LASER RADIATION PROTECTION*

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Abstract—Although most health physicists and others in the field of radiation protection have confined their efforts primarily to the hazards from the so-called ionizing radiations (X-rays, gamma-rays, neutrons, high energy particles, etc.), an increasing number of workers in this field are being called upon to protect personnel from laser radiation. The phenomenal development of laser technology during the past three years has introduced new hazards for industry, for governmental agencies, particularly the military and space agencies, and for universities and medical schools.

The necessity for such criteria will be examined. Since the eye is the most vulnerable organ of man to laser radiation, the effects of wavelength, pulse duration, intensity of irradiation (power density), energy density, and other factors on the eye will be given. Current data from several laboratories will be reviewed briefly. Finally, protective practices and equipment in current use in the United States will be discussed.

HISTORICAL BACKGROUND

Man lives in a natural radiation environment. He is exposed daily to the electromagnetic radiation spectrum from a nuclear fireball—the sun—to natural radioactivity both within and surrounding his body, and to cosmic rays coming from intergalactic space. Were this his integral radiation exposure there would be no need for radiation protection and health physics. Although solar radiation may produce thermal injury to the skin (sunburn) and to the eyes (retinal burns), not to mention the painful inflammation of the cornea resulting from ultraviolet (UV) rays, nonetheless, experience through the ages has taught man how to protect himself from the natural radiation background. Not content with the radiations provided naturally, man has extended and broadened the electromagnetic spectrum to include wavelengths which have increased the hazards to his health. Maxwell's theory and the production of electromagnetic waves by Hertz led to the modern development of radio, radar, and television with a consequent increase in the hazards from microwaves. At the other end of the electromagnetic spectrum, Röntgen produced X-rays, opening the "floodgates" to the biological effects of ionizing radiation. Becquerel and the Curies completed the spectrum by discovering radioactivity, thus providing both the particulate alpha- and beta-rays and the very short wavelength gamma-rays. All of this took place before the beginning of the 20th century. The study of atomic and nuclear structure by Rutherford, Bohr, and many others led inevitably to the production of giant accelerators to study the nucleus and the interactions between the elementary particles of physics. By the late 1930's man had increased his arsenal of radiations to include neutrons, positrons, and mesons, to mention but a few. Then came the discovery of fission at the beginning of World War II. By the end of the war the world had been introduced to the nuclear age. Man had created a new radiation environment which had tremendous potentialities for good and evil. The knowledge of how to handle, manipulate, and dispose of large quantities of radioactive materials grew out of the Manhattan project. The peaceful applications of nuclear

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energy to modern civilization are now well advanced, but over mankind still hangs the spectre of nuclear war with the possibility of world-wide radioactive contamination on a scale that might threaten the survival of mammalian life. In this atmosphere of hope and fear, the Health Physics Society was founded in 1955. The Society is dedicated to radiation protection with a special emphasis on "ionizing radiation".

Meanwhile, the first operating optical maser was described by Gordon, Zeiger, and Townes [(1)] in 1954 at a time when active efforts were under way to form the Health Physics Society. Townes had suggested as early as 1951 that it should be theoretically possible to obtain amplification by using a molecular generator at a specific frequency inherent to the molecule. He and his colleagues used a beam of ammonia gas passing through a microwave cavity tuned to approximately 24,000 Mc/s, a frequency corresponding to a natural resonance in NH_3. Townes coined the acronym maser—*m*icrowave *a*mplification by the *s*timulated *e*mission of *r*adiation. When, in 1958, Schawlow and Townes [(2)] demonstrated the feasibility of extending the maser principle to the optical region of the electromagnetic spectrum by employing solid state devices, the term "optical maser" was suggested. It was Maiman, [(3)] however, in 1959, who first operated a solid state maser by producing stimulated emission from a ruby crystal. Since this was radiation in the visible or optical region of the spectrum (694.3 nanometers, nm), laser rather than maser came into use to denote *l*ight instead of *m*icrowave. The term laser has been adopted by most workers in this field and is used generally to denote the emission of stimulated light from all sources and under all operating conditions. Javan, Bennett, and Herriott [(4)] made a notable contribution in 1961 when they succeeded in producing the first continuous wave (CW) gas laser from a mixture of helium and neon. The production of "giant pulses" of laser radiation by utilizing a "Q-spoiling" technique was announced by McClung and Hellwarth [(5)] in 1963 and represented another notable advance in laser technology.

