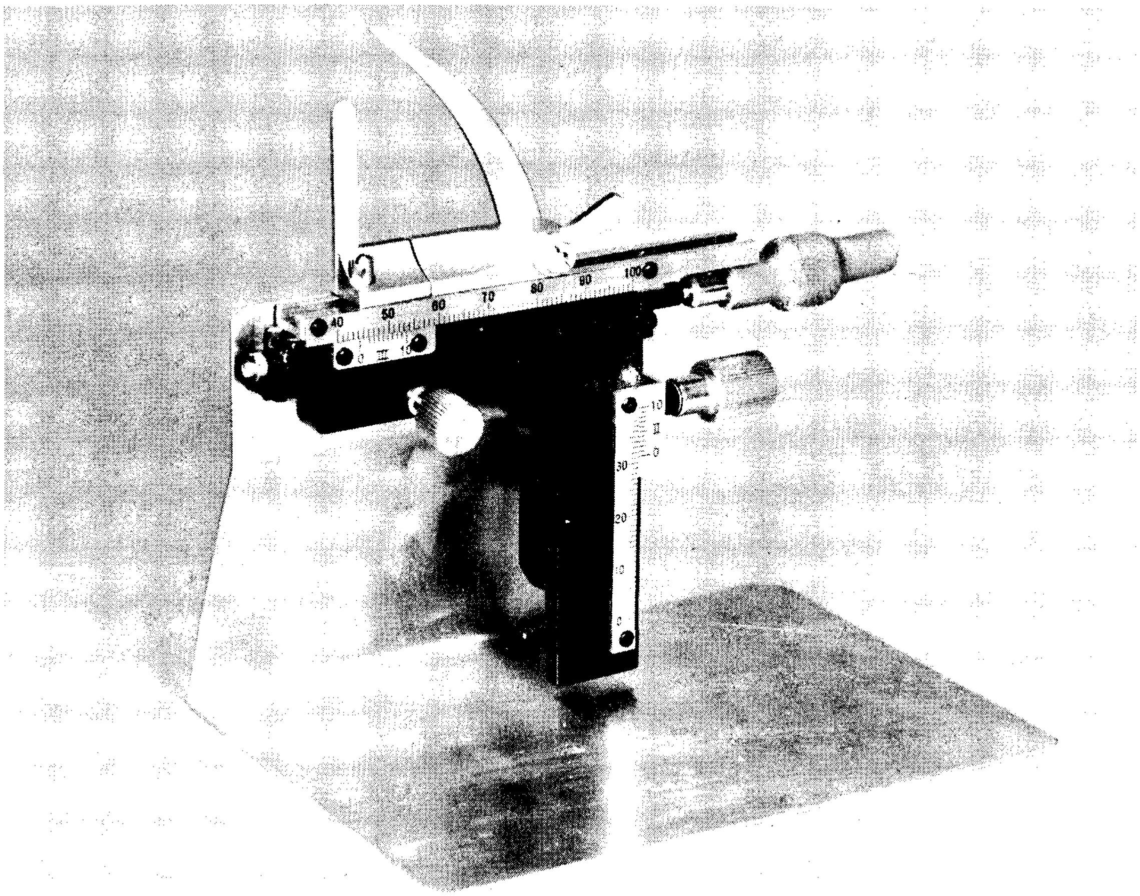

Figure 6. Stand and microwave stage to hold fibre light pipe (not visible in photograph). The horizontal drive screw is connected to a linear potentiator which furnishes the x drive for an x-y recorder system.

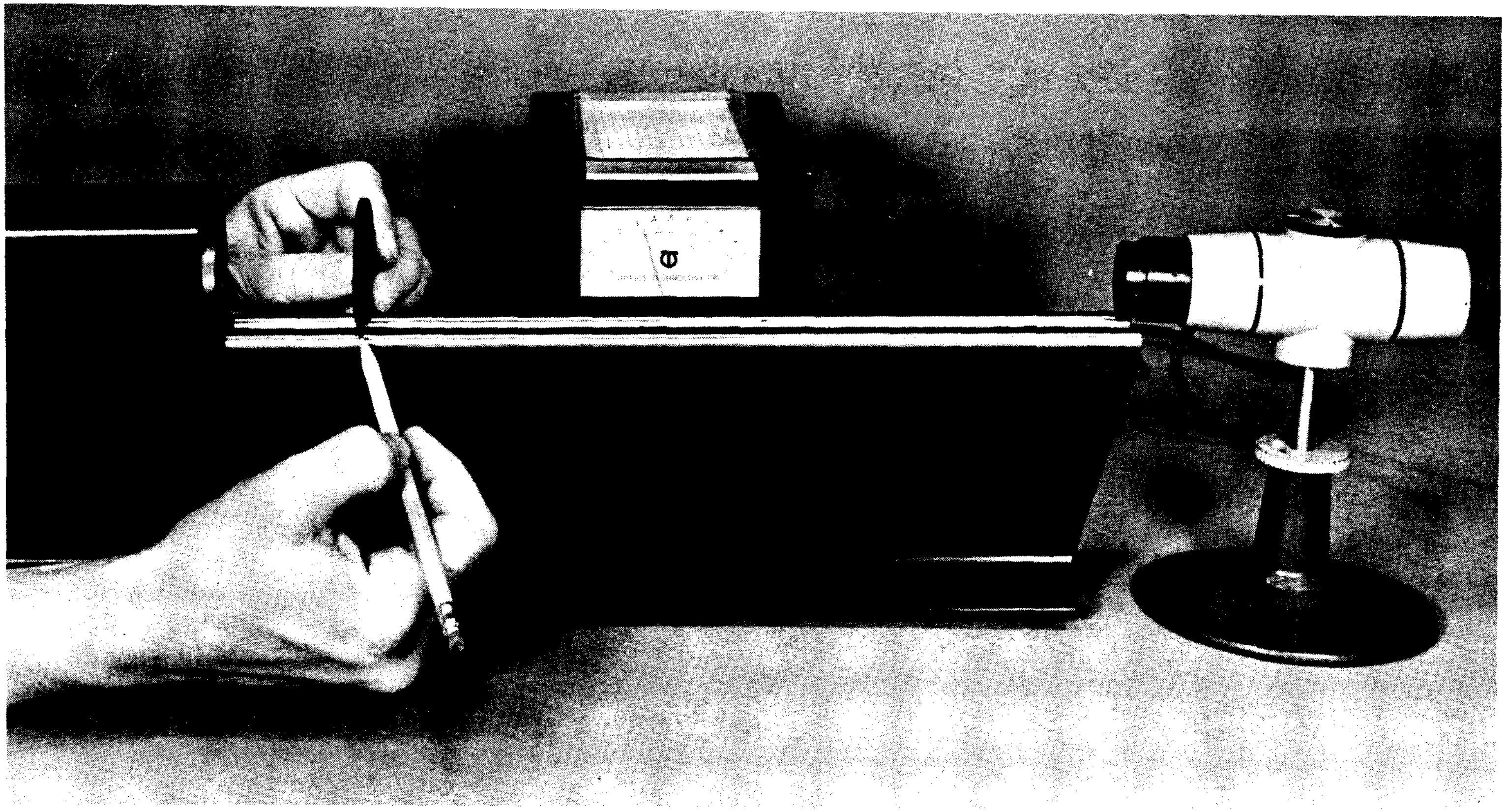

Figure 7. Polarizing filter, marked in degrees on the ring holding the filter, determines the polarization on the laser output when rotated.

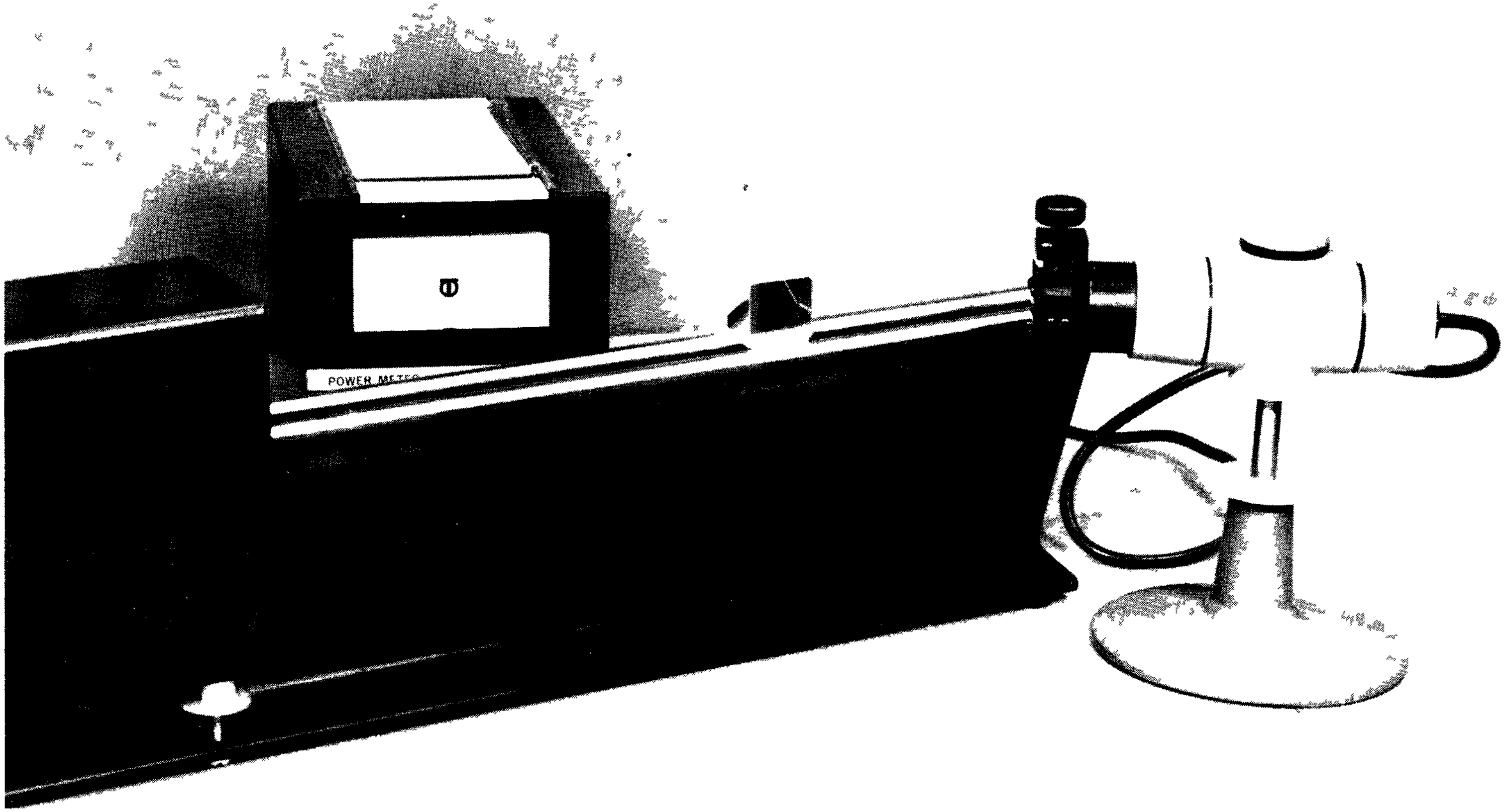

Figure 8. A single slip aperture inserted in the detector adapter ring and a prism are used to detect fluorescence radiation contributions. In practice a much greater prism-to-slit aperture separation is used.

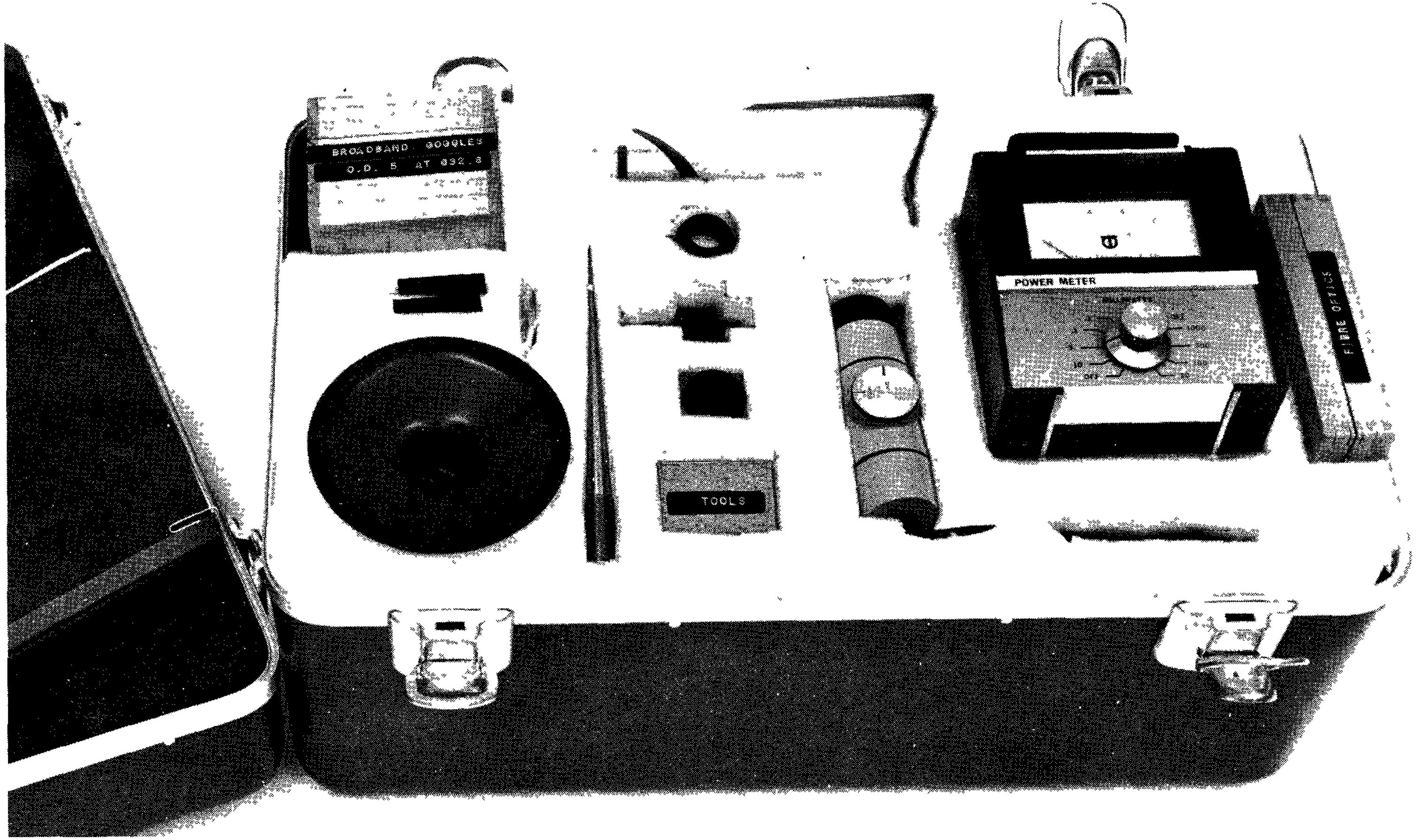

Figure 9. The completed kit. Spaces are provided for small tools and protective goggles, as well as the other items discussed in the paper.

A SAFETY ORIENTED LASER MANUAL FOR SCIENCE TEACHERS

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The Electronic Products Studies Group of the Southwestern Radiological Health Laboratory, a field laboratory of the Bureau of Radiological Health, U. S. Public Health Service, has been given the responsibility for the technicological implementation of P. L. 90-602 with respect to lasers. This paper reports on some of the work done at the laboratory, particularly in regard to the training of classroom users of laser devices.

A typical classroom laser is a helium-neon device with a rated output of 1 mW, a beam diameter of 1 mm at the exit port and a divergence of 1 mrad. If the power density of the beam is calculated at a distance of 1 meter from the exit port, it will be found to be 32 mW/cm^2. Comparing this figure to the guides for recommended maximum exposure as published by the American Conference of Governmental Industrial Hygienists (ACGIH), it will be seen that the power density at 1 meter exceeds the guides by a factor of 1590. Without belaboring the validity of this comparison, we believe it is appropriate to say that the typical 1 mW laser just described is not necessarily safe.

We became concerned in the spring of 1969 about the increasing use of lasers in educational institutions. Advertisements in trade journals indicated that great numbers of low-power lasers were being sold and the price of a classroom-type laser had dropped to less than $100.

To determine just what the situation was in our local area, we sent a questionnaire to science teachers in the Clark County (Las Vegas) Nevada School District. One of the questions asked was whether the teachers would be interested in a short evening course on laser fundamentals and experiments conducted by the U.S.P.H.S. A surprising number of affirmative replies were received, some coming from as far as Mesquite, Nevada, 70 miles from Las Vegas. Based on these responses, we decided that the course should indeed be presented. Class sessions were held for one hour on Tuesday and Wednesday evenings of two successive weeks. Forty teachers and five students attended. Although there were no lasers in the school district at that time, some of the teachers had ordered classroom lasers and others were considering ordering them. The students were either building or planning to build lasers as a science project.

The enthusiasm generated by the teachers and students prompted us to rewrite the course lectures in the form of a manual which could serve as a basis for similar future courses. The manual is entitled, "Laser Fundamentals and Experiments." This manual is broken into four sections, each of which can serve as the subject of one class session.

The first section covers laser physics and is intended to give the teacher a basic understanding of how the laser works. This section contains no formulae, requiring the teacher to know only elementary, classical physics. It is primarily directed toward the He-Ne and ruby lasers, explaining just what is happening in the little black box.

The second section deals with the biological effects of laser radiation; the skin and the eye are shown to be the areas of prime concern. The biological effects of the laser are presented and some indication given as to the levels of laser radiation which produce these effects. No safety standards are presented because, as of this time, the U.S.P.H.S. has not endorsed nor promulgated any standards, but the teacher is informed of where he can write to obtain interim guides, such as those prepared by the Laser Safety Conference and ACGIH.

The third section is devoted to laser safety. This section is intended to show the teacher how he can operate the laser with reasonable safety in a classroom situation and is divided into three parts. The first part lists general area and personnel safety rules designed for the classroom. The second part presents the teacher with formula which he can use to calculate a first approximation of the hazard posed by his laser, using the manufacturer's figures. The teacher is warned that the advertised figures for a particular model laser are not necessarily true for individual units of that model. Actual performance figures often exceed advertised figures by a factor of two or more. This fact is verified by actual experience and recognized by laser manufacturers.

The third part of this section advocates the use of several safety aids, some of which were developed at SWRHL and three of which we would like to see included in the design of future lasers aimed at the classroom market.