Technical advances in the production and application of laser beams have been extremely rapid during the past 3 years. Parallel beams of intense radiation which are plane polarized, monochromatic, and coherent both in space and time, are available throughout the electromagnetic spectrum from the far infrared (IR) to the near ultraviolet. There is even the possibility of producing laser sources in the far ultraviolet and the X-ray region, and some consideration has been given to a gamma-ray laser. Sources involve gaseous, liquid, and solid state lasers and power levels range from milliwatts to gigawatts. Lasers may be operated continuously to produce CW radiation or pulsed to produce multiple spikes of radiation or single giant pulses which last for only a few nanoseconds. Power densities can reach the gigawatt/cm^2 level, and even optical materials like quartz are broken down by the intense electric field strengths generated by a focused laser beam. When focused in air a "fireball" is produced, rising to temperatures high enough to produce a plasma, so that multiple ionization and even X-rays are observed. [(6)] High power densities in solids and liquids have produced many so-called non-linear effects such as frequency doubling, multiple photon absorption, intensified Raman and Brillouin scattering, and self-focusing in certain media. Theoretical optics and optical physics have received new impetus from the rapidly developing field of laser technology. Quantum theory and the classical theory of the electromagnetic field meet in a bewildering variety of phenomena which has stimulated much interest among both theoreticians and experimental physicists.

In view of the above it is not surprising to learn that the effects and applications of laser radiation are being studied throughout the industrial complex of the country, in the military establishments, and in the universities and research institutions, both private and public. Range finding, memory devices for computers, holography, communications, weapons, light coagulation of the eye, and welding devices are some of the many applications being developed. The escalation in laser research has produced a growing radiation hazard which demands the best efforts available for radiation protection. Many health physicists in industrial, governmental, and university positions are being "saddled" with this new responsibility in radiation protection, and there is a growing clamor from industrial and governmental agencies for an organized effort to establish safety criteria for this "new-yet-old" type of radiation. As yet, no specific agency or society or group has stepped forward to assume responsibility, though there are several movements afoot to cope with the problem.

PHYSICAL ASPECTS OF LASER ACTION

A brief and rudimentary description of the physics of laser action is in order before discussing the radiation hazards. The ruby laser is chosen as typical and a former paper by the authors [7] will be used for this purpose.

The primary element of a ruby laser consists of a crystal of sapphire (Al_2O_3) doped with chromium ion (Cr^{3+}) usually to about 0.05% by weight, giving approximately 1.6×10^{19} chromium atoms per cm^3. Each ion in the sapphire crystal is bonded to 8 oxygen atoms. The energy levels of the chromium ion determine laser action, the sapphire serving only as a crystal matrix to fix the foreign ions. Ruby crystals are usually in the form of cylinders, varying in diameter from 0.25 to 0.625 in. and having lengths of from 3 to 6 in. It is essential that the ends of the ruby cylinder be parallel and optically flat to a high degree of precision. Most ruby crystals are cut with the optic axis at 60 or 90 degrees to the axis of the cylinder so that plane polarized light is emitted during laser action.

Irradiation of a ruby crystal with white light shows two strong absorption bands in the green and yellow portions of the spectrum. A characteristic feature of ruby is the large fluorescent quantum efficiency which is defined as the ratio of the number of fluorescent photons emitted to the number of exciting photons absorbed. Maiman found this to be 70% in ruby. This means that a large percentage of the photons absorbed in the green and yellow bands undergo a relatively fast radiationless transition to a metastable doublet state before having time to return to the ground state. This metastable doublet state has a half-life of approximately 3.5 msec before returning to the ground state with the spontaneous emission of two monochromatic lines at wavelengths of 694.3 and 692.9 nm respectively. This is why, of course, ruby exhibits its characteristic red color. Under ordinary conditions of irradiation with white light, the number of chromium atoms in the ground state greatly exceeds the number in the excited state. But by using an intense source of white light to optically "pump" chromium atoms into the excited state, Maiman was able to achieve a population inversion; that is, the number of chromium atoms in the excited state exceeded the number in the ground state, violating Boltzmann statistics and creating a so-called "negative temperature". The optical pump consisted of a xenon flash tube wound in the form of a helix with the ruby cylinder placed along the central axis of the helix. A highly reflecting sheath of polished aluminum surrounded the xenon helix. A condenser bank charged to a high voltage was discharged suddenly through the xenon flash tube, thereby irradiating or pumping the ruby crystal with an intense source of white light.