The first device is a beam chopper or shutter, as illustrated in figure I. Such a device should have a positive, perhaps spring loaded, action and could be simply and inexpensively fabricated from sheet metal and easily attached to the laser head. This shutter could be used to stop the beam whenever it is not required, such as when the experimental setup in front of the laser is being changed.

The second device is a key lock which turns the laser power supply off and on. Retention of the key by the teacher in charge of the laser will help prevent unauthorized use of the device.

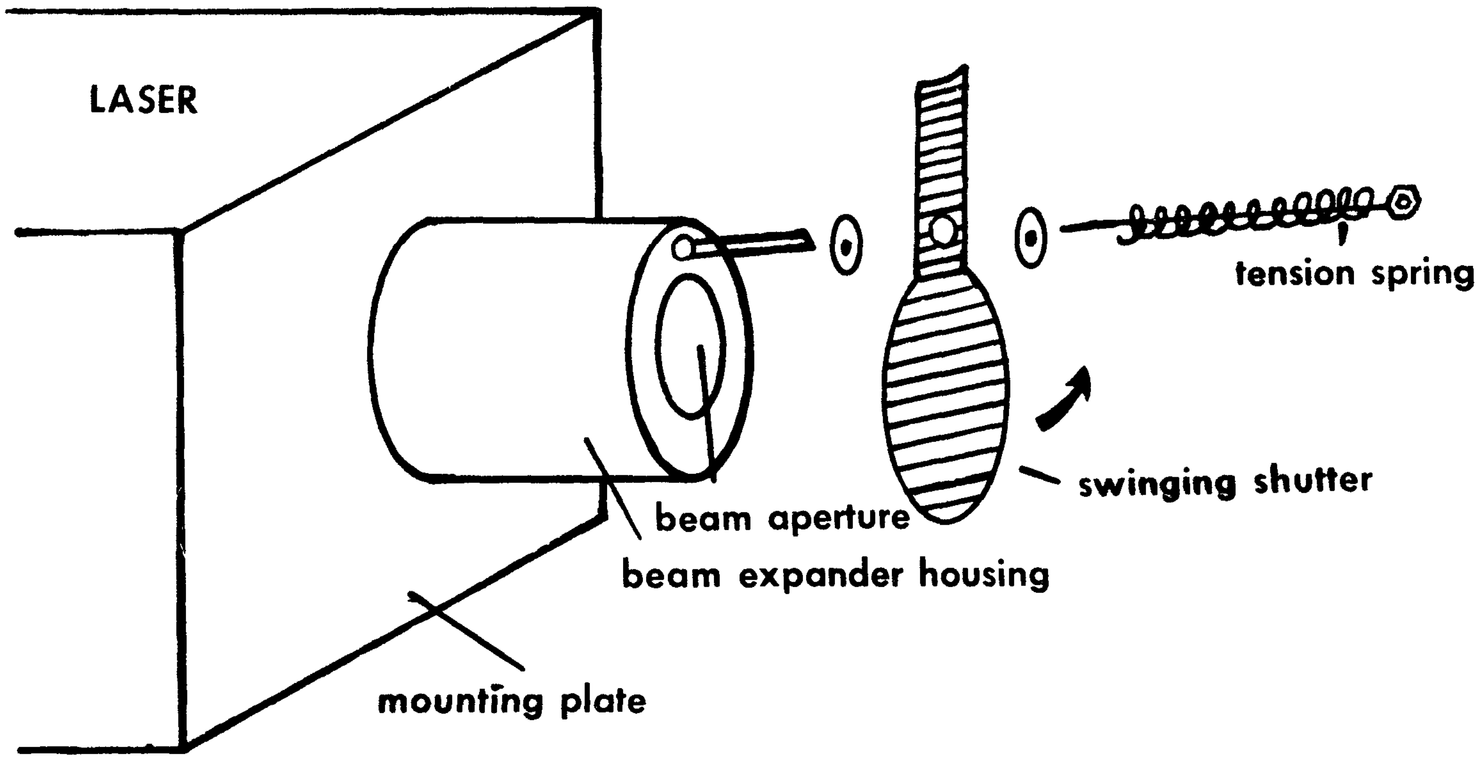

Figure 1. Beam control shutter.

The third safety aid is a beam expander, illustrated in figure 2, which can be made of two inexpensive lenses which expand and recollimate the beam to a diameter of about 1 cm. Few classroom experiments require a narrow beam, and expansion of the beam diameter from 1 mm to 1 cm introduces a safety factor of 100 into the power density of the beam.

A set of laser experiments for classroom demonstration is presented in the fourth section. Each experiment includes an explanation of the properties of light to be demonstrated. These explanations are designed to again give the teacher a basic understanding of the phenomena involved. Performance of these experiments gives the teacher a "feel" for the laser, what it can do in the classroom, and where potential hazards may lie in each experimental setup.

As you can see, the entire manual is safety oriented - from the explanation of theory to the actual guides given for laser operation.

Requests for copies of the manual should be made to:

Electronic Products Studies Group
Southwestern Radiological Health Laboratory
P.O. Box 15027
Las Vegas, Nevada 89114

References:

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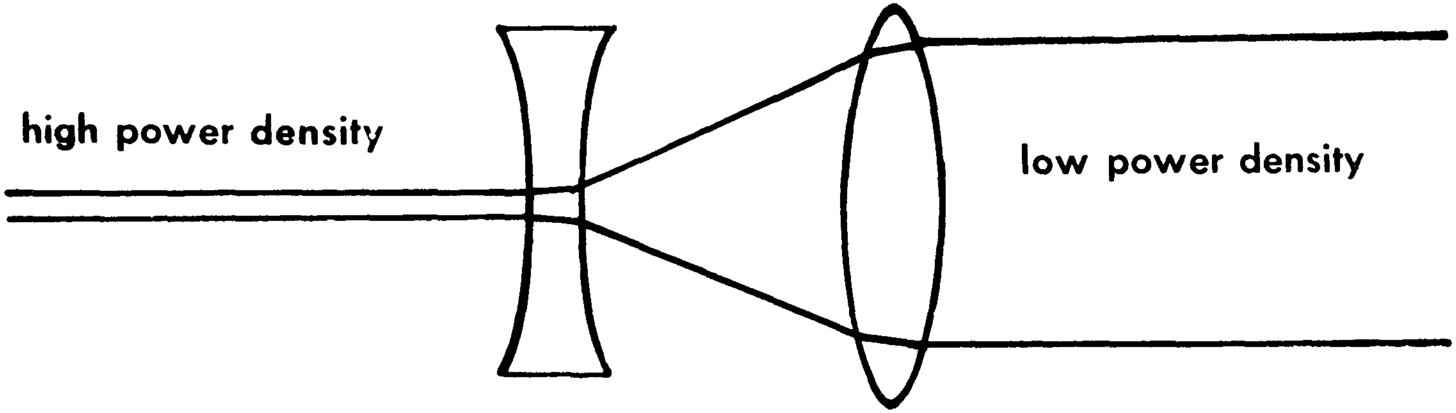
2. A Guide for Uniform Industrial Hygiene Codes or Regulations for Laser Installations, issued by the American Conference of Governmental Hygienists in Laser Focus, October 1968.



MOUNT PERMANENTLY ON LASER

Figure 2. Beam expander.
(inexpensive lenses work quite well)

A GENERAL CONSIDERATION OF THE BIOLOGICAL HAZARDS OF OCCUPATIONAL EXPOSURE TO ULTRAVIOLET RADIATION

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Sources of occupational exposure to ultraviolet radiation are found in many educational and research establishments. The purpose of this report is to consider in a general way the biological basis for the establishment of permissible exposures to ultraviolet radiation. The permissible exposure values will be commented on.

Instrumentation for monitoring exposures to ultraviolet will be mentioned but will not represent a major portion of this review.

INTRODUCTION

The purpose of this paper is to present a broad overview of the potential sources of exposure from ultraviolet radiation (UV) and the physiological effects of such exposure which may be of interest to Health Physicists. Obviously, the constraints imposed by space and time preclude an in-depth analysis of this problem. For those with a more serious interest in ultraviolet radiation, there are several excellent sources of material on this subject, including the recently published proceedings of an international congress on the biological effects of ultraviolet radiation. Some of these sources are listed under the heading of general references at the end of this paper.

The most common source of ultraviolet radiation is the sun. The Health Physicist may find several other sources of ultraviolet radiation in the course of his normal duties. Besides the extensive use of ultraviolet in photobiological research, ultraviolet lamps may be found in such uses as food sterilization, air sterilization, phototherapy, and so forth. More recently, the introduction of lasers which produce ultraviolet radiation has reawakened the interest of Health Physicists and Industrial Hygienists in the biological hazards of such radiation.

A BRIEF HISTORICAL SKETCH

Ultraviolet radiation was first discovered as a part of the sun's spectrum. Extending the previous work of Sir William Herschell on infrared radiation, J.W. Ritter demonstrated in 1801 that chemical changes were produced by some form of energy in the region of the sun's spectrum beyond the violet which was not visible to the naked eye. The observed chemical change was the blackening of silver chloride.

Later, in 1804, Thomas Young showed that this invisible radiation was subject to the laws of interference. This work and that of many others has established that these invisible rays (variously called chemical rays, actinic rays and now ultraviolet rays) are a part of the electromagnetic spectrum.

Even before these very early physical experiments were performed, however, it was apparent that the beneficial effects of solar ultraviolet radiation (or would it be more correct to say sunlight in general?) were appreciated by primitive man. This probably explains the evolution of sun worship as a religious exercise. While the sun is no longer a diety, "sun worship" has by no means diminished.

For reasons that are not entirely clear, the beneficial effects of ultraviolet radiation have not always been fully appreciated. This may be explained in part because of the association of the sun with pagan worship by the Christian world. Regardless of the reason, it was late in the 19th century before the beneficial effects were appreciated by scientists. The therapeutic potential of UV was recognized by N. R. Finsen when he showed in 1899 that sunburn was caused by the ultraviolet portion of the solar spectrum. This discovery opened the way for serious scientific work on the biological effects of ultraviolet radiation. Finsen received the Nobel Prize in 1903 for his pioneering work on the use of UV radiation in therapy.

Ultraviolet radiation is now used for a variety of medical applications in addition to its industrial and public health role in disinfecting and sterilizing.

PHYSICAL DESCRIPTION OF ULTRAVIOLET RADIATION

Ultraviolet radiation occupies that portion of the electromagnetic spectrum from about 4 millimicrons (mμ) to 400 millimicrons (or 40 Å to 4,000 Å). The visible spectrum is normally considered to occupy the spectrum from about 380 mμ to 780 mμ. Thus, ultraviolet bridges the gap between visible radiation and the long wavelength x rays (grenz rays).

The ultraviolet spectrum can be divided into several subdivisions. One such subdivision is shown in table 1 (1). In the German literature the ultraviolet radiation is subdivided as follows (2):

UV-C	from 200 to 280 mμ
UV-B	from 280 to 315 mμ
UV-A	from 315 to 400 mμ

The direct biological effects of solar ultraviolet radiation is a result of wavelengths from about 300 mμ and longer. Below 300 mμ the ultraviolet radiation is effectively filtered out by the ozone in the atmosphere. This absorbed radiation, however, can contribute to many indirect effects through photochemical reactions with environmental pollutants (3-5). The vacuum ultraviolet is so called because in this range of wavelengths, the radiation is so strongly absorbed by air that experimental work must be done in a vacuum.

The restricted range of wavelengths available from the sun has been overcome by the development of a variety of artificial sources of ultraviolet. Several discussions and descriptions of these sources are available (1, 2, 6). Table 2 summarizes useful information on some of the more common types of UV generators. The spectral distribution of the available ultraviolet radiation is markedly affected by the use of filters and the presence of metals other than mercury in the mercury lamps (2).

TABLE 1. *Classification of ultraviolet radiation*

Classification	Abbreviation	Wavelength interval
Vacuum ultraviolet (or extreme ultraviolet)	XUV	10 to 100 mμ
Far ultraviolet	FUV	100 to 200 mμ
Middle ultraviolet	MUV	200 to 300 mμ
Near ultraviolet	NUV	300 to 400 mμ

TABLE 2. *Ultraviolet generators*

Type	Spectral range	Comments
Hot quartz lamp	580-185 mμ	multiple line spectrum
Cold quartz lamp	253 mμ	essential single line spectrum
Filtered xenon lamp	300-800+ mμ	closely resembles global radiation

Ultraviolet radiation is normally considered to be nonionizing although at the shorter wavelengths the quanta are energetic enough to be ionizing. The primary action appears to be in molecular excitation. Because of the mode of action of ultraviolet radiation, the survey instruments which the Health Physicist is normally used to working with are not generally satisfactory for measurement. Geiger-counters and thermoluminescent materials (for example (9)) have been suggested for quantitating ultraviolet radiation but the most widely used instruments at present appear to depend upon the chemical action of ultraviolet, that is, actinometers (10) or various types of photoelectric cells (11-13). Other methods are available including biological monitors. Recent discussions of the general methodology used for measuring ultraviolet radiation are available (for example (10) (14-16))and the reader is referred to these articles for critical details.

There is a continuing need for the development of improved monitors for ultraviolet radiation. This development, of course, must go hand in hand with an improved understanding of what basic physical parameter is most characteristic of the biological action of ultraviolet radiation. Quantities and units for UV dosimetry are still quite rudimentary. It seems to me that a great deal of thought needs to be given to sort out this problem.

Several quantities and units have been suggested for characterizing ultraviolet. The choice of quantity depends upon the effect of interest. Some of these are:

Finsen Unit (FU)	A radiant flux of 10 microwatts (100 ergs) per square centimeter per second of homogenous radiation of the wavelength 2,967 Å (17).
Minimal Erythema Dose (MED)	The shortest exposure at a certain distance which will produce a perceptible reddening of the skin after 8 hours which disappears within 24 hours (18).
Minimum Perceptible Erythema (MPE)	A just perceptible erythema which disappears in 24 hours (this is essentially the same as the MED) (19).
Erythemal Unit (EU)	Twenty microwatts per square centimeter of homogenous radiation of wavelength 296.7 millimicrons (3).
Germicidal Unit (GU)	One hundred microwatts per square centimeter of radiation of wavelength 253.7 millimicrons (20).
Subvesicular Dose (SVD)	A dose large enough to produce a reddening of the order of 6-8 percent reflex difference (that is, between green-blue) which, however, does not produce blistering (21).
Minimal Color Dose (MCD)	The time of exposure of a 1 X 1 cm square test area to a high-pressure mercury quartz lamp that gave a reaction after 48 hours (22).

The quantity most often used by those characterizing the physiological effects of UV is the MED. This quantity is not entirely free from ambiguity. While the MED will of course depend upon the spectral characteristics of the lamp, the area to be irradiated, the seasonal variations, and so forth, the meaning of the MED itself is not uniform. As an example, Wucherpfennig has defined the MED as the least dose which uniformly reddens at 24 hours the irradiated site so that it presents sharp edges (23).

Specifying the quality and quantity of ultraviolet radiation is now best done by giving as complete a spectral description of the source as possible, the exposure rate in ergs per square centimeter per second, the total time per exposure, the radiation field, and so forth. This would remove some of the ambiguity which exists in much of the work being reported today. The more qualitative designations such as MED can then be stated in terms of the experimental details.

USES OF ULTRAVIOLET RADIATION

Ultraviolet radiation results from a variety of industrial processes, including some hot metal operations, various kinds of lamps specifically designed for ultraviolet emission and, of course, natural sources such as sunlight. In the late 19th century when serious scientific work on ultraviolet radiation was being carried out, the bactericidal effects were early recognized. Finsen demonstrated that it was the UV portion of the sun's spectrum that caused sunburn and he also used UV to treat tuberculosis of the skin. While modern drugs have largely replaced natural UV as a therapeutic modality for tuberculosis, this was a tremendous scientific advance in the late 19th century and as we have already mentioned, Finsen received the Nobel Prize in 1903 for this pioneering work.

The degenerative and bactericidal effects of ultraviolet have continued to be applied in medicine for therapeutic and diagnostic purposes. To quote Knapp, "Ultraviolet radiation has been recommended for such a ridiculously large variety of diseases that it would be absurd to name all of them here . . ." (24). These include rickets, tuberculosis, a variety of skin diseases, burns, and so forth. Of course, the therapeutic use of ultraviolet radiation is being dramatically changed with the availability of newer drugs. Epstein (25) has given a useful summary of the diagnostic uses of ultraviolet radiation.

In addition to the medical applications of ultraviolet, there is a growing list of industrial and public health uses. Many of these have been summarized by Koller (19). Most of the applications deal with the germicidal effects of UV for disinfecting a wide variety of organisms. This use has been suggested for airborne infections in hospitals, schools, and other places where large groups of people may congregate, such as human shelters during natural catastrophes (26,27); water purification for humidifiers in hospitals (28); providing potable water supplies on transoceanic ships (29); and so forth. Intense sources of ultraviolet are used in photobiological research (30) and the use of ultraviolet in holography has been suggested (31).

There are other uses for UV, such as in analytical equipment, but the above does provide a broad perspective to the wide variety of applications in which a Health Physicist may find himself involved.

EFFECTS OF ULTRAVIOLET RADIATION

As a part of the biological effects of exposure to ultraviolet radiation, we must consider the effects on single cell organisms as well as those on higher organisms, such as man. There is a very extensive literature on both of these subjects. The usefulness of the germicidal effects of UV have been indicated and germicidal effects will not be considered further. Only a few of the effects on man will be summarized.

Except for therapeutic applications, the primary beneficial effect of UV exposure is cosmetic, that is, sun tanning. This fact is attested to by the great horde of modern day "sun worshipers." The more historical phrophylactic benefits of UV in preventing rickets has been largely replaced by dietary vitamin D.

The destructive aspects of UV, which are used to good advantage in therapy, can also cause unwanted effects. Because of the low penetrating power of UV, these effects will be confined to the external parts of the body. Thus, the target organs (or tissues) will be exposed skin and the eyes.

Ferris has provided a useful summary of some of the biological effects of UV. His table 1 has been reproduced here in table 3 (32). Of those listed, the most debilitating, of course, is carcinogenesis and probably the most widely experienced is erythema.

The carcinogenic effects of ultraviolet have been extensively reviewed by Blum (33) and more recently he has introduced a new quantitative model for cancer induction (34). Premalignant and malignant tumors are more prone to develop in the skin of outdoor workers which develop the dry, coarse and leathery texture. This type of skin is often called farmer's skin and sailor's skin (35). Szabo and Horkay (36) have reported on the histomorphological changes caused by UV light.