Under normal conditions the number of photons/cm^2/sec of wavelength 694.3 nm incident normally on an end face of the ruby cylinder would exceed the number of photons/cm^2/sec leaving the opposite end face by an amount determined by the linear absorption coefficient for the ruby wavelength according to the well known law of Beer. However, under the conditions of population inversion, the absorption coefficient changes sign. This means that the number of photons/cm^2/sec leaving an exit face exceeds the flux entering the opposite face of the ruby crystal, i.e. amplification by the stimulated emission of radiation has taken place. Photons of the proper wavelength, 694.3 nm, stimulate the excited atoms of chromium to return to the ground state with the emission of additional photons. Moreover, the stimulated photons are in phase with the photons producing the stimulation as would be predicted from the classical theory of dipole radiation.

High fluorescent quantum efficiency and broad band absorption are necessary conditions in any solid state substance before amplification by stimulated emission of radiation can take place. However, something more is needed before laser action can be attained. Some method must be devised for increasing the effective path length of the stimulating photons in the crystal. Photons which by chance are emitted parallel to the crystal axis will be reflected back normally into the crystal, while those inclined at an appreciable angle to the crystal axis will escape. Thus, an avalanche of highly directional and phase coherent photons is built up suddenly. If one of the reflectors is partially transparent, an intense beam of parallel light which is plane polarized, coherent in time and space, and monochromatic is emitted. By placing an optical shutter between the ruby rod and one of the reflectors, Q-spoiling can be accomplished. The shutter is closed normally when the pumping light irradiates the ruby rod. After a time of the order of a few hundred microseconds, a sufficient number of excited chromium atoms have been accumulated to accomplish population inversion but laser action is withheld because the light path to the reflector is blocked. If now, this light block is removed suddenly, a giant pulse of radiation is emitted. This is the principle of the so-called Q-switch. The shutter employed by McClung and Hellwarth was an electro-optical Kerr cell, but rotating mirrors and substances which lose their opaqueness when irradiated have also been employed successfully to produce Q-switched pulses lasting for only a few nanoseconds. Another and equally valid way of presenting laser action is to consider the laser rod with its highly reflecting mirrors as a high Q cavity which can oscillate in any one or several of a number of modes appropriate to the frequency to which the cavity is tuned. The higher the Q, the less the pumping energy needed to attain laser action. Light waves traveling along the axis of the crystal and bouncing back and forth through an amplifying medium between the mirrors set up a coherent standing wave of light. Waves traveling off normal soon miss the mirrors and are lost. In essence, this is a "Fabry-Perot" type of structure which serves as a resonant cavity for oscillations. Obviously, in Q-switching, the cavity Q is raised suddenly to a very high value, thereby allowing a giant pulse to be emitted from the system.

The rudimentary principles of pulsed laser action as elucidated above are appropriate to all pulsed laser systems. Normal pulsed laser action produces multiple spikes in which the overall duration of the pulse may extend from a few hundred microseconds to several milliseconds, depending upon the system involved. Q-spoiling generally produces single spikes or pulses lasting from 5 to 100 nsecs. Neodymium-doped glass lasers and ruby lasers are the two solid state systems most prevalent among the pulsed systems. Their wavelengths, 1060 nm and 694.3 nm respectively, together with their frequency doubling wavelengths, 530 nm and 347 nm, constitute the principal hazards from pulsed laser systems at the present time. Among the CW systems which constitute a hazard are the gas lasers, CO_2 at 10.6 microns, He-NE 632.8 nm, and the argon laser at several wavelengths in the region of 480–500 nm. All of these sources are capable of emitting electromagnetic radiations which are hazardous to man.