Erythemal production by UV irradiation has been the subject of many reports. Based upon early work, a standard curve of erythemal effectiveness has been proposed and is reproduced in most standard books dealing with ultraviolet radiation. This curve is shown in figure 1. This curve shows two maxima of erythemal effectiveness, one around 250 mμ and another around 300 mμ. Because of these two maxima, some people have apparently concluded that the erythema resulting from the shorter wavelengths was different from that produced by the longer wavelengths (37). Everett et al., in series of experiments, have shown that quite a different curve may be obtained. Their data are shown in figure 2 (37). The difference of these two curves may be explained by the fact that the "standard curve" was apparently proposed after considering measurements taken under quite different circumstances, that is, differing anatomic

TABLE 3. *Summary of some biologic effects of ultraviolet radiation*

Effect	Radiation
Ionization	100 A range - overlays with "soft" X-ray
Germicidal	2600 A maximum - effect falls rapidly at shorter or longer wavelengths; effective range associated with absorption band of nucleoproteins
Carcinogenic	2000-4000 A - maximum effect 2900-3200 A
Ozone production	In germicidal range
Photosensitization	Wavelength at which this occurs varies with absorption characteristic of chemical compounds involved
Pigmentation	2800-3200 stimulates formation of melanin - little tanning; 3000-6500 A, maximum 3600-5000 A oxidizes preformed melanin - tanning
Thickening of stratum corneum	In solar range 3000-4000 A
Degeneration of collagen	Parallels cumulated exposure in solar range 3000-4000 A
Keratoconjunctivitis	Greater effect at shorter wavelengths - 0.15×10^6 ergs at 2880 A will produce effect
Antirachitic	Ergosterol to Vit. D; 1 international unit of Vit. D formed from ergosterol when 900 ergs 2490 to 3130 A absorbed
Erythema	2967 A 25,000 μ W, sec/cm^2 minimal amount of power to produce erythema at this wavelength, which is wavelength of maximum sensitivity; erythema can be produced by shorter or longer wavelengths (within a limited range) but more power is necessary; with extremely short wavelength UV there is overlap with soft X-rays, and skin erythema results from effects of ionization

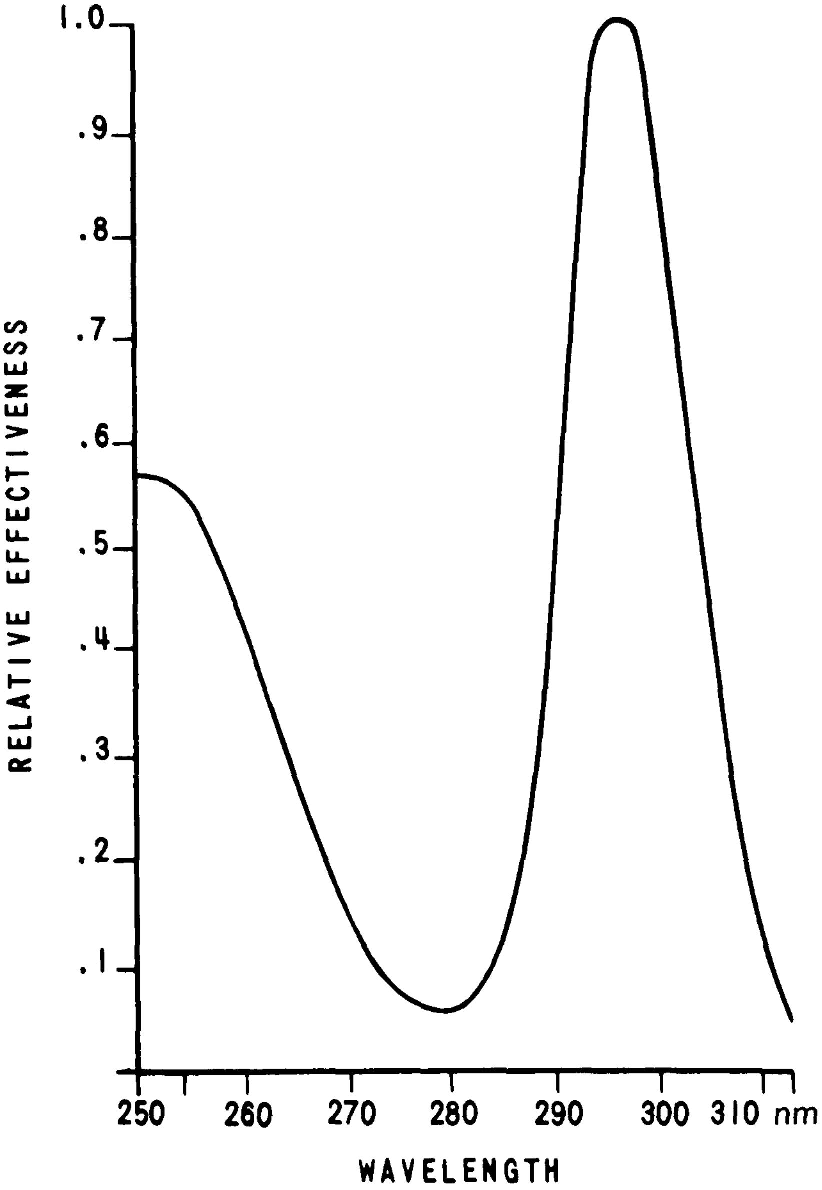

Figure 1. Standard curve of erythemal effectiveness (reproduced with the permission of authors (37) and Pergamon Press).

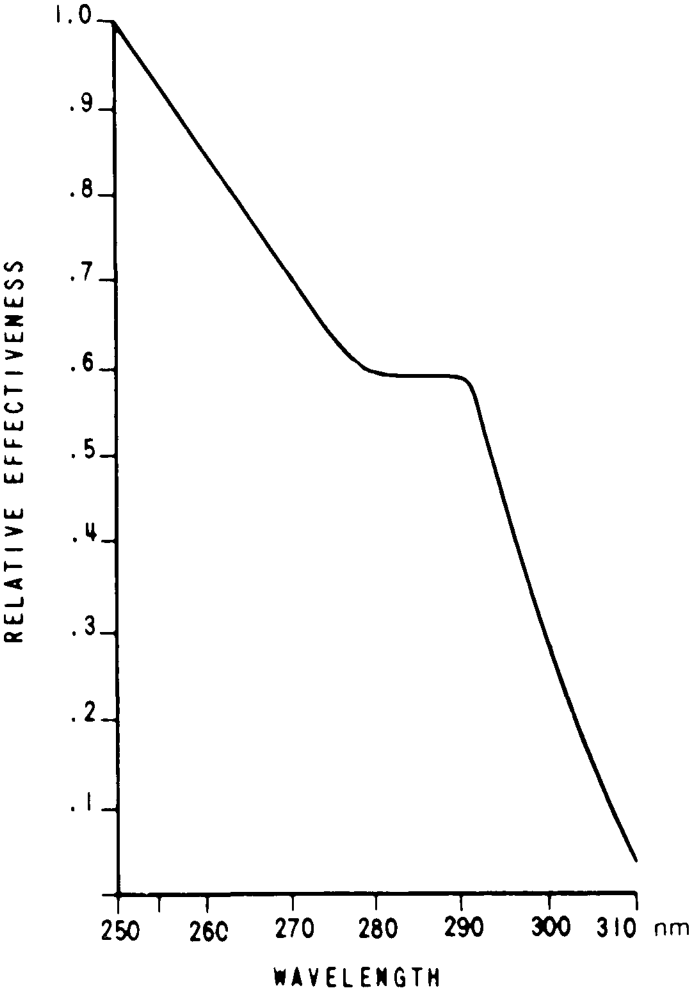

Figure 2. Erythemal effectiveness (reproduced with the permission of authors (37) and Pergamon Press).

site, time, UV source, field size, and so forth (37). However, Rottier indicates that these two sensitivity peaks are a regular experience (38). Clearly, this difference in results should be pursued further.

Buessler has given a short account of the opthalmologic aspects of ultraviolet irradiation in medicine. He states that,

> Photo-opthalmia induced by ultraviolet radiation consists of punctate erosions of the epethelium of the exposed cornea and conjuctiva. It is accompanied by marked photophobia, ciliary spasm and blepharospasm. The symptoms are severe and incapacitating at the time but the injury seldom results in permanent disability (39).

Freeman and Knox (40) have reported on corneal tumors in different animal species induced by ultraviolet radiation.

SAFETY STANDARDS

It is unfortunate with the wide variety of applications of ultraviolet radiation and the unquestioned epidemiological and medical importance of these rays that there is such scant information on accepted guidelines for ultraviolet exposure. The increasing awareness of "energy pollution" in our environment will undoubtedly bring pressure to bear to have this whole problem critically reevaluated.

The only accepted guidelines which I am aware have been published by the Council on Physical Medicine of the AMA (41). They state that,

> If the reciprocity law holds for very low intensities and long exposures, then the total intensity of the ultraviolet radiation (diffusely reflected from the walls and fixtures and emanating directly from the lamp) incident on the occupant for seven hours or less should not exceed five-tenths microwatt per square centimeter (0.5 $\mu W/cm^2$) and for continuous exposure (twenty-four hours a day) should not exceed 0.10 microwatt per square centimeter of wavelength 2,537 Å.

This work was supported in part by a grant from the Medical Staff Fund of the Kansas City General Hospital and Medical Center.

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THE DETECTION OF ULTRAVIOLET RADIATION USING THE THERMOLUMINESCENCE OF SAPPHIRE

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INTRODUCTION

Ultraviolet (uv) radiation is widely used for disinfection of certain media by using its germicidal effects and has numerous technical applications in therapy. It also produces deleterious effects on man, such as erythema (sunburn is a common example), painful inflammation of the membrane of the eye called conjunctivitis, and possibly skin cancer.[1]

Recognizing uv radiation as a potential hazard, the Council on Physical Medicine and Rehabilitation of the American Medical Association has set limits of exposure tolerance to be 0.1 μwatt/cm^2 for continuous radiation exposures from germicidal lamps.[2] For a comparison of magnitude a 15 watt General Electric G15T8 germicidal lamp yields an ultraviolet intensity of about 75 μwatts/cm^2 at one meter from the central portion of the tube.

Several techniques now exist for monitoring uv radiation. One commercial instrument using a photoelectric cell measures from as low as 10 μwatts/cm^2 up to 5,000 μwatts/cm^2.[3] Photomultiplier tubes with their associated circuitry are also commonly used, and the use of chemical photolysis is increasing.[4]

There is a need for an ultraviolet detector that measures uv radiation from below 0.1 μwatt/cm^2 up to high levels of exposure. The detector should be small, portable, stable, and unaffected by normal room lights. This paper describes the thermoluminescent response of sapphire to uv radiation and the feasibility of using sapphire as a uv detector.

DESCRIPTION OF MATERIALS AND INSTRUMENTATION

Sapphire crystals were obtained from the Semi-Elements Company. The crystals contained rather high impurities of manganese (possibly 1%) and chromium as detected by X-ray fluorescence and an emission spectrograph. The samples were crushed to 200 mesh powder with a stainless steel mortar and pestle and then annealed by heating for 15 minutes in an air oven at 400°C. The powder was then allowed to cool to room temperature by removing the crucible from the oven.

The powder was excited by using three different uv sources. One source of uv radiation was a 1000 watt tungsten-halogen lamp which was compared with a standard lamp (Epply EPRIC). Comparison of the lamp to the standard was done by using a thermopile and galvanometer circuit and a set of Optics Technology monopass band filters. The other uv sources were a Bausch and Lomb high pressure mercury lamp and a 15 watt germicidal lamp (General Electric type G15T8).

A Harshaw Model 2000 Thermoluminescence Unit employing an EMI 9635QA photomultiplier tube was used to detect the thermoluminescence. A Moseley 7000A X-Y recorder was used to plot the photomultiplier tube current versus sample temperature. The powder sample sizes used in this apparatus were about 30 milligrams.

The spectral emission of sapphire was determined by heating excited samples at a rate of 20°C/min and directing the resulting thermoluminescence through a Bausch and Lomb monochromator. The radiation emanating from the exit slit of the monochromator was detected by a thermoelectrically cooled EMI 9558QA photomultiplier tube. The spectral emission was also determined by placing band pass filters over the sample as it was heated in the Harshaw analyzer.

RESULTS AND DISCUSSION

Figure 1 shows the glow curve of sapphire after samples were stimulated by uv radiation and heated to a maximum temperature of 240°C at a rate of 7°C/sec. A small 65°C peak and a large broad 165°C peak were produced.

After exposure to the tungsten-halogen lamp the sapphire samples were allowed to remain in the dark at room temperature. The thermoluminescence integrals of the samples were obtained at particular intervals of time after uv exposure. Figure 2 shows that the current integral of the thermoluminescence glow curve after various storage times was stable for at least eight days.

The spectral response of sapphire is shown in Table 1. Optics Technology monopass filters were placed between the sample and the lamp as it was exposed, allowing only a selected wavelength band to reach the sample. These experiments show that almost all of the excitation was due to wavelengths shorter than 4100Å.

To test for room light effects, several samples were exposed to a 15 watt Kenrad Cool White fluorescent bulb at a distance of 1 inch. After a three hour exposure only a very small 65°C peak was observed. This peak contributes less than 1/25th of the total thermoluminescence in the normal glow curves of uv excited sapphire. It also decays rapidly at room temperature and is virtually non-existent after the sample remains at room temperature for 15 minutes.

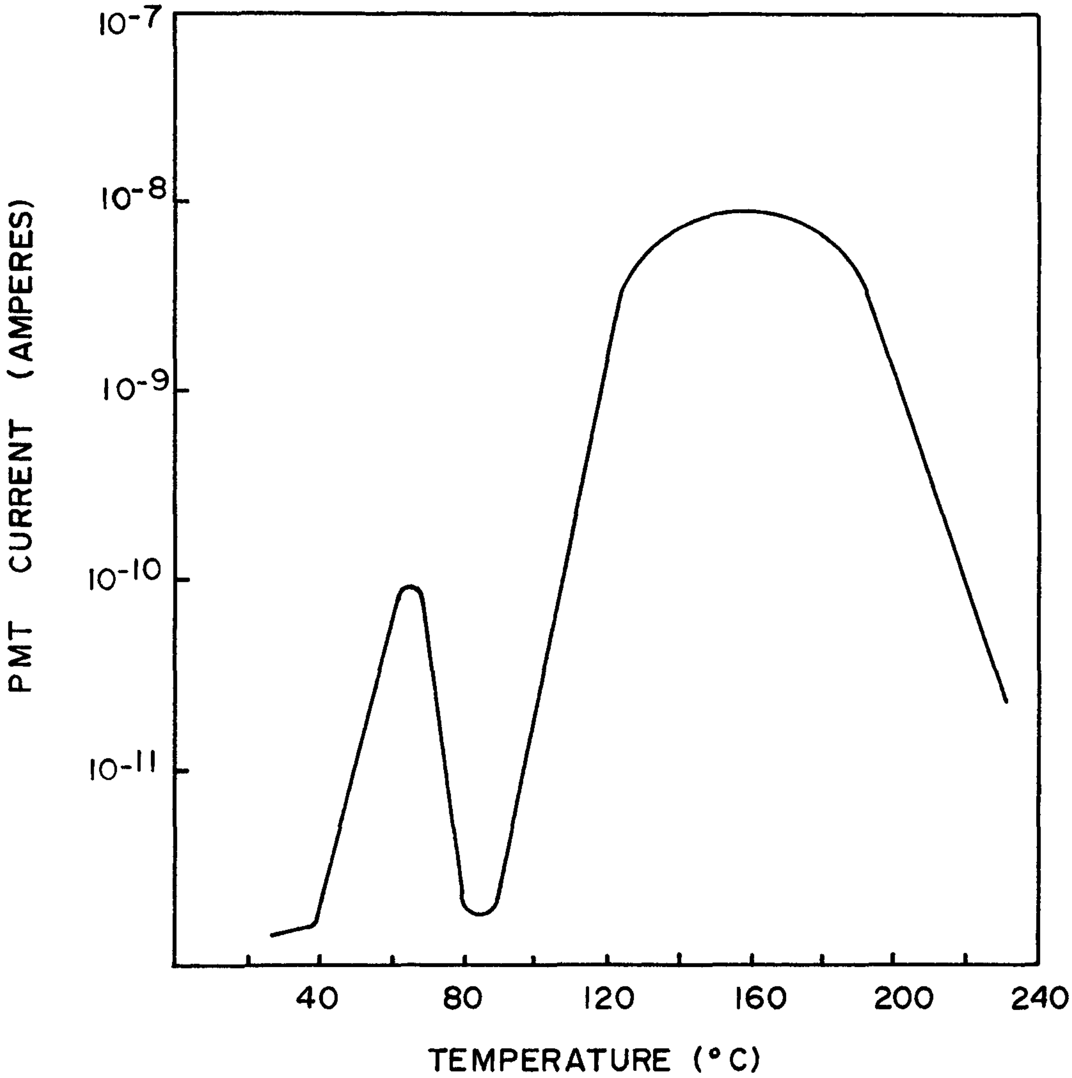

Figure 1. The thermoluminescence glow curve of sapphire after ultraviolet radiation excitation.

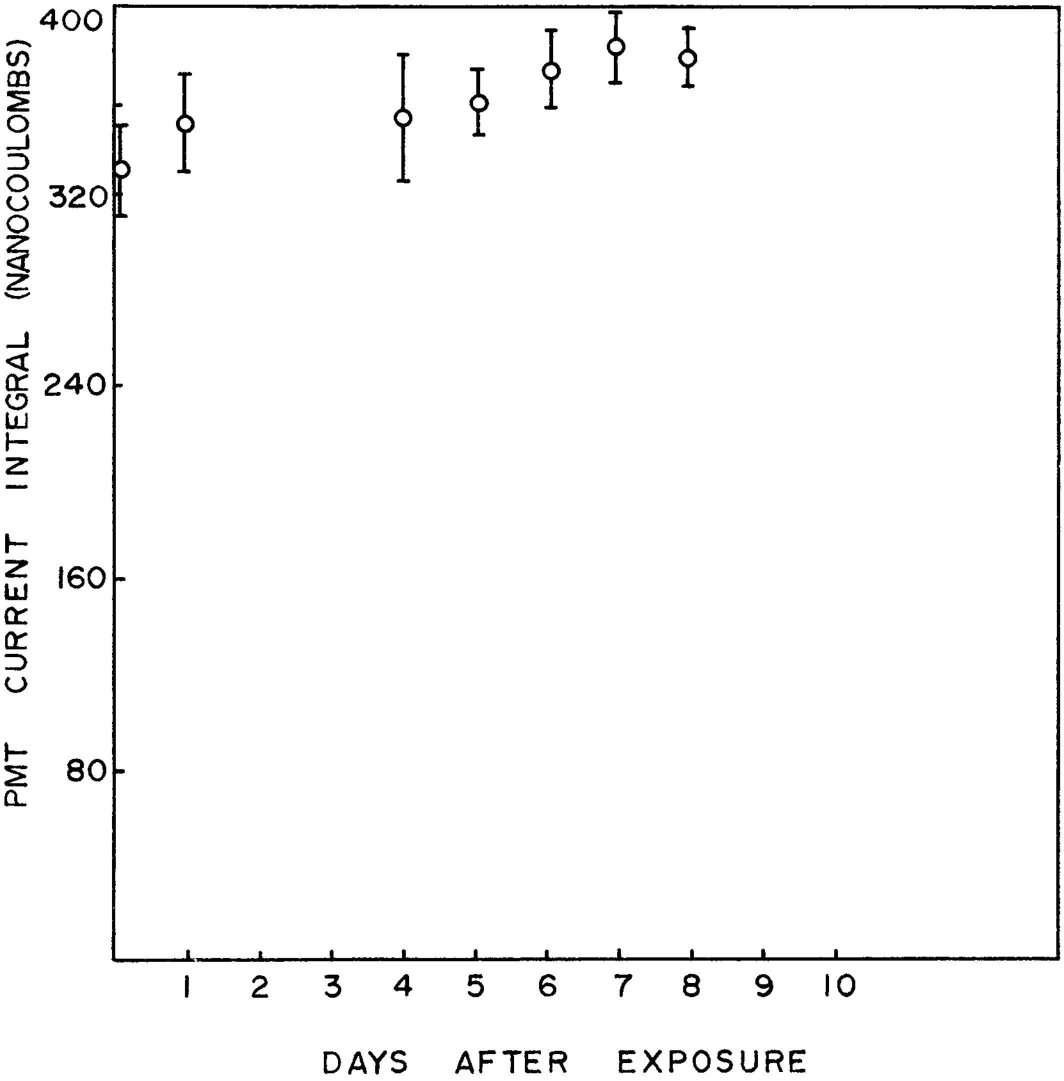

Figure 2. The stability of sapphire at room temperature.

Table 1

SPECTRAL RESPONSE OF SAPPHIRE

Wavelengths	Total Incident Energy	Integral Current	Sensitivity
Angstroms	μjoules/cm^2	Nanocoulombs	Ratio of Integral Current to Incident Energy
2,537	6,000	2,700	.45
3,100	3,600	627	.174
3,300	14,400	715	.050
3,500	17,640	629	.036
3,700	30,402	557	.018
4,000	135,000	1,200	.009
4,330	144,000	378	.003
4,660	261,000	125	.0005

The emission spectrum of sapphire was determined by exciting a sapphire chip with a high pressure mercury lamp. The chip was then heated, and the resulting thermoluminescence was directed through a monochrometer to a photomultiplier tube. Figure 3 shows that after excitation the chip emitted a small peak at 3000Å and a very large sharp peak at 4100Å. The emission spectrum from sapphire that had been stimulated by a tungsten-halogen lamp yielded similar results.

Figure 4 shows the integrated glow curve current as a function of the length of exposure to the complete spectrum of a General Electric G15T8 15 watt germicidal lamp. The exposure rate was approximately 10 μwatts/cm^2. Observe that the curve is linear for low uv exposures and becomes nonlinear after 10 minutes.

Samples exposed to intensities below 0.3 μwatts/cm^2 for 30 minutes yielded appreciable thermoluminescence. It is expected that very low uv radiation levels can be measured by extending the exposure time, since the method of detection is an integration method.

The dependence of the thermoluminescence on the intensity was measured for exposure rates of 10 μwatts/cm^2 to 100 μwatts/cm^2, with a total incident energy density of 6,000 μjoules/cm^2. Within experimental error, the response was independent of the intensity.

The thermoluminescence measurements yielded fractional standard deviations of about 7%. It is expected that more patience and refinements will lower this to below 3%.

CONCLUSIONS

Nominally pure sapphire containing chromium and a high concentration of manganese as impurities was obtained from Semi-Elements, Inc. This sapphire had the following characteristics:

(1) Sensitivity to low levels of uv exposure.
(2) A linear response at low exposure.
(3) Stability at room temperature for at least 8 days.
(4) An emission spectrum that will match the response of photomultiplier tubes most commonly used in thermoluminescence.
(5) A negligible stimulation by room lights.

Because of the characteristics of this sapphire it can be used as a practical uv dosimeter.

ACKNOWLEDGEMENTS

This investigation was supported by Western Kentucky University and the U.S. Public Health Service Research Grant No. 1 R01 EC 00118-02, National Center for Radioligical Health.

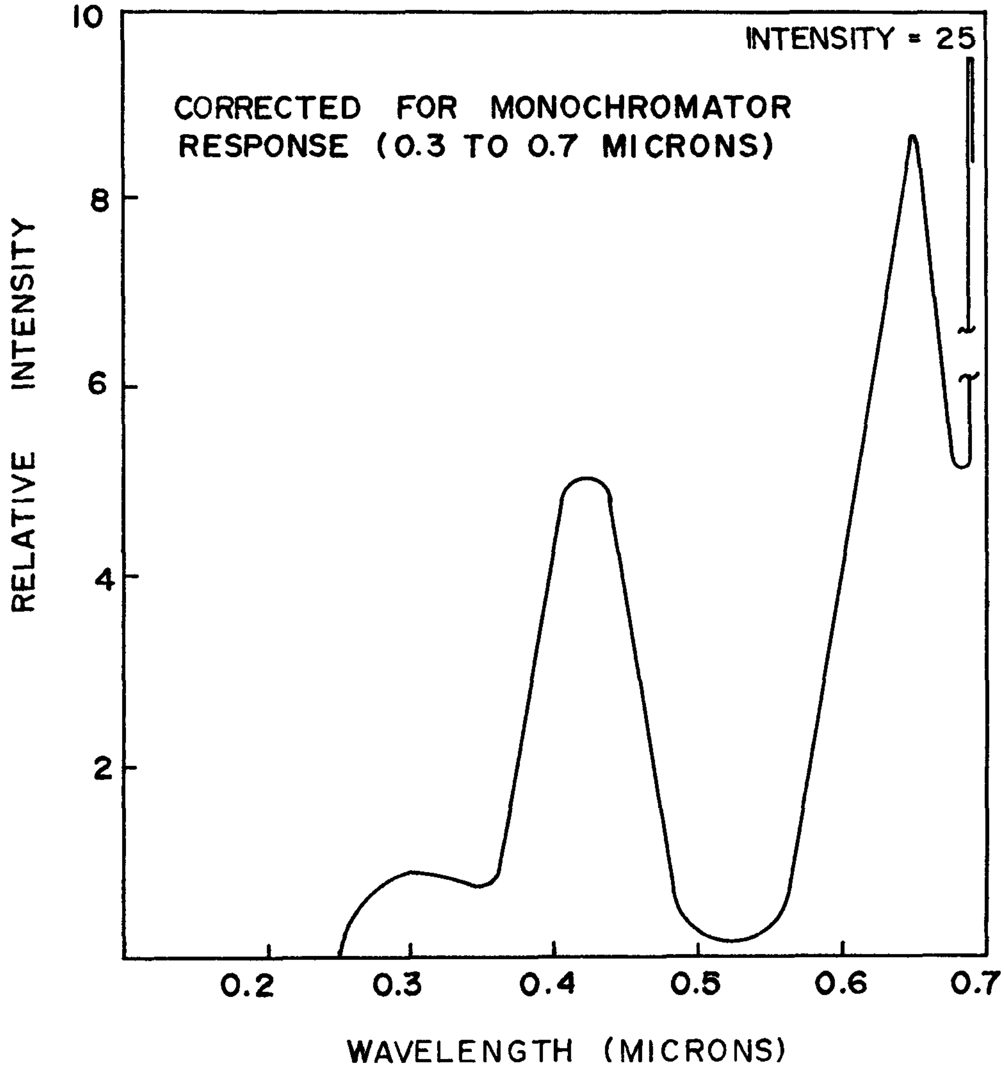

Figure 3. The thermoluminescence emission spectrum of sapphire after ultraviolet excitation.

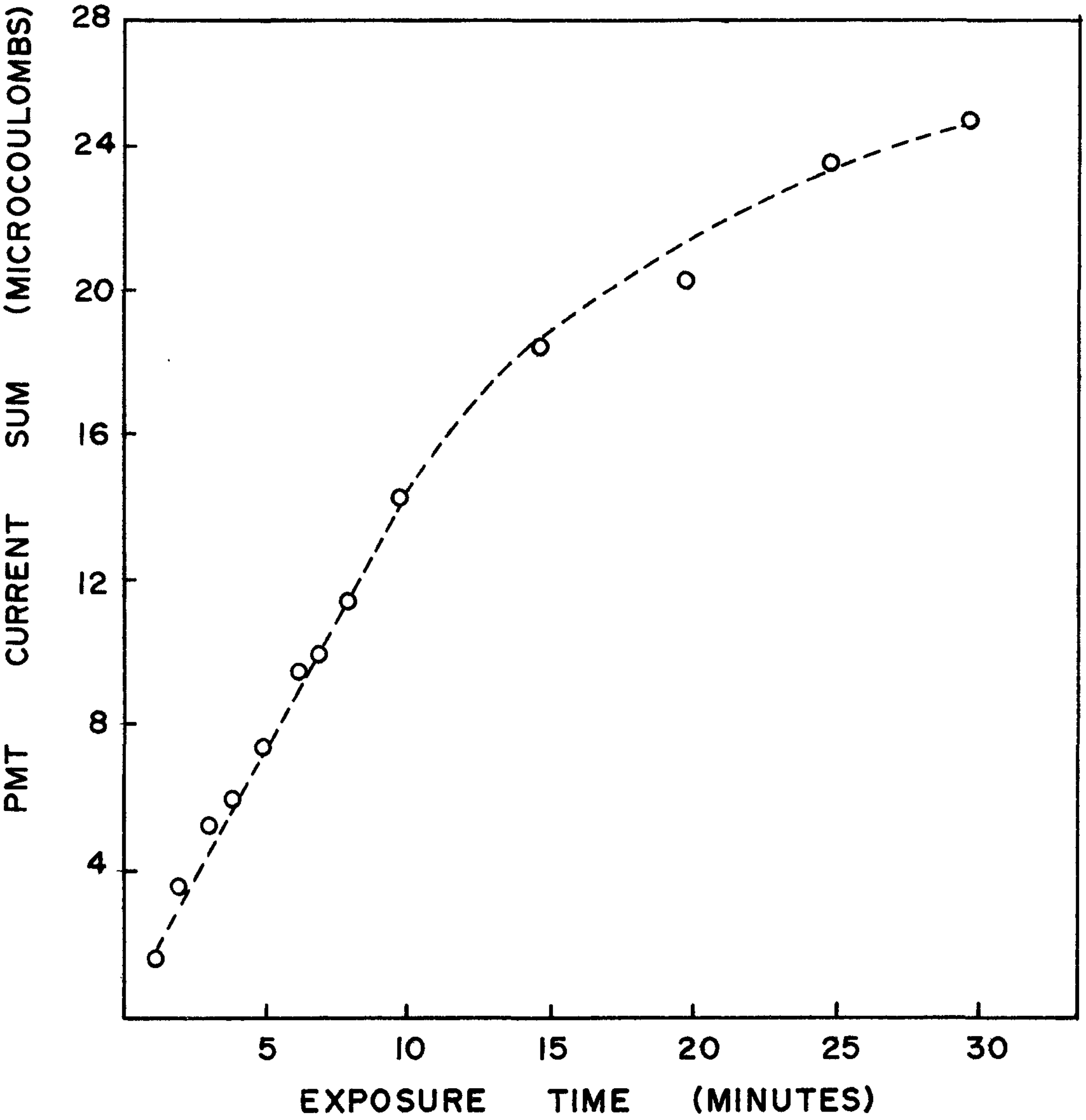

Figure 4. Integrated thermoluminescence glow curve current versus exposure to the germicidal lamp.

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THE ORBITING ASTRONOMICAL OBSERVATORY (Abstract)

Banquet Speaker: J. E. Kupperian, Jr.

THE ORBITING ASTRONOMICAL OBSERVATORY

JAMES E. KUPPERIAN, JR., PH.D.

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The Orbiting Astronomical Observatory (OAO) OAO-II was placed in a 480 statute mile circular orbit at 0945 Greenwich Mean Time on December 7, 1968. From that time the spacecraft and observing instruments of the University of Wisconsin and the Smithsonian Astrophysical Observatory have been performing their intended mission.

The orbit of the OAO-II is above the absorbing atmosphere of earth and allows the astronomers an unobstructed view of the celestial sphere in the wavelength range from 1000 to 3000 Å. The vast amount of new data obtained includes four color TV photographs of the sky, multicolor absolute photometry of stars, nebulae, and galaxies, and moderate resolution spectra of the brighter stars. These data have supplied new information in a number of fields of interest in astrophysics and geophysics.

Discoveries include ultraviolet bright galaxies, bright reflection nebula, the varied nature of interstellar matter, bright galactic background, and numerous pecularities in stellar spectra. These are the result of the analysis of a small portion of the data. As we begin the second year of OAO-II operation the astronomers find their observing lists longer and their excitment higher than ever before.

SESSION V. MICROWAVE AND RF RADIATION, INVITED PAPERS

Chairman: Russell L. Carpenter

EQUIPMENT SURVEYS FOR RF RADIATION HAZARDS

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One of the worlds largest users of radio frequency (RF) generating equipment is the United States Air Force. Safeguarding the health of its personnel from the attendant RF radiation hazard requires a continuous hazard prevention program. This paper supplies some detail of the program now in effect. The equipment, the siting and various actions taken to promote safety are described.

The United States Government has many thousands of units of electronic equipment capable of radiating RF power at levels exceeding the recognized 10 mw/cm^2 safe limit. Certainly the US Air Force has its share of such equipment and with it, the job of protecting their personnel from the attendant hazards. The USAF Radiation Hazard Prevention program(1) has, for about 11 years, provided that protection. This program must be labeled a success. There has not been a single case of RF damage to personnel since its inception. This morning I will talk about a facet of the program that all of us here are concerned with. I will call it the radiation hazard field survey and define this as virtually all actions which make use of the hazard criteria to effect a safe environment at an equipment location.

The radiation hazard work in GEEIA takes our personnel into virtually every Air Force activity that has RF equipment. A better feel for what is involved in the GEEIA responsibility might ensue from a viewing of the USAF Radiation Hazard Training Film.(2) The film and its content may provide useful information for those that must establish their own safety programs. I would like to present this film to you now with the explanation that the film is directed to a lay audience and that it contains, in addition to the direct RF hazard to personnel, information on fuel and electroexplosives which constitute indirect hazards to personnel.

FILM USAF TF6143 23 Minutes Color

I would now like to add to what you have seen and explain what I think goes into a proper radiation hazard survey.

The survey should include a pre-planning phase wherein as many hazard areas as is practical are located or identified by a process of prediction. Obviously such predicted results greatly aid the measurement task. However, care should be exercised in the use of such predictions. They are most usually incomplete and very often wrong. The lack of accurate technical parameters to support these predictions and the existence of reflections are the main constraints to accurate results.

The amount of effort required to perform a radiation hazard survey depends to a great extent upon the existence or absence of previous survey work at the site involved. As an example, the training film depicted many areas where measurements may be required. The survey effort is reduced if these areas only need spot checking for changes incurred since the last previous survey.

Inexperienced measurement personnel may fail to check areas of high side or bottom lobe radiation. Reflection areas, or areas where reflections may cause a concentration of energy to exceed the hazard limit, should be investigated. A very special reflection area that must not be overlooked is the area well beyond the predicted 10 milliwatt/cm^2 distance arrived at by simple use of the inverse square formula. This area can receive coherent reflections of RF energy with the result that the 10 milliwatt level is extended to greater distances.

The survey must of course include more than measurements. It should be sensitive to existing hazard problems that site or facility people might not be aware of. Lack of general hazard information and a non-functioning local prevention program at the facility should obviously receive attention.

Other specific key areas of concern during a proper survey may include: the accuracy of existing radiation hazard drawings; the site standard operation procedure (SOP) file and the radiation hazard warning sign deployment. Special sites may have warning devices which should be checked. Delving into these areas may result in the need for additional measurements and ultimately in recommendations for changed procedures regarding site hazard control.

Radar and other special equipment with scanning antennas, as depicted in the training film, often employ RF blanking. This blanking may be relied upon to provide hazard safety. The angles involved in this blanking should be checked periodically. Incidentally, I would suggest that people involved with this type of equipment consider the use of some form of redundancy in the blanking scheme to more or less guarantee protection. Examples of this might take the form of double microswitches in the blanking initiation circuitry or, perhaps employ the use of a radar speed trap alarm to signal blanking failure.

A few moments ago I mentioned a pre-planning phase as part of the field survey. Part of the prediction process mentioned, of course, involves mathematical operations, but more than this, it must often involve a familiarization of the equipment and site layout. For instance, if the team is considering a hazard survey of a communications site they may be confronted with a simple monopole transmitting antenna such as was shown in the training film illustration. One might expect that the RF field around such an antenna would be uniform in azimuth and decaying in power level by some function which quickly settles down to the inverse square function. Such may not be the case. Consider the fact that beneath these antennas there is often buried what are called ground radials. A knowledge of where these radials are located will make obvious where measurements should be included in the survey.

Very important to hazard prevention work is the skilled use of test equipment. "Skilled", connotes training, and we do train our people to use power density and field intensity measuring equipment. Much has been said however concerning the limited accuracy of presently available test equipment. I largely discount the seriousness of this problem as it concerns my colleagues and myself. I hasten to explain this so that I do not offend those that do fight this battle for better equipment. I believe that our personnel are adequately instrumented to measure against the present safety limit of 10 mw/cm^2. There are two reasons for this feeling or attitude. Neither is steeped in the rigorous physics of measurement. First, consider the very simple way in which the limit is stated, that is, in terms of power density. We are not required to measure separately the E and H fields and we know that the researchers responsible for the hazard limit measured power the way we do. Indeed, the term "power density" suffers from a lack of definition when we are as usual, involved with antenna near-field phenomenon. Secondly, and from a practical standpoint, we must consider the safety factor built into the limit. We know that the limit resulted from research which indicated serious concern at power levels at least two orders of magnitude above it. I will readily admit that there are in my opinion some disquieting research reports appearing in the medical and biological information channels. If such research results in changed criteria and I mean changed in level or in the way it is stated, then we may have reason to be concerned about our test equipment capability.

Though obvious to many I will emphasize that the medical researcher in contrast does have a critical need for much better test equipment.