THE RADIATION HAZARD

Since the mammalian eye is acknowledged to be the most sensitive organ to laser radiation, this discussion will be confined to ocular hazards. This is permissible since it is highly unlikely that other types of deleterious effects can take place at distances and at laser intensities where ocular effects are negligible. Verhoeff and Bell[(8)] in a classic paper published in 1916 demonstrated that the pathological effects of radiant energy on the eye could be explained in terms of thermal injury resulting from the absorption of radiation in the pigment epithelium (PE) and in the choroid. In considering the ocular hazards from lasers it is fortunate that a large body of knowledge on retinal burns has been accumulated over the past two decades. Some of the data most pertinent to laser hazards has been collected in recent publications by the authors.[(9)]

Solon, Aronson, and Gould[(10)] have discussed the physical principles of image formation by the human eye when exposed to laser beams in the near and the far field. Laser sources emit highly directional beams of radiation with angular divergences ranging from fractions of a milliradian to about 10 mrad. For nearfield illumination the entire cone of radiation may enter the eye depending on the beam diameter relative to the diameter of the pupil. Under these conditions the diameter of the image focussed on the retina will be given by the product of the angle of divergence and the equivalent focal length of the human eye, usually taken as

17 mm. For angles of divergence exceeding 1 mrad the image diameter may exceed the minimum size as determined by diffraction in the human eye. There is no general agreement among authorities as to what constitutes the diffraction limited size of the image on the human retina but most estimates place it as being between 10 and 20 microns. In the far field from a laser source the cone of radiation illuminates the entire eye with almost parallel light, resulting in a diffraction limited image on expected the transmission through the human OM is similar to that of water. Wavelengths shorter than 400 nm are absorbed primarily in the outer layers of the cornea producing an acute inflammation similar to snowblindness. Thus, laser sources producing radiation beams in the UV will produce corneal damage rather than retinal damage. Wavelengths beyond 1400 nm do not penetrate the OM to produce retinal images. The CO^2 laser which produces a strong beam of CW radiation at 10.6 microns

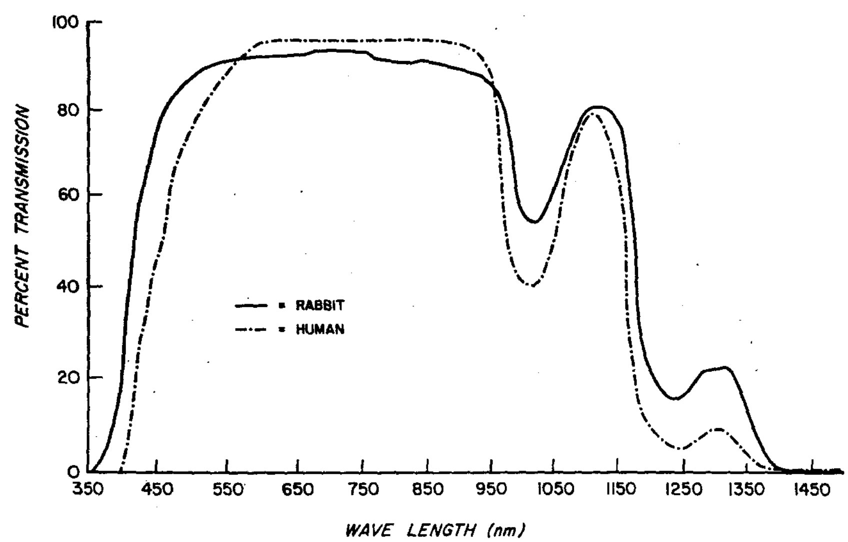

FIG. 1. Percent transmission through the ocular media vs. wavelength for light of uniform intensity incident on the cornea; comparison between man and rabbit.

the retina (10–20 microns). Thus, unless optical instrumentation is employed laser beams produce small images on the retina, varying from perhaps 170 microns to 10 or 20 microns in diameter. For purposes of comparison the image of the sun on the human retina is approximately 160 microns.

Transmission of light through the ocular media (OM) of the human and rabbit eye has been measured by the authors[11] and is illustrated in Fig. 1; it extends from approximately 350 nm to 1450 nm, exceeding 0.80 in the range 500–950 nm. There are two peaks in the near IR, a large one at 1100 nm and a much smaller one (0.10) at 1300 nm. As might be would be dangerous to the cornea since the half-value layer in water for this wavelength is about 10 microns. In the far infrared the hazard becomes that which has been observed for microwaves, usually heat damage to the proteins of the crystalline lens resulting in a type of cataract commonly designated as infrared cataract. In the range of wavelengths 350–1450 nm the human eye can focus an image on the retina. The hazard here is thermal injury or retinal burns for CW lasers producing enough power to raise the temperature of the retina to levels above ambient where denaturation of proteins can occur. Some proteins are damaged irreversibly at temperatures as low as 45°C if maintained at this temperature for considerable periods of time. Time-temperature history must be considered in any evaluation of thermal injury to biological substances. The authors have shown that an irradiance of 6 W/cm^2 on the rabbit retina for a period of 3 min produced a mild retinal burn which appeared first at the center of the retinal spot which was about 800 microns in diameter. It is estimated from theoretical calculations that the temperature of the retinal tissues was maintained at approximately 17°C above ambient during the exposure. The source of radiation was a high pressure xenon lamp producing white light. Wavelengths beyond 900 nm were removed by a filter. Considerations of heat conduction indicate that the temperature attained at equilibrium and the time taken to reach equilibrium temperature are strong functions of the image size. The smaller the image size the lower the equilibrium temperature and the shorter the time taken to attain it. Equilibrium is reached in a matter of milliseconds. Thus, the small images produced by CW lasers having small angular divergences should withstand irradiances well above 6 W/cm^2 before attaining temperatures comparable to those produced on the retina by the xenon lamp. On the other hand, 17°C above ambient is certainly too high a temperature for sensitive retinal tissue. It is recommended that CW retinal irradiances be kept well below 1 W/cm^2 regardless of image size until more definitive data are available. The safety criteria for exposure to CW lasers in the spectral range 350–1450 nm should be based ideally on retinal irradiances which produce equilibrium temperatures which will not cause irreversible damage to retinal tissues, even over long periods of time. Such temperatures may be only a few °C above ambient.

A major portion of the radiation impinging on the retina is absorbed in the PE and the choroid. The authors have investigated absorption vs. wavelength in these elements for 24 human eyes.[(11)] In Fig. 2 it can be seen that maximum and minimum absorption in the PE at the ruby wavelength (694.3 nm) is 0.40 and 0.15 respectively; for neodymium doped glass at wavelength 1060 nm the coefficients are 0.15 and 0.05 respectively. Peak absorption in the PE for light incident on the cornea occurs between 500–550 nm. The first harmonic for neodymium doped glass at 530 nm and the green lines in the argon CW laser are in the region of maximum absorption by the PE. Actually, for light incident on the cornea, the absorption in the PE and in the choroid is approximately equal for the 24 eyes studied. However, the PE is roughly 10 microns in thickness, whereas the choroid is about 100–150 microns in thickness. Therefore, the energy absorbed per unit volume (joules/cm^3) in the PE will exceed that in the choroid by a large factor. It is not surprising, under these circumstances, to learn that for mild lesions of the retina produced by laser pulses of relatively short time duration (0.2 msec–2.0 msec) damage is observed histologically to occur in the PE and in the strata of the retina immediately adjacent to the PE rather than in the choroid.

The authors have investigated the production of mild lesions in the rabbit retina by pulsed ruby lasers, both in the multiple spiked mode involving exposure times of 10, 50, 100 and 200 μsecs and in the Q-switched mode, exposure time 30 nsecs. Fig. 3 is a schematic diagram of the optical system used to produce these lesions and Fig. 4 illustrates the modified ophthalmoscope used in conjunction with the system. Mild lesions are defined as being just visible ophthalmoscopically within 5 min after exposure. These lesions are not considered to be threshold burns since irreversible damage has been demonstrated at lower levels of irradiance by more refined techniques such as histochemistry, electroretinography, and electron microscopy. Figure 5 is a log–log plot of watts/cm^2 vs. exposure time in seconds for minimal lesions of 800 microns diameter in the rabbit retina. Irradiances in the range 2–3 kw/cm^2 for exposure times of 200–300 μsec produce very mild lesions on the rabbit retina. The lesions are thermal in nature and correspond rather closely to those produced by a white light source. The irradiance required to produce these lesions is reasonably independent of image size. No damage has been detected in the rabbit retina when these irradiances are reduced by a factor of two.