In closing, I would like to reflect upon the various operations that involve the intentional radiation of RF power. The USAF radiation hazard prevention program has not involved serious operational constraints nor overly expensive procedures. This is mainly due to the fact that in the US Air Force this radiation is largely into space devoid of personnel. Those of you that are more involved in electronics ovens or similar equipment may have a different problem.

References:

(1) USAF Radiation Hazard Prevention Program in part, the subject of AFR 100-6, 18 Dec 1966.

(2) USAF Training Film, TF6143 "Radiation Hazards" 1968.

A COMPARISON OF MICROWAVE DETECTION INSTRUMENTS

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Introduction

Microwave energy is currently being employed in several different ways, with increased emphasis on use in consumer products. When used as a source of power for a consumer product, microwaves are generally intended to be used in a completely shielded enclosure which allows no access while the microwave source is operating. Since there is concern about the biological effects of such radiation, it is necessary to detect and quantitate leakage from products using this type of energy source.

All of the commercial instrumentation available at the time of this evaluation respond to the electric field intensity and are calibrated in terms of power density measured in free space.

Types of Microwave Power Density Instrumentation

Several classification methods for microwave power density instrumentation are possible. The three categories we have chosen are intended use, method of detection, and method of indication. There are two distinct equipment use categories, either as a laboratory instrument or as a survey instrument. A laboratory instrument would ideally be sensitive enough to measure whatever power densities are desired with the capability of covering an extremely wide dynamic range. It should create no disturbance to the propagating field and should be stable with a very fast response time. It should be able to indicate accurately at any distance from the source.

If the instrument is designed for survey use, it should meet additional major requirements, i.e., it should be lightweight, battery operated with low battery drain, easily readable, rugged and have a minimum number of switch settings. The probe should be burnout-proof and directionally independent. For operator safety, it is also very important that a survey device not read low when it is in a potentially hazardous field.

The detection methods category can be divided into thermal detectors and electrical detectors. Thermal detectors act on the principle of producing a detectable physical change (temperature) in a thermally sensitive element. This change is then measured, usually by electrical means. There are three general types of thermally sensitive elements in use today. The first is the thermistor. The resistance of the thermistor decreases when its temperature rises. The thermistor is heated by coupling it to the electromagnetic field. It is the r.f. (radio-frequency) current which causes the heating of the thermistor, but the detection of this heating is done by measuring the d.c. resistance of the thermistor. Another device closely akin to the thermistor is the baretter which has a positive temperature coefficient of resistance rather than a negative one. These are both known as bolometer detectors, a term which means any device which changes its resistance as it changes temperature.

Another type of temperature sensitive device is the thermocouple. A thermocouple produces a voltage when heated. Therefore, all that is necessary to make a detection device from a thermocouple is an antenna and a current or voltage measuring device. The voltage and current levels encountered when using these detectors are very small, so that a sensitive meter must be used, generally in conjunction with some type of direct-current amplifier.

A third and rather novel approach to thermal microwave measurement is the air-pressure system. This system involves the measurement of a small pressure change in a confined gas when its container is heated slightly by absorbing some r.f. energy. The container for the gas is usually some sort of electrical insulator covered by a carbon compound which absorbs r.f. energy quite well.

The three thermal detection schemes discussed have individual and common deficiencies. They all are, of course, ambient temperature dependent in their simple form. More sophisticated methods of measuring the difference in output from matched thermal detectors with only one exposed to r.f. heating have been developed and such instruments are superior for general application.

A somewhat different approach to power density measurement is that of direct electrical energy conversion. The detected r.f. power directly activates the meter needle for measurement. This effect is accomplished by using a semiconductor diode or rectifier. This device, of the same type as used in early radio sets, rectifies the alternating r.f. current into direct current which may then be applied to a meter movement calibrated to indicate power. Knowing the effective antenna area, the power density may be calculated. The diode detector type of indicator may be made extremely sensitive. In fact, this is one of the drawbacks of high frequency diodes -- even moderate signal strengths must be attenuated before reaching the detector in order not to overload it. This is sometimes rather complicated and may lead to measurement inaccuracies. This is probably the reason that the thermal detectors are preferred over diode detectors for survey type power density meters.

With the exception of the air-pressure detector, all detectors or sensors require an antenna to convert the propagating radio-frequency wave into wire-conducted radio frequency currents which are then detected by either a thermistor, thermocouple, or diode. It is this antenna that determines the major characteristics of the measuring instrument. There are two attributes of an antenna which are important to the user of the instrument: directionality and polarization sensitivity. Directionality of an antenna is the dependence of its response on the direction from which the wave comes. One would like an antenna which is somewhat directional so that the effect of reflections from survey personnel will be minimal, but at the same time not too directional so that orientation towards the source becomes critical.

The second attribute is polarization sensitivity. Polarization of an electromagnetic wave refers to the direction of the electric field vector. This vector may be varying in orientation (random polarization), fixed in orientation (plane polarization), rotating in orientation at the radio frequency (elliptical polarization), or any combination of these. There is no single antenna which will respond to all polarizations simultaneously. This causes a great problem in antenna design. To achieve true polarization independence, one must use two antennas which are identical to each other except that they accept orthogonal polarizations. The power captured by these antennas must be added arithmetically in the metering circuit, which places added constraints on the design. To design a survey meter with true polarization independence is no easy task. Generally this is accomplished by using two perpendicular dipole antennas with independent detectors.

The third category for classification of microwave power density instrumentation is method of indication. Quantitative methods are an analog scale and digital indication calibrated either in milliwatts per square centimeter or decibels relative to some reference. These methods seem to be the most practical in a laboratory or survey meter. If the instrument is used to measure product performance against a standard then it is very helpful to have the indication in the same terms as set forth in the standard. Visual qualitative devices such as variously colored gaseous glows or an audible alarm which sounds when some power density limit is exceeded are useful devices under certain conditions, e.g., quickly locating microwave leakage from an oven.

Commercial Instruments Tested by DEP

The commercial survey instruments which were tested in the DEP laboratory include:

(1) a pocket dosimeter employing a multiturn coil as an antenna;[1]

(2) a preignited neon-mercury tube designed to indicate a microwave field;[2]

(3) a survey meter employing a dipole antenna with a thermocouple detector;[3]

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[1] Model C-1 Dosimeter, Scientific Protection Devices, Inc.
[2] International Crystal 285 Microlite, International Crystal Mfg. Co.
[3] Wayne-Kerr Rad 200, Wayne Kerr Co. Ltd.

(4) a survey meter employing a horn antenna with a thermistor detector;[4]

(5) a survey meter employing a lefthand helix antenna with diode detector.[5]

The pocket dosimeter was found to be totally unsuitable as a quantitative instrument. It exhibited marked differences from theoretical values because of r.f. leakage of the instrument components. The response of the unit was severely dependent on the polarization of the radiation and exposures to extremes of temperature.

The inexpensive instrument utilizing a preignited neon-mercury tube as detector and readout was also found to be unreliable for quantitative measurements for the following reasons:

(1) Variation of sensitivity between instruments. As stated by the manufacturer of the neon-mercury tube used in the instrument, "The tube was never designed for this application and consequently the gas pressure and other important parameters are not at all controlled for this type of application" (1).

(2) Variation with time. It has been reported that a tube left unused for some time will often change appreciably its ignition threshold (2). A tube which glows fully at 10 mW/cm^2 may later fail to detect a considerably stronger field.

(3) Variation with direction. Different evaluations of the field will be obtained for different orientations of the instrument. Optimally the instrument glows fully at a level of approximately 10 mW/cm^2 in the most favorable orientation -- thus when the instrument is in any other orientation, the field will be underestimated.

(4) Subjective nature of determination. There is no definite threshold for ignition or for full tube length glow. Even with no microwave power present, a faint blue glow is discernible at the ignition end of the tube. As the power level is increased, small blue flashes begin to appear, and their size and frequency are continuous functions of power. There is a wide range between the power density for the first flash which extends the length of the tube, for instance, and that at which the full tube can be said to be glowing.

(5) Lack of warning of high power density. It was observed that at power density levels between 20 and 100 mW/cm^2 no change was seen in the quality of the light emitted by the tube.

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[4] Ramcor Model 1200, Model 1270, Ramcor, Inc.

[5] Narda Model 8100, Narda Microwave, Inc.

(6) Variation with lighting conditions. Especially at low power density levels, the visibility of the blue flashes is considerably enhanced by viewing the tube against a black background or at low ambient light levels.

The principal advantage of this instrument is its low cost, about thirty dollars. It can be used to detect microwave leakage, but with considerable uncertainty as to the power density level of the leaks detected. A glowing tube indicates the presence of microwave power; however, a tube that does not glow is no indication that high levels are absent.

The following tabulation compares the characteristics of commercial devices utilizing thermocouple sensing elements, thermistors set in a bridge circuit, and a helix antenna with a diode detector circuit. Although these devices operate over different frequency ranges, they are all designed to include 2450 MHz; therefore the devices will be compared at this frequency using a plane electromagnetic wave. This frequency was chosen since it is used for most microwave consumer products such as microwave ovens.

(1) Sensitivity: Smallest readable indication

  a. Thermocouple device: 0.01 mW/cm^2

  b. Thermistor device: 1 mW/cm^2

  c. Helix with diode detector: 0.5 mW/cm^2

(2) Readable range

  a. Thermocouple device: 0.01 mW/cm^2 - 200 mW/cm^2

  b. Thermistor device: 1 mW/cm^2 - 500 mW/cm^2 with external attenuators

(3) Ease of Measurement

  a. Thermocouple device: This unit is completely portable. The three probes to be used with the meter are restricted to the three feet of cable attached to each probe. The sensing end of the probe is pointed toward the source of the radiation for optimum effect.

  b. Thermistor device: This unit is completely portable. The antenna can be fastened to the instrument body either directly or through a coaxial cable. However, the meter scale is small and difficult to interpret, and the antenna responds only to an electric field parallel to the wand or across the short dimension of the antenna horn depending on the model used.

c. Helix with diode detector: The unit is completely portable and self-powered with the exception of mercury cells to operate a circuit to check meter operation. The antenna must be oriented toward the microwave source and has a beam width at half power response of about 55 degrees.

(4) Accuracy[6]

a. Thermocouple device: Approximately ± 25 percent at level of calibration of each probe

b. Thermistor device: Approximately ± 25 percent at 10 mW/cm^2

c. Helix with diode detector: -0 percent and + 59 percent. The inaccuracy approaches 59 percent at the higher end of the scale.

(5) Reliability and repairability

a. Thermocouple device: This instrument did not exhibit polarization sensitivity. However, it suffers probe failures at overloads of 50 percent above maximum range. Once a probe is burned out the sensing device must be replaced and calibrated by a factory technician.

b. Thermistor detector: This instrument is markedly affected by polarized microwave radiation. Either the probe must be held parallel to a linearly polarized electric field or else two readings 90 degrees apart must be taken to achieve accurate results. The instrument is not troubled by overloads with the exception of the attenuator mounted in series between the detector and the meter. However, the meter is troubled by zero drift.

c. Helix with diode detector: This instrument will respond correctly to any direction of plane polarization, but will not respond correctly to elliptically polarized waves. No experience has been encountered with repairability of the instrument.

(6) Cost

a.	Thermocouple device:	$885.00
b.	Thermistor device:	$605.00
c.	Helix with diode detecor	$450.00

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[6] From Manufacturers' specifications.

(7) Stability: The thermocouple instrument is quite stable and its accuracy has little temperature dependence (eight percent change from initial value when brought from 5°C to 22°C). The thermistor device has a rather unstable zero adjustment and its accuracy specifications are exceeded at extremes of temperature (thirty percent change from initial value when brought from 5°C to 22°C). No information about the stability or the temperature dependence of measurement accuracy of the instrument using the helix with the diode detector is presently available.

Conclusions

There are advantages and limitations for all the various instruments described in this report. Almost all of the instruments will serve some useful purpose within their limitations while a change of frequency and test conditions may change the selection of one device over another. As a result of the tests outlined in this report it was found that the thermocouple device is best suited to measure leakage close to a slot source such as a microwave oven at the frequency of 2450 MHz.

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INTERACTION OF MICROWAVE AND RF ENERGY ON BIOLOGICAL MATERIAL

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Presented on January 30, 1970 at the Fourth Annual Midyear Topical Symposium of the Health Physics Society, Brown Hotel, Louisville, Ky.

This lecture is divided into three parts: (a) the nature of the radiation with which we are dealing; (b) the ways the radiation can interact with material in general; and (c) the ways it interacts with biological material.

The Nature of "Microwave" Radiation

First, we are considering electromagnetic radiation with a frequency range of 50 megahertz to 10, 000 megahertz. The corresponding range of photon energies is 2×10^{-7} to 4×10^{-5} ev. The wavelength varies from 6 meters to 3 centimeters, that is from three times the length to about 1/50 of the length of an average adult human being. That size ratio is important in a number of considerations which follow. Diffraction of energy in this frequency range occurs quite readily, so that the shadows are not dark. Diffraction interferes with many attempts to shield portions of the body while irradiating other portions. Shielding is not so easily done as it might appear.

The radiation is characterized by a near field and a far field, the distinction relating to the nature of the radiation's source. For those who do not have much familiarity with electromagnetic radiation, antenna design, and propagation theory, I will summarize some characteristics of the near field and the far field. These characteristics are quite important in the discussions which follow.

The far field has a relatively simple radiation pattern which is not closely dependent on the nature of the source. That is, one could change the source geometry slightly and not change the far field pattern very much.

The far field radiation pattern has sinusoidal properties in time and, locally, in space. That is, it has a sinusoidal form in space at an instant in time, and in time at a spot in space. The electric field vector has a fixed relationship with the magnetic field vector and with the vector denoting the flow of power. These relationships are relatively simple to derive from Maxwell's equations. The concept of power flow in a far field is a meaningful one and the units of milliwatts per square centimeter are entirely appropriate and meaningful. They imply exactly what you expect them to imply. The power, of course, follows the inverse square law in the far field. You should note that the electric field vector does not follow the inverse square law. It falls as the inverse first power of the distance.

The near field is quite different. It has a complex pattern which is very closely dependent on the detailed nature of the radiating source and its immediate environment. It is sinusoidal in time at any spot in space, but it is not necessarily sinusoidal in space at an instant in time. The electric field vector has no fixed relationship to the magnetic field vector. The vector denoting power flow, which we speak about so glibly, is not a meaningful quantity in the near field. It can be measured with power flow measuring instruments; the result of the measurement, however, is meaningless. The extent of the near field is proportional to the directivity of the source. The more directional the antenna, in general, the farther out the near field extends. There is a possible analogy with a rifle: If you consider the propagation of a bullet to have a near field in the rifle barrel and a far field once it gets outside of the rifle barrel, then, at least for certain rifle barrel lengths, the longer the length, that is, the longer the near field, the more directive the bullet. In the electromagnetic case, the longer the near field, the more directive the beam. It is almost as if there were something about the near field which helps the beam to be directive, or as if the non-propagated energy which is in the near field somehow acts in space to guide the far field beam. Further speculations on that idea are probably not useful.

The distinction between the near and the far field, as you notice, is extreme. It deserves emphasis, since the personnel hazard is often greater in just those areas for which the currently available dosimetry equipment is ineffective, i.e., in the near field.

As noted, "power density" is meaningful only in the far field. In microwave technology used for communications, power densities are generally orders of magnitude less than what would constitute a personnel hazard, microwatts per square centimeter being typical. Hazards in the microwave communications field really exist only for those people who work right at the source (where near-field conditions may prevail). The two-way communications problem, that is radar, where you must broadcast enough energy out so that a useable amount will be reflected back, naturally requires more energy, milliwatts per square centimeter being typical values in the general environment of the source. So the hazard exists from radar usage not only immediately at the source but some distance out from the source. That amount of energy which is reflected back is similar to that required for one-way communications, and the reflected power, assuming a typically distant reflector, is usually again in microwatts,or less, per square centimeter. Microwaves also are used for delivery of power, as in microwave ovens. There, the power density is often in watts per square centimeter, providing that the measurement is taken in the far field. In the near field, a different measure must be used.

In the context of microwatts, milliwatts, and watts per square centimeter, it would be useful to mention another figure. Sunlight, in the visible and adjacent spectral regions delivers about a hundred milliwatts per square centimeter in summer at this latitude.

The Interaction of "Microwave" Radiation with Objects

Some generalizations are possible when considering the interaction of microwave radiation with objects. If we restrict our discussions to the frequency range from 50 megahertz to 10 gigahertz--note that 1 gigahertz equals 1, 000 megahertz--we are talking about wavelengths which range from 2% to 300% of the length of a human adult. Now if an object is very small compared to the wavelength (Figure 1), the object feels only the time-harmonic property of the field, so that it is possible to duplicate what the object feels in a non-microwave experiment.
One can, for example, set up a capacitor in which the simple field will have, at any instant of time, the same electric field vector which is experienced by that small object. This kind of simplistic approximation is not valid for an object which is comparable to the wavelength.

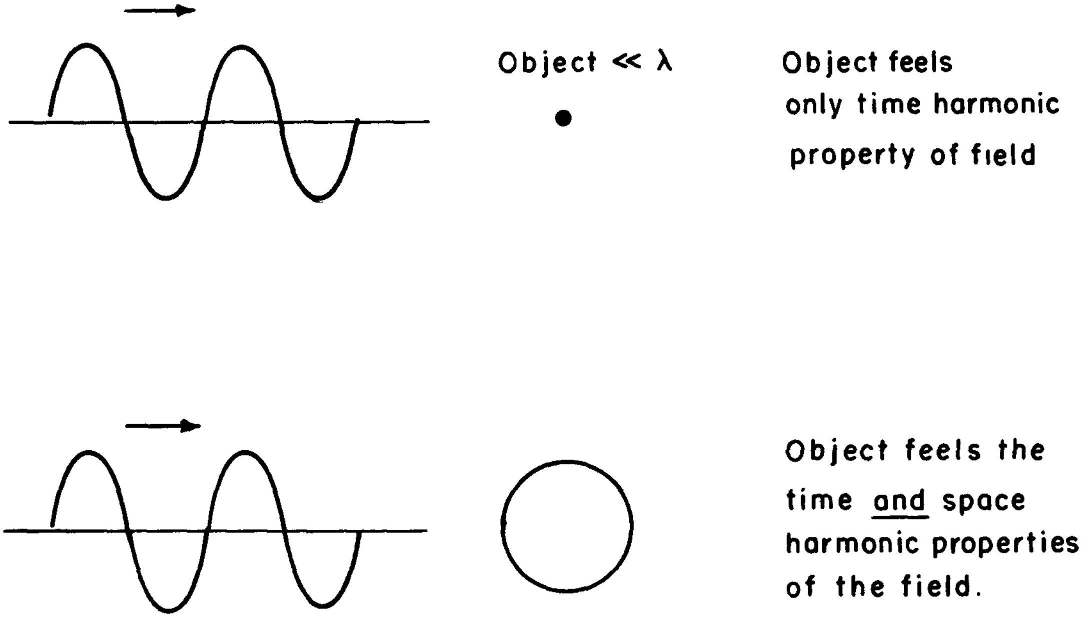


Figure 1. Effect of size of irradiated object on nature of interaction.

It feels both the time-harmonic and the space-harmonic properties of the field. The interaction is quite complex. It is characterized, in fact, by what one might call complexity but not perplexity. There is no inherent difficulty in making a theoretical analysis. It is just a practical problem of handling the complex boundary value problem. In practice, unless the shape of the object is particularly simple, the exact analysis cannot be done, so that either an approximate analysis or empirical means must be used.

The interaction of microwave radiation with different kinds of materials is illustrated in Figure 2. In the case of a near perfect conductor like a metal, the energy is reflected completely, with very minute penetration. (Seawater is a poorer conductor, but the same circumstances apply--hence the difficulty of communicating with submerged submarines.) Skipping to the third case in Figure 2, the perfect insulator, we see the absence of absorption mechanisms in that most of the energy simply goes right through as if the non-conductor were not there. To be sure, there is some reflection at both surfaces, as witness the optical reflection from an air-glass interface, but the net transmission usually is much greater than the net reflection. In the second case, that of biological tissue, there is some surface reflection, some absorption, and some transmission, the proportions depending mostly on the thickness of the tissue. Common experience in microwave cooking illustrates these principles: That which resembles biological tissue, like roast beef, will heat up from the absorbed energy, provided that it is not wrapped

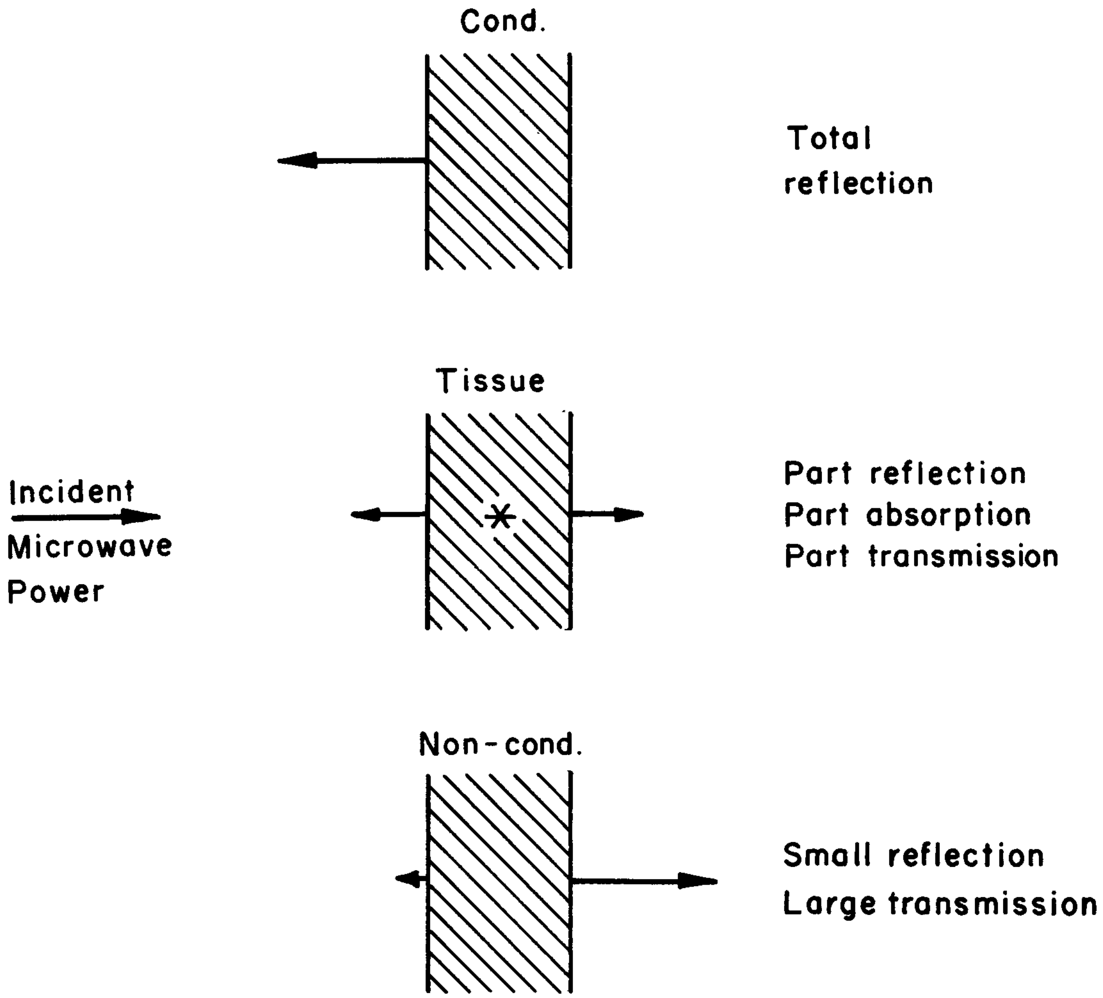


Figure 2. Interaction of microwave radiation with electrical conductors, biological tissue, and electrical insulators.

in a perfect conductor like aluminum foil, which will essentially reflect away all incident energy. Were the foil replaced by cardboard, as is used in packaging many frozen foods, then the energy will penetrate easily to the food, since the cardboard, being a poor conductor, is essentially transparent to microwave energy.

An electric field and a magnetic field co-exist in the propagating microwave radiation, but their effects can be discussed separately. In particular, the magnetic field does not interact with biological material whose magnetic properties are virtually the same as those of free space or of air. Thus, the magnetic field just does not notice that its medium of travel may have changed from air to muscle. Magnetically, we are essentially "invisible". There have been some reports of magnetic interactions with biological material, but, if present, they were very weak and do not constitute any basis for concern in the present context.

The Interaction of "Microwave" Radiation with Biological Material

The interactions of biological material with the electric field are substantial (Figure 3). Microwave energy coming into a biological tissue can lead to a marked heat development induced by the electric field. There is also the possibility of inducing some mechanical forces on constituents in the tissue as a result of the electric field. This possibility will be discussed more quantitatively. The interaction of the electric field with biological tissue has a very simple origin, namely, the force which is the product of charge and the electric field strength (Fig.

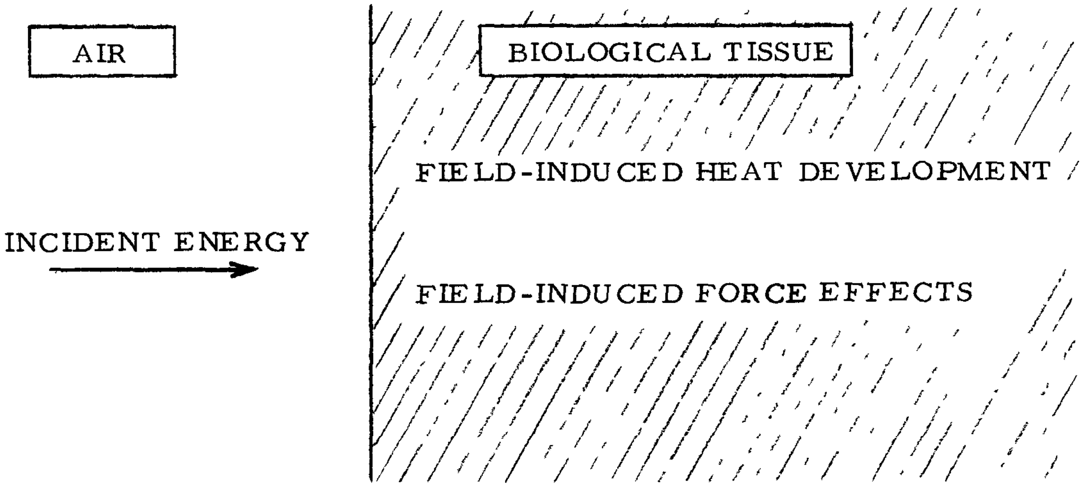


Figure 3. Microwave interaction with biomaterials can, in general, be classified as either field-induced heat development or field-induced force effects. In either case, the field must supply energy to produce any observed effect. If the capacity of the field to supply this energy, that is, the field's average or r.m.s. power, is increased or decreased, the likelihood of both illustrated effects is affected. Therefore whether a field is pulsed or not is irrelevant—only the average power level is important from this point of view.

The charges exist as simple ions in all biological fluids, as well as in a variety of complex charged groups associated with biological macromolecules. Such charges, if they are mobile, will tend to move in the presence of the electric field. The moving charge is a current. The current, squared, times the resistance of the tissue is a measure of the power lost. Energy, in other words, is dissipated when the charges move. When the charges are not capable of freely moving, but are basically tied in one position, they still move slightly when an electric field is applied. When the field is removed, the charges return to their normal position, so the energy, which was stored in the "elastic" constraints tends to be returned to the field.

The effects, purely for purposes of convenience, can be classified as thermal or non-thermal. In discussing the thermal interaction, one can first ask the question, "What is a significant amount of exogenous heating of the human body?" Figure 5 lists some common sources of endogenous and exogenous heating of the whole human body. The basic metabolic rate is 70 or 80 watts, and with increasing amounts of activity, man generates increasing amounts of internal heat. From exogenous sources, the Russian Radiation Protection Guide permits a maximum of 1 milliwatt per square centimeter, which, over a 1 square meter object, such as a man, would lead to about 10 watts absorbed. The U. S. Radiation Protection Guide of 10 milliwatts per square centimeter leads to an absorbed power of about a hundred watts, which is comparable to the basic metabolic rate. In fact, if you sat in a warm, body-termerature bath,

$$\boxed{E \cdot \text{charge} = \text{Force}}$$

Mobile charges move $\Longrightarrow$ i^2R losses

Energy is dissipated

Immobile charges move slightly $\Longrightarrow$ energy storage

Energy is stored and returned each cycle

Figure 4. The mechanism for the interaction of electric fields with tissues can always be reduced to the simple relationship shown in the box.

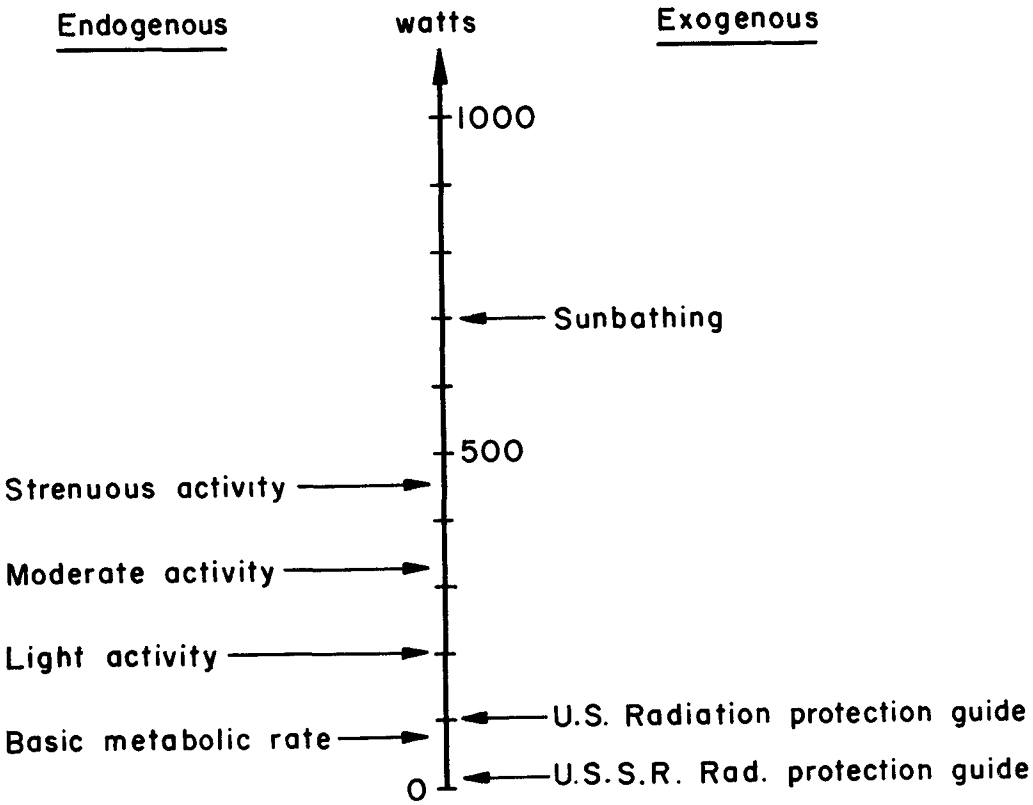


Figure 5. The human adult body is heated by internal and external sources of energy at rates which are indicated on the ordinate in watts. Note that 1 watt $\approx$ 1 kilocalorie per hour.

so as to block off your ability to dissipate the 70 or 80 watts of heat that you are normally generating, then your body temperature will rise at about the same rate that it would if you were in a 10 milliwatt per square centimeter field. The common experience of sunbathing is not quite comparable, since the heat is deposited on the surface where it is more readily dissipated by evaporating cooling. But most people have observed that in the absence of wind it is almost impossible to lie on the beach in summer for an extended time. After 20 minutes or so, anyone but a masochist just has to get up and do something to decrease his thermal input or increase his thermal output. Figure 5 suggests that a significant exogenous heat input to the body is about 10 milliwatts per square centimeter, that is, about 100 watts, and that the Russian Radiation Protection Guide cannot be based on thermal considerations.

The next interesting question is how much microwave heating of man is there from a known microwave field. It is possible to set up a microwave field whose far-field parameters can be measured with precision using suitable power-measuring technology. However, when a man enters the field, how much of that power will he absorb? If he absorbs 1%, then we have to rethink the Radiation Protection Guide. In other words, the absorption cross section is a crucial quantity from the thermal point of view. It is convenient to use an absorption cross section which is normalized in terms of the irradiated geometric cross section; it is called a "relative absorption cross section." An example of the use of this parameter is best given for the optical frequencies where we can appreciate better what is happening. Thus, black velvet has a relative absorption cross section of one and a good mirror, of zero. Note that in each case, the figure is dimensionless. In the case of irradiation by microwaves, Figure 6 shows that the relative absorption cross section approaches zero for spherical objects whose radius, "a," is very small compared to the wavelength, λ. The objects for which this graph is plotted have a dielectric constant and an electrical conductivity equal to that of human muscle tissue at microwave frequencies. The calculations underlying the graph further assume that the frequency of the irradiating field is 2880 megahertz, a choice dictated at the time by the availability microwave of generating equipment at that frequency.

For larger objects, as shown in Figure 7, which has the same ordinate and abscissa as Figure 6, the relative absorption cross section grows rapidly with "a/λ". Note that the early part of this figure corresponds to the entirety of the previous figure. You can see that for spheres with passive electrical properties equal to those of human muscle tissue at 2880 megahertz, the relative absorption cross section rises above one. That means that more power is absorbed by the object than was incident upon its geometrical cross section before it occupied that location. The field is actually sucked into the object. The peaks in the figure, which have the appearance of some kind of resonance peaks, then damp out as the object gets larger and larger. The curve tends to an asymptotic value between zero and one as indeed it must, since a semi-infinite medium--that is, a very large sphere--cannot

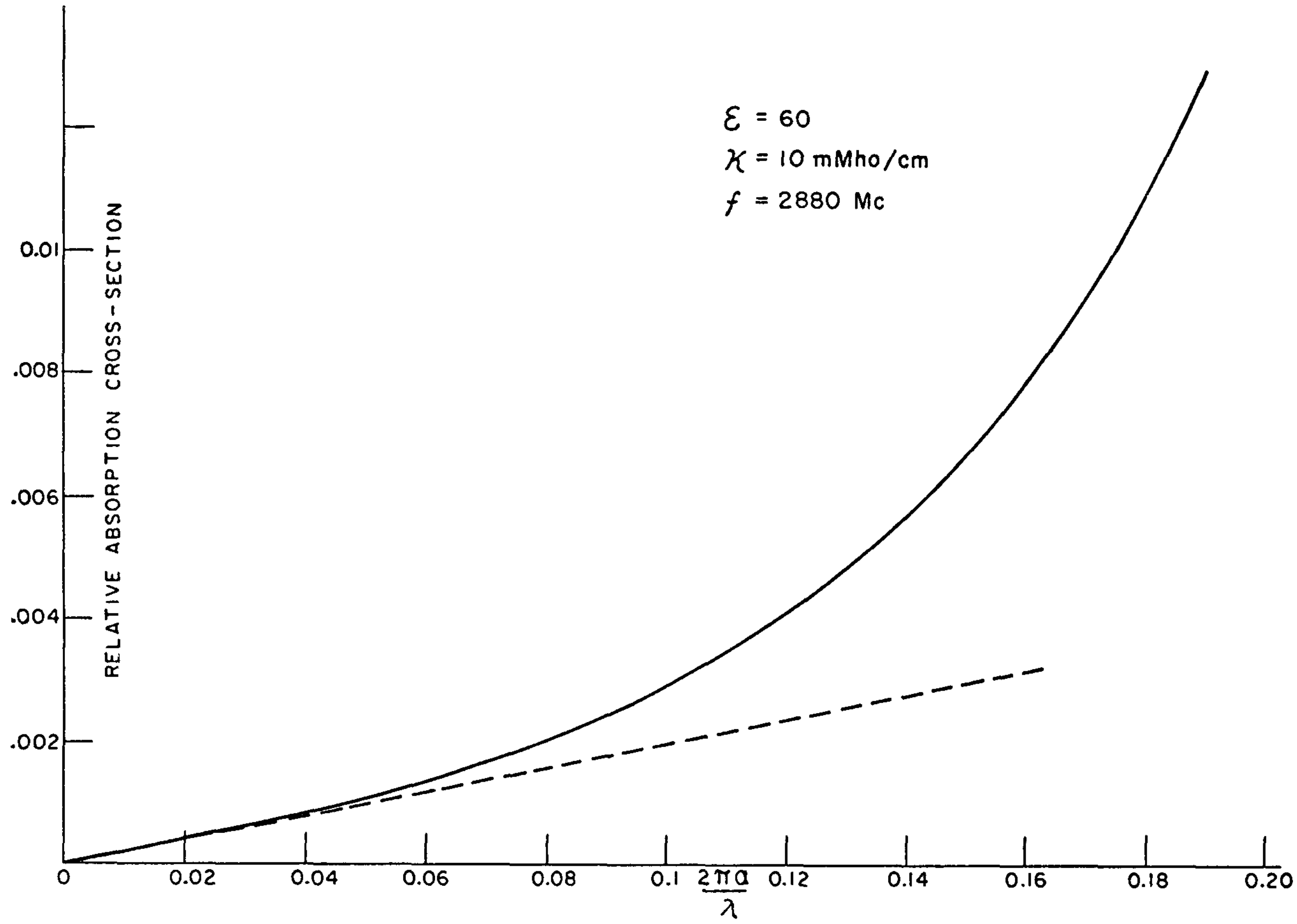


Figure 6. Relative absorption cross section (calculated) versus the circumberence of an irradiated sphere. Note that the circumference, $2\pi a$, is measured in terms of wavelengths in air (at 2,880 MHz in this case). The graph covers the specific case of a homogeneous sphere whose electrical properties are the same as those of human muscle tissue at 2,880 MHz. The dotted line is the limiting slope of the curve near the origin.