In the Q-switched mode, irradiances of from 3–5 MW/cm^2 delivered in 30 nsec produce mild lesions as defined above. These lesions

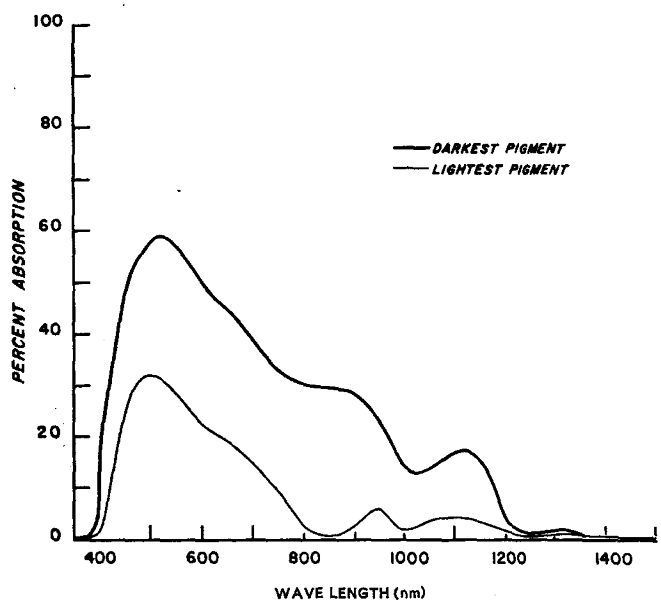

FIG. 2. Graph of percent absorption in human pigment epithelium vs. wavelength for light of uniform intensity incident on the cornea; plots are for the lightest and darkest pigmented eyes studied.

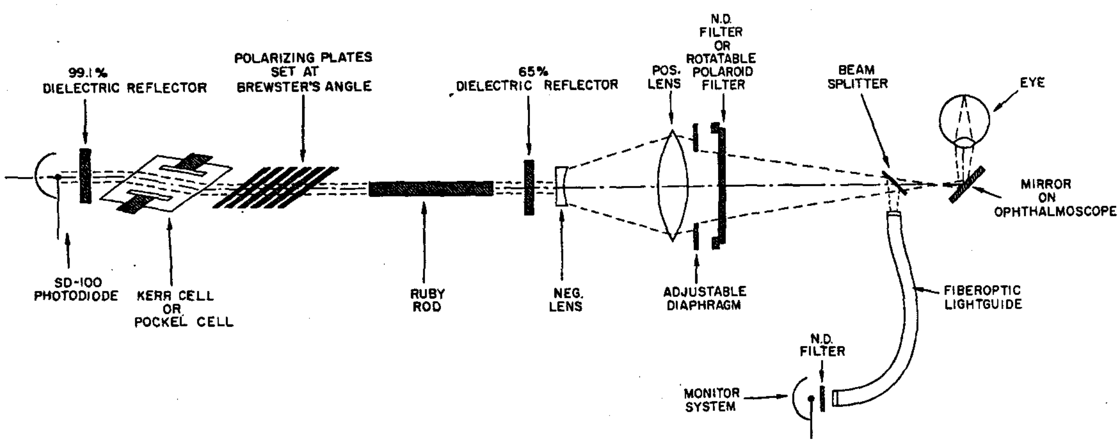

FIG. 3. Schematic diagram of laser optical system used to produce experimental lesions in the rabbit eye.

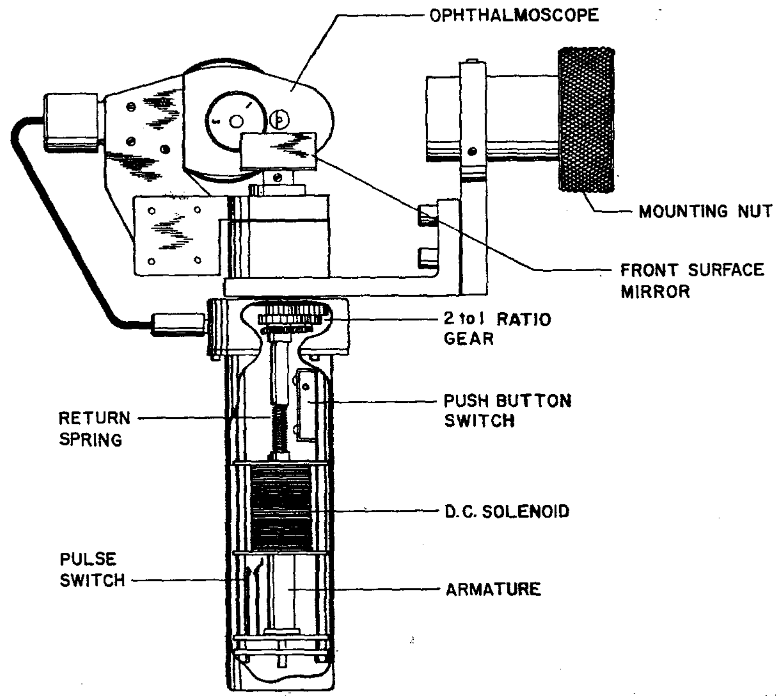

FIG. 4. Schematic drawing of modified ophthalmoscope used in conjunction with the laser optical system for producing and observing lesions in the experimental animal eye.

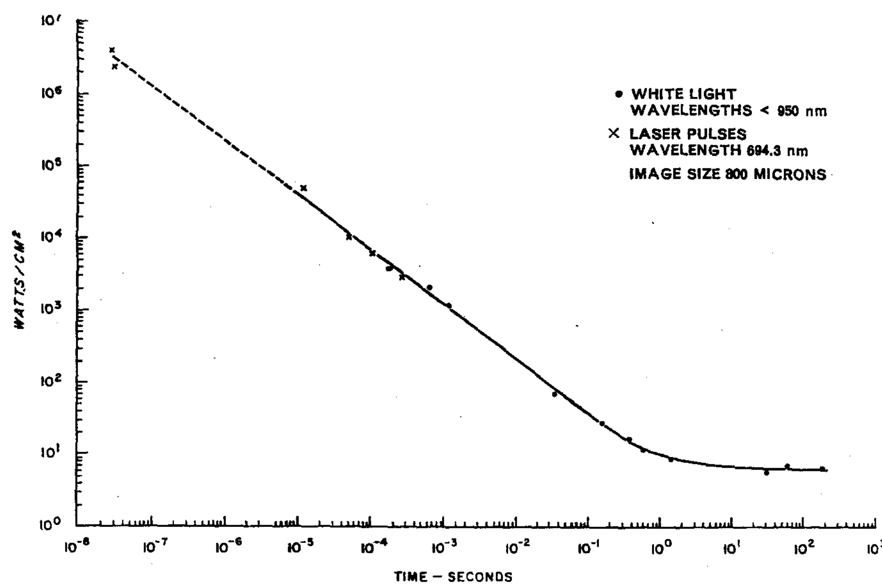

FIG. 5. Log–log plot of watts/cm² vs. time in seconds for minimal lesions observed within 5 min after exposure; image diameter, 800 microns. The data include both white light (wavelength <850 nm) and ruby laser exposures.

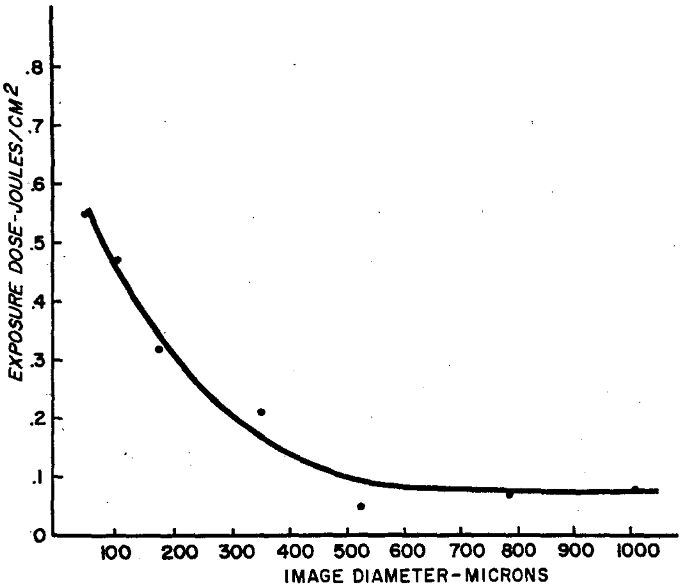

FIG. 6. Exposure dose. J/cm^2 vs. image diameter, microns, for minimal lesions observed with the ophthalmoscope immediately after exposure to 30 nsec Q-switched ruby laser.

may not be entirely similar to those produced at lower power densities. There is the possibility that non-linear effects may play a role in producing these lesions and the authors are unwilling to call them thermal burns until further investigations have been made. In addition to the Q-switched data shown in Fig. 5 for lesions of 800 microns diameter, the authors have investigated the energy density needed to produce minimal lesions at much smaller image diameters. Figure 6 is a graph of energy density in joules/cm^2 vs. image diameter in microns for minimal lesions in the rabbit retina as produced by the Q-switched ruby laser. These data, in fair agreement with recent findings by Tengroth and Bergqvist,[12] seem to indicate that larger energy densities are needed to produce minimal damage as the image diameter is reduced. However, both the authors and Tengroth *et al.* are inclined to believe that this may be an artifact resulting from the difficulty of observing damage at the smaller image sizes. When irradiances are raised to 25–50 MW/cm^2, material is extruded into the vitreous, hemorrhaging occurs, and there is evidence to suggest that shock waves may be partially responsible for the damage.

CURRENT STATUS OF RADIATION PROTECTION FROM LASERS

The purpose of the above outline of ocular damage is to illustrate that data are available to make an intelligent estimate of safe exposure levels to laser radiation under various conditions of operation. The question arises naturally as to what can be done to protect the public from the hazards of laser radiation and who should propose these measures and see that they are enforced. The answer to the first question is relatively simple. Protective devices and certain operational procedures are known and practiced by many reputable firms and organizations. For example, goggles specifically designed to protect against laser radiation are manufactured by several optical companies in America and in Europe.[13] Several designs for a protective symbol against lasers have been proposed.

In answer to the second question, no single group, society, agency or organization has stepped forth as yet to establish basic criteria for radiation protection and permissible levels of exposure to laser radiation. This is not because the large and growing group of scientists, military personnel, and technicians involved in laser research and development are unaware of the hazards involved or because they wish to be left alone to cope with their own problems. On the contrary there is a genuine concern about radiation protection from lasers. Many health physicists, often without adequate background or information, have been saddled with company or organizational responsibility for laser safety. In recent months the Martin Marietta Corporation has developed a "laser hazard" slide rule and published a company brochure on "Determination of Laser Hazards".(14) This is typical of the concern over laser hazards in American industry. Several companies have established their own rules and procedures for laser safety. The Hughes Aircraft Company has published a report on laser eye damage levels.(15) Quite recently, a draft of guidelines for safe operation of laser systems was prepared by the Commission on Environmental Hygiene of the U.S. Armed Forces Epidemiological Board.(16) A conference on laser safety was held in May 1966 in Orlando, Florida. More than 150 participants from all over the United States attended this conference. The proceedings were published in 1966 by the Martin Company, Orlando Division.(17) The National Academy of Sciences National Research Council has formed a laser committee to consider the hazards of laser radiation. This committee reported informally on its findings at the second Gordon Conference on lasers in medicine and biology, held at Andover, N.H., in July 1966. Symposia on the biological effects of laser radiation have been held by the Optical Society of America(18) and by the Armed Forces Institute of Pathology.(19) A safety group on optical masers has been organized by interested groups in the Department of Defense and in university circles. The NCRP has been approached informally as to what its attitude might be regarding radiation protection from lasers.

Despite the efforts listed above no centralized agency comparable to IRPA or its member societies has volunteered to establish safety criteria and permissible levels of exposure to laser radiation. Whether IRPA and its member societies should attempt to amalgamate current efforts into a responsible organization with official status comparable to that enjoyed by the NCRP, the ICRP, and the American Board of Health Physics is a question which should be presented to this first International Congress on Radiation Protection.

REFERENCES

1. J. P. Gordon, H. J. Zeiger and C. H. Townes. *Phys. Rev.* **95,** 282 (1954).
2. A. L. Schawlow and C. H. Townes. *Phys