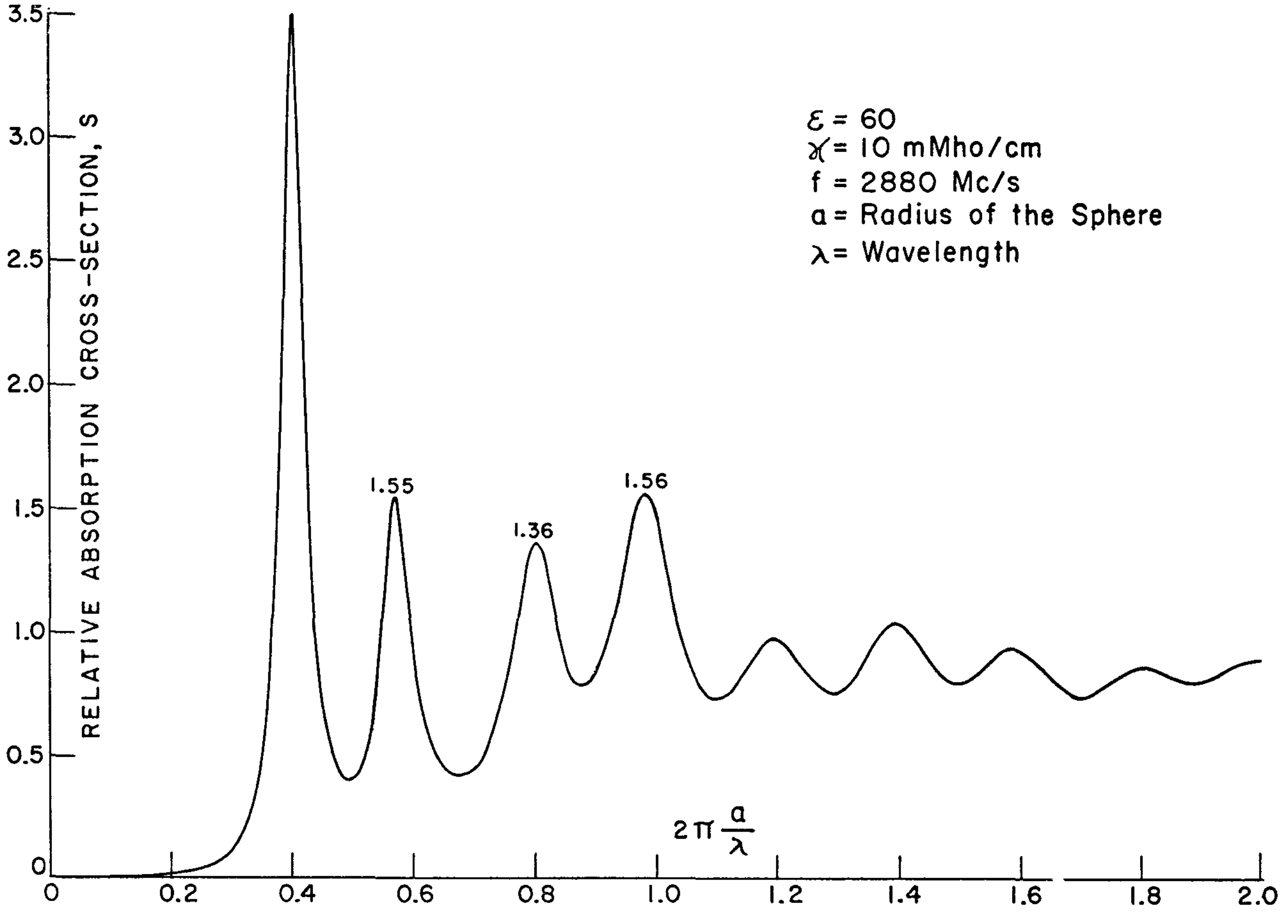


Figure 7. Same as figure 6, except for scale. The prominence of the resonance peaks is related to the sphere's high degree of geometrical symmetry and can be viewed as analogous to acoustic resonances in a hollow space of similar shape.

absorb more energy than is incident upon it. These objects, I repeat, are spheres and are not necessarily representative of the complex shapes of the human body. These curves were calculated theoretically and were verified experimentally.

Knowledge of the relative absorption cross section for objects of human shape must be derived empirically. For this purpose, we used hollow dolls filled with a liquid which has the dielectric constant and the electrical conductivity of human muscle, as was done in the previous experiments with spheres. We used three sizes of dolls so that the absorption which the dolls experience, and thus the rate of their temperature rise, could be extrapolated to the condition where the doll is life size. The dolls used were 38, 51 and 80 centimeters tall. The results, extrapolated to a man whose height is 70 inches, appear in the bottom row of Figure 8 in the three right hand boxes. Since the scaling of size upward requires a scaling of the frequency downward, effectively we have results for a man of height 70 inches, exposed from the front, side, and top, at three different frequencies which cover a narrow but significant range from 600 to 1400 megahertz. As you see, the relative absorption cross section for frontal radiation varies in a range from 0.50 to 0.60. That is, 50 or 60 per cent of the radiation which was incident on the geometric cross section before he entered the field will now be absorbed by his body after he enters the field. For side radiation, the relative absorption cross section is about the same. For irradiation from the top, it is much closer to 100% absorption,

Part of Doll Subjected To Incident Plane Wave	RELATIVE ABSORPTION CROSS SECTION (PERCENT)				
	Natural Size		Scaled To A Height Of 177.8 cm (70 inches)		
	Doll 1 Height = 38.1 cm	Doll 2 Height = 50.8 cm	Doll 1 Height = 38.1 cm	Doll 2 Height = 50.8 cm	Doll 3 Height = 87.0 cm
Front or Back	46	58	57	56	50
Side	56	48	55	59	50
Top	90	92	92	97	83
Applicable Frequency (MHz)	2880	2880	617	623	1409

Figure 8. Table of relative absorption cross section of dolls whose electrical properties were made to be the same as those of human muscle tissue at the frequencies indicated.

perhaps because the cross section being irradiated is small and the opportunity for the field to interact with the body in passing is relatively large. The result of this study is that the relative absorption cross section of a muscular man 70 inches tall and exposed to microwave energy in the 600 to 1400 megahertz frequency range is somewhat less than 100%, but not dramatically less.

If we now make the additional approximation that this mass of muscle is covered with a layer of fat (Figure 9), we find that the problem becomes very complicated. Figure 10 illustrates, at least, that absorption by a fat-muscle combination is very different than for just muscle. Within the fat layer, there are, evidently, standing wave patterns caused by the superposition of incoming waves and reflected waves. The reflected waves come from the fat-muscle interface where the discontinuity in electrical properties would be expected to yield reflections. Note that the standing wave patterns are present at all of the frequencies for which the figure gives data, but the patterns are clearly seen only in those cases where the wavelength in fat is less than the fat thickness. Thus, at 10,000 megahertz, the standing wave pattern is obvious; at 3,000 megahertz it contains only one wave; and at the lower frequencies it contains only the trailing edge of one wave.

Such theoretical studies of microwave absorption by a fat-muscle combination, suitably confirmed by experiments conducted in model systems, indicate that under certain conditions, a layer of fat can help the microwave radiation to penetrate the muscle layer more effectively

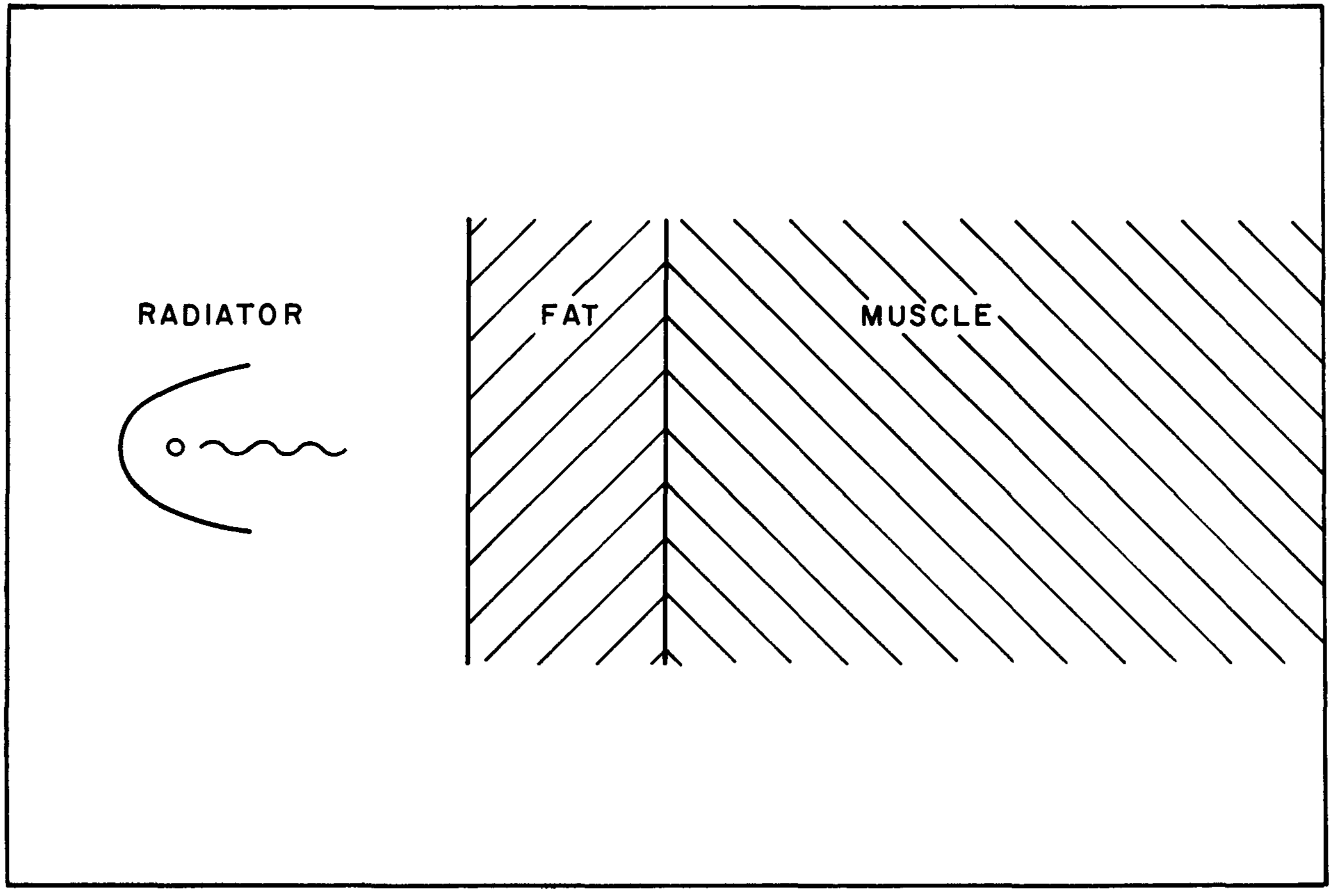


Figure 9. The fat-muscle model for studies on relative absorption cross section of man.

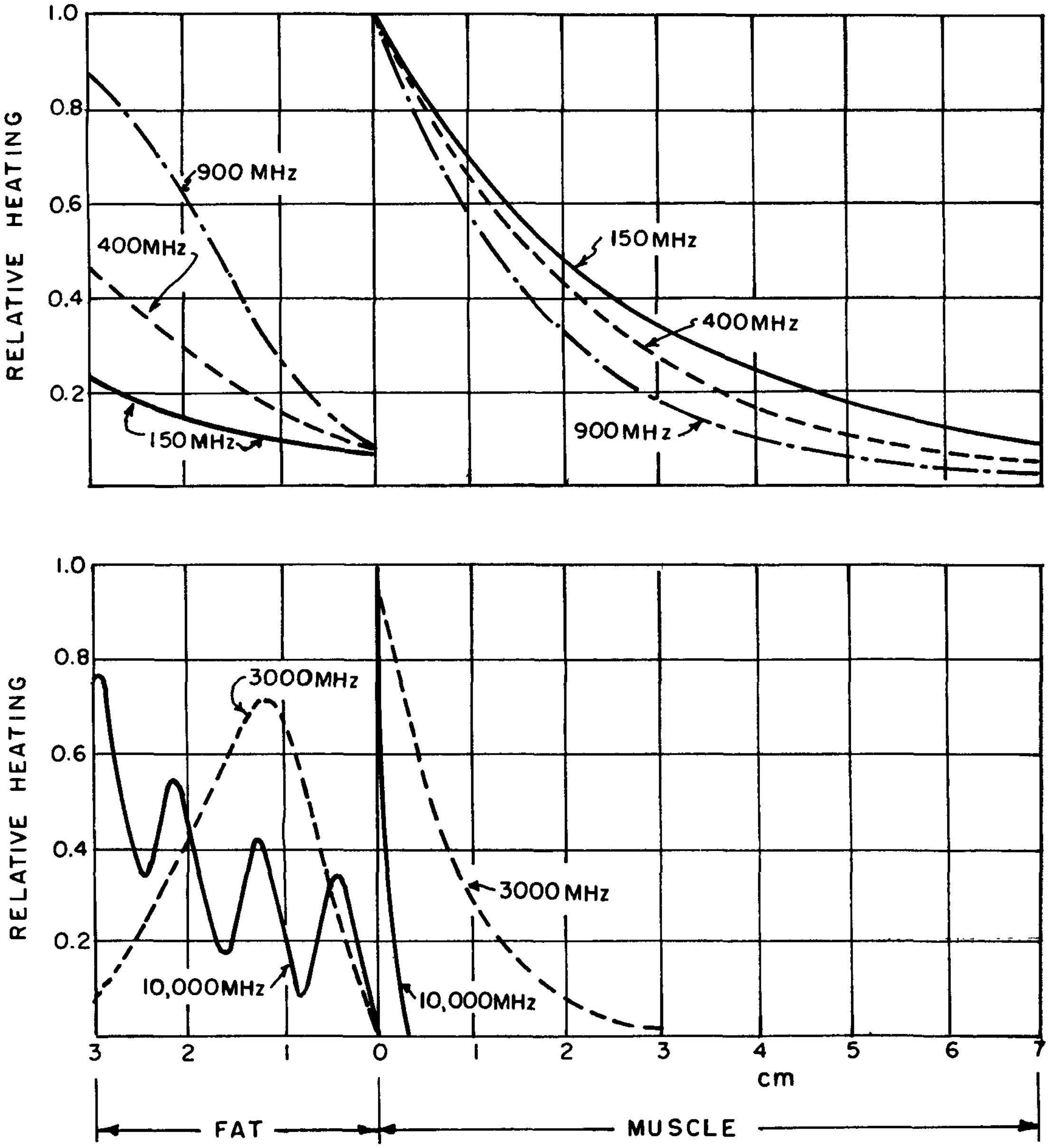


Figure 10. Relative heating in the fat-muscle model as a result of microwave irradiation at the frequencies indicated. The duplication of axes was necessary to preserve legibiligy. All five curves have been normalized so that their relative heating at the fat-muscle interface is 1.0. Therefore, the curves cannot be compared to each other quantitatively.

than if the fat were absent. That is, the fat layer acts like an impedance transformer, helping to ease the discontinuity of electrical properties which would normally cause reflections, as the energy passes from air to muscle. The improvement in absorption can be as much as 50% in selected optimum configurations.

Combining the previous results (covering a limited frequency range) for the relative absorption cross section of a human shape made just of muscle with the potential improvement in absorption made possible by including a layer of fat over the muscle, we arrive at a rough but useful working rule that a man absorbs all radiation incident on his geometric cross section. The simplicity of this rule should not obscure the fact that it is not at all obvious. The inclusion of skin, as in a skin-fat muscle model, would make changes in this working rule which are small compared to the uncertainty which it already includes as a result of uncertain fat thickness. The rule, furthermore, becomes increasingly conservative for frequencies which are increasingly higher or lower than the frequency range for which it was derived. In the case of higher frequencies, the skin intercepts an increasingly large fraction of the incident energy, so that the heat development is at a site from which it can be dissipated from the body most easily. In the case of lower frequencies, the electrical properties of body tissues, which are themselves strong functions of frequency, change in such a way that surface reflection becomes more pronounced, i.e., that the relative absorption cross section decreases. Rather than consider the complexities of absorption variation with fat layer thickness, angle of incidence, frequency, and other parameters, it has been fruitful to continue to maintain simply and conservatively that man absorbs all microwave energy incident on his geometric cross section.

What is simple for man, however, is not necessarily simple for smaller animals, animals which have often been used for experimental studies of effects of microwave radiation. Not only is their surface-to-volume ratio different, but their mechanisms for heat dissipation are usually much different. Furthermore, some of the foregoing curves have shown that when an object is comparable in size to the incident wavelength, wide fluctuations in the absorption are possible. Animal experimentation, therefore, must be done with considerable care, lest the results be non-extrapolatable.

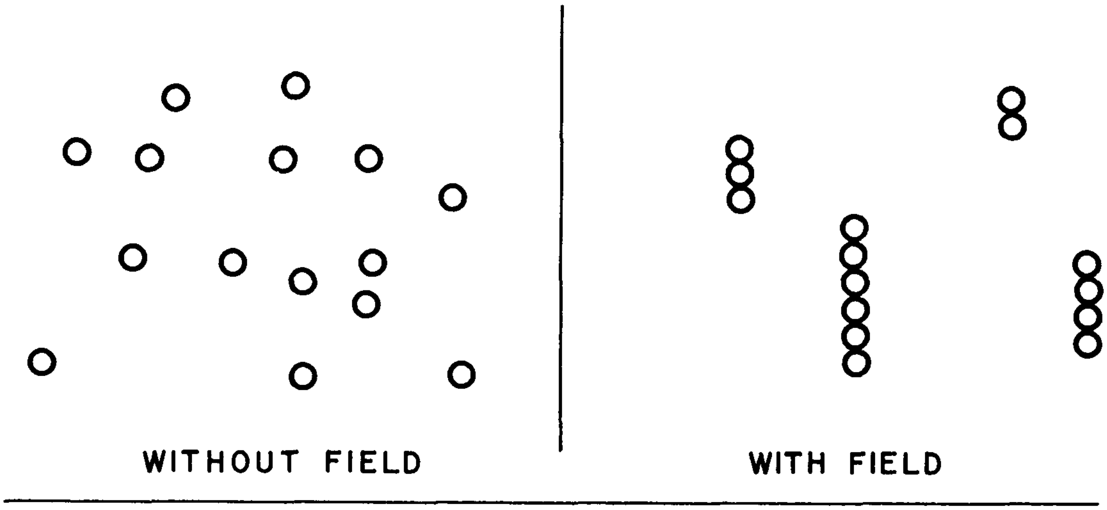
The thermal hazard to man from microwave radiation would be no more interesting than the comparable hazard from fire if man were equally aware of the former, as a heat load. The question must therefore be faced as to the capacity of man to recognize a thermal input due to microwave exposure. The answer, briefly, is that man's capacity for such self-protection is limited to the higher frequencies, for example above about 10 gigahertz. From that frequency upward to and through the infra-red portion of the spectrum, that is, through about five orders of magnitude of increase in frequency, man senses the thermal input via his cutaneous thermal receptors and is unlikely to sustain thermal damage if voluntary withdrawal is possible.

The foregoing briefly summarizes what is known about the thermal interaction. There are several problems remaining. For example, do the physiological effects of microwave whole body heating differ from effects due to other methods of whole body heating, such as metabolic methods? Which tissues, if any, are particularly sensitive to damage from microwave-induced heating? Are significant effects possible on germinal and eye tissues via microwave heating at levels currently considered to be safe? The answers to these and other questions require careful and, at the current state of the art, difficult considerations of dosimetry. Finally, one cannot consider the hazards of any new technology without considering the hazards of the technology which it replaces. The latter point deserves emphasis in the case of microwave ovens, which, at this time and without further refinement, shows promise of dramatically reducing the level of kitchen hazards.

The state of microwave dosimetry, unfortunately, is decades behind the state of microwave generation. It is, perhaps, where dosimetry in ionizing radiation was 40 years ago. For example, the near field has, in general, an ability to heat tissues more rapidly than the far field from the same source. However, presently available dosimeters are increasingly inaccurate as they approach the near field, and, once in it, are totally unreliable, even to the extent of possibly reading zero at a place wher the heating ability of the field is very intense. It has been suggested (by Schwan) that, in the near field, one should seek to measure just that quantity which is directly responsible for heat development, namely, electric current density in the surface of the irradiated object. This suggestion may indeed be the only feasible way to effectively handle the near-field dosimetry problem. But in this case, it is a long step from the idea to the commercially available instrument.

Possible non-thermal interactions of microwave energy with biological material have been the subject of scores, if not hundreds, of investigations in the past 15 years. There have been two main approaches used: To irradiate some biological material or system with a power level which yields no biologically significant temperature rise and to look for bioeffects; and to seek a qualitative and quantitative understanding of any and all mechanisms which could possibly account for a non-thermal effect, if it existed. The former approach, inherently precarious, has not led to definitive results, largely because one can always question whether a positive result indicates a non-thermal effect or an insufficient control of temperature rise.

The latter approach has by contrast led to the concept of field-induced force effects (Figure 11). Such effects are clearly non-thermal in origin and are easily produced with biological or non-biological particles. We have learned a great deal about field-induced force effects and find that they can usefully be categorized as shown in Figure 12. Here it may be useful to point out that although Figure 12 mentions four categories, there are really only two mechanisms, as implied in the figure. And the two mechanisms might even be reduced to one, namely the force of



ORIENTATION

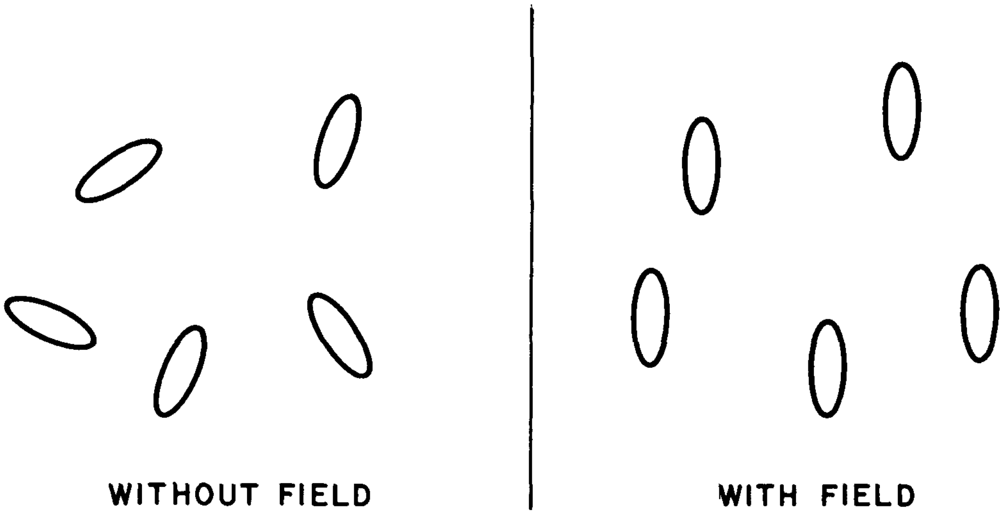


Figure 11. Examples of two field-induced force effects. The circles, representing spheres, and the ellipses, representing ellipsoids, respond to the presence of a sufficiently strong electric field (ac or dc) as shown. The oriented ellipsoids can link together into chains. For any particle to display a field-induced force effect, its electrical properties must differ from those of the medium at the frequency used.

FIELD-INDUCED FORCE EFFECTS

1. ELECTROPHORESIS	(a force effect on charges)
2. DIELECTROPHORESIS	(a force effect on dielectrics)
3. ORIENTATION	(a force effect on dielectrics)
4. PEARL-CHAIN FORMATION	(a force effect on dielectrics)

Figure 12. A possible listing of field-induced force effects. Several of these effects can occur simultaneously, even within the same set of responding particles.

an electrical field on a real or induced charge. But regardless of the physics, there are several, observable, field-induced force effects which look different and which can be quantitated as shown in Figure 13 for the case of pearl-chain formation.

Bioeffects are possible via field-induced force effects as shown in Figure 14. But an effect on isolated cells or tissues should not be construed as necessarily having any significance for human exposure to microwaves. For just as a given source of ionizing radiation will affect isolated material differently from the same material in situ, if only because of intervening structures, the clinical significance of whole animal exposure to microwave energy is not the sum of the effects elicitable by separately irradiating the component parts. Quantitative work on field-induced force effects has lead to the general conclusion that this mechanism cannot lead to any biologically significant effect for irradiation of man with power levels which are generally accepted as being thermally safe. That is, such non-thermal effects are possible, but they are always swamped by thermal effects. So if one protects himself from undue thermal effects, he achieves automatic protection from such non-thermal effects--whose biological significance, incidentally, is unknown. Mechanisms for non-thermal effects other than field-induced force effects have not been demonstrated.

This brief summary of non-thermal effects has concluded by stating, essentially, that the U.S. Radiation Protection Guide, which has been formulated on a thermal basis, offers protection against both thermal and

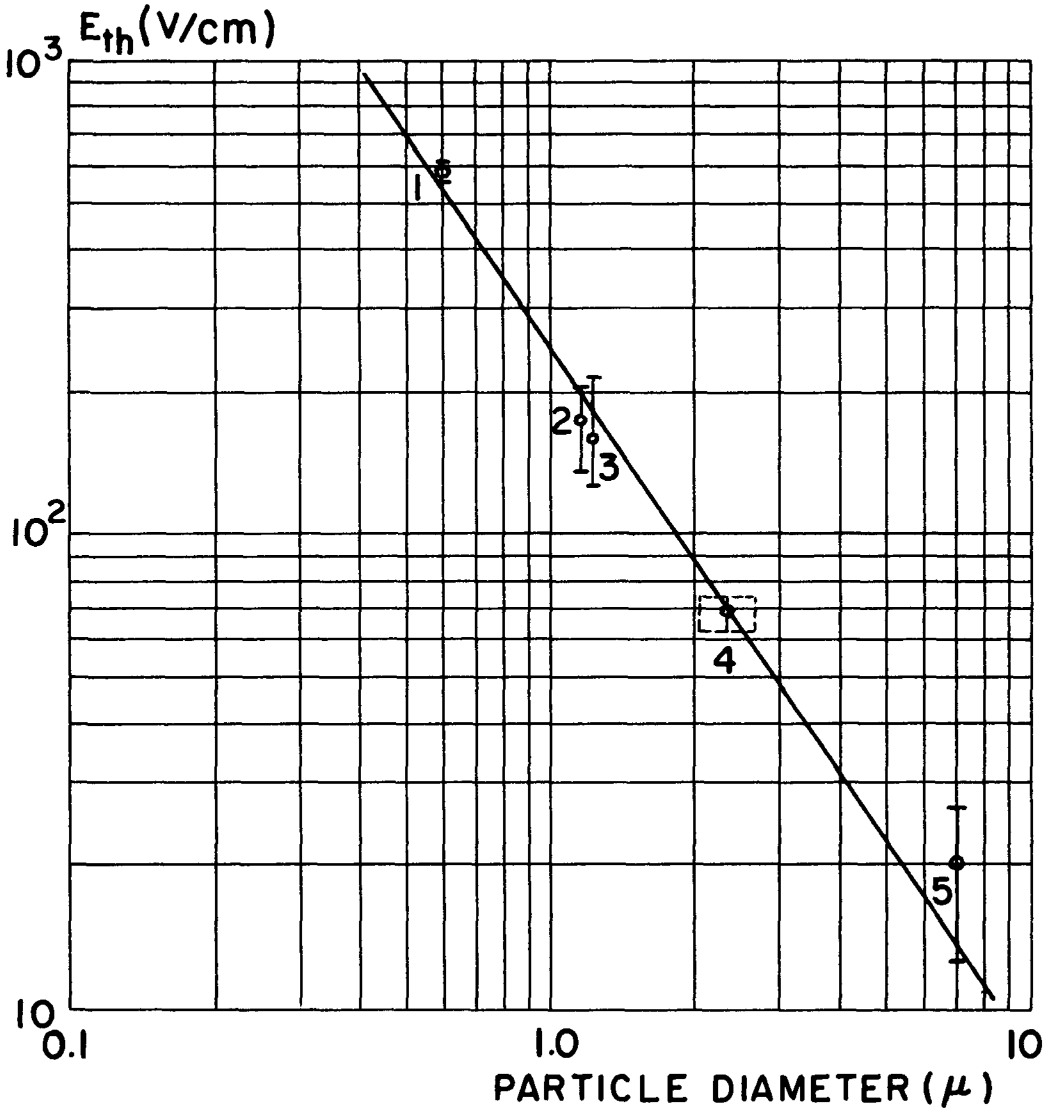


Figure 13. Experimental results (points) and theoretical results (line) for the threshold field strength of pearl-chain formation versus particle diameter. The numbers correspond to different particle systems used: (1) and (4) silicone emulsions, (2) polystyrene sphere suspension, (3) E. coli, (5) human erythrocytes.

	THERMAL	NON-THERMAL
Humans and animals	Diathermy Production of cataracts Temporary fertility reduction (?)	"RF hearing"
Tissues	Warming Cooking	Mechanical vibratory forces of small magnitude
Cells	Heating via thermal conduction from the medium	Alignment in many-particle chains Orienting of single particles Movement of single particles in non-uniform fields Chromosomal aberrations (?)
Molecules	Protein denaturation via thermal conduction from the medium	Whole molecule rotation (1 MHz - 1 GHz) Water molecule rotation (20 GHz) Movement of charged side chains (> 30 GHz)

Figure 14. The interactions shown are ones which may occur under favorable circumstances. The effects, furthermore, may be linked so that, for example, alignment would exist in a medium of physiological electrical conductivity only if accompanied by a substantial heating of the medium.

non-thermal effects. The Radiation Protection Guide for the United States and for the Soviet Union is summarized in Figure 15. You see that the Soviet Union's Guide is more conservative, by orders of magnitude, than the Guide for the U.S. and appears to be based, as nearly as we can determine, on the incidence of non-thermal effects. However, they have published no quantitative or statistically compelling evidence underlying their Radiation Protection Guide. Also, we feel that in their military, at least, they do not follow it themselves. It appears, therefore, to be designed more to confuse us than it is to protect them.

To summarize, there are no known mechanisms which can account for any biological effect in a physiologic tissue environment from continuous or pulsed microwave fields which do not exceed the U.S. Radiation Protection Guide.

Thank you.

ACKNOWLEDGEMENT

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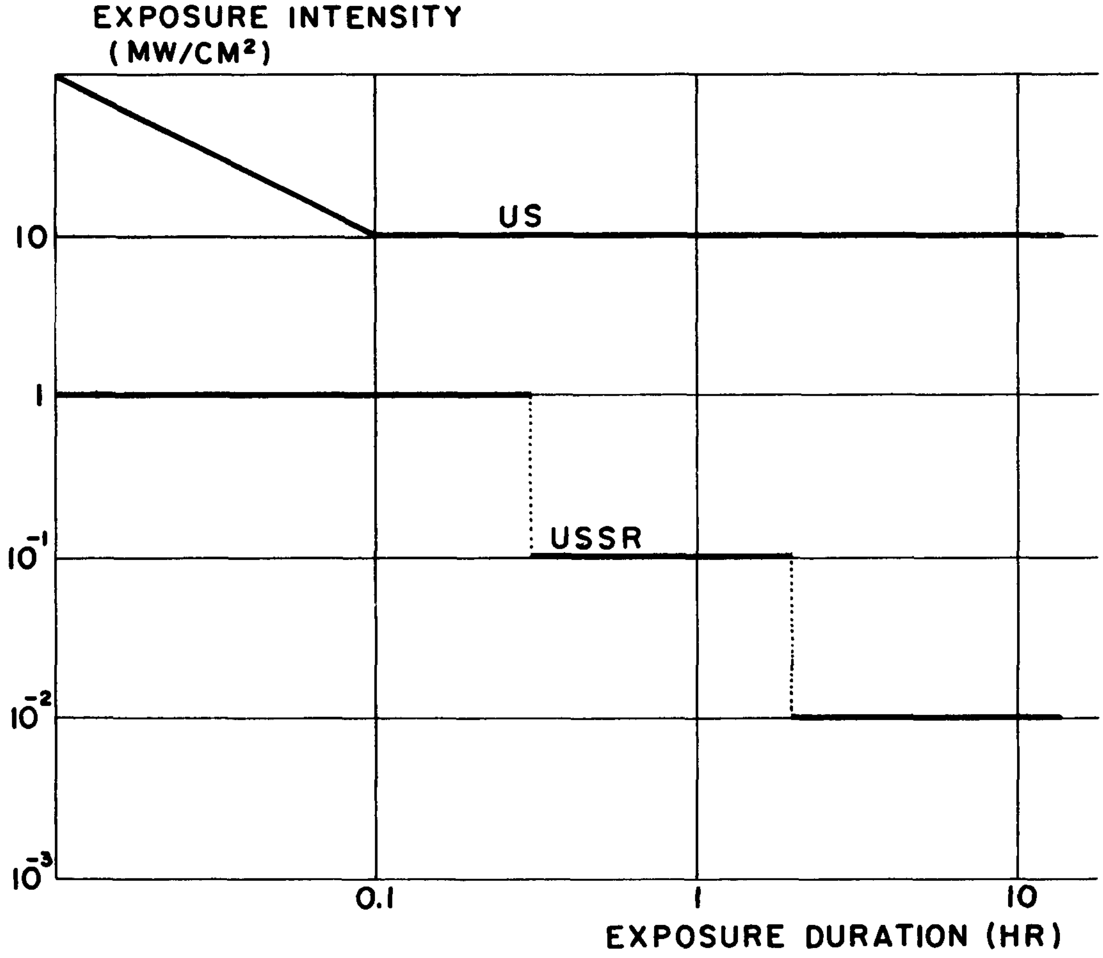

Figure 15. Radiation protection guides for the United States and the U.S.S.R. The extraordinary conservatism of the Russian guide implies that it has been formulated on a basis unrelated to thermal problems.

MICROWAVE HAZARDS SURVEILLANCE AND CONTROL

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For the past ten years, microwave hazards from high-powered radars located on the Air Force Eastern Test Range have been surveyed and evaluated. The program involved:

1. Careful review of operating conditions for each radar prior to making physical measurements.
2. Accurate measurement of microwave energy in the transmission system as well as the antenna field.
3. Recommendations for personnel protection.
4. Ophthalmological examination of potentially exposed and exposed workers.

Techniques were described for evaluating system data and operating characteristics of each radar system; calculations to determine theoretical distances of hazardous power levels, as well as the equipment and methods for making accurate microwave measurements. Examples of reflection effects were given. These techniques have been developed from the surveillance of more than forty different radar installations. They involved X-Band, C-Band, S-Band, and L-Band systems with maximum power levels of ten megawatts.

In addition, experience from the surveillance of microwave ovens was described. Discrepancies found included worn hinges, loose screws, faulty interlocks and improperly installed viewing screens.

Of particular interest was the ophthalmological surveillance of human subjects working in the microwave field.

Reconstruction of exposure incidents has provided some indication of microwave levels resulting in detectable eye damage. More than two hundred workers have been included in the eye examination program during the past six years. Of this number, 18.5 percent have been found to possess the first indication of microwave eye damage.

In lay terms, early eye damage was determined by slit-lamp examination and usually resulted in localized opacification of the posterior portion of the lens capsule. It sometimes had a honey-comb appearance. This capsule is a thin optically transparent membrane in its normal condition. Clouding of this membrane does not produce measurable reduction in visual acuity.

Progression of the cloudiness of the lens membranes have been photographed and reexamined annually over a six-year period. Only one case of incipient cataracts has been reported on the Air Force Eastern Test Range. Because of the cost and time involved, no control studies have been conducted.

Annual ophthalmological review of exposed subjects will be continued. Each instance involving potential exposure will be reconstructed to determine, as accurately as possible, the exposure levels. It is expected that the microwave hazards control program will provide significant technical data to better understand the mechanisms of microwave-induced eye damage. Ophthalmological examinations appear to provide a suitable method for determining early indications of microwave exposure.

(A more complete description of our microwave hazards control program has been published in the March 1970 issue of Archives of Environmental Health, page 350.)

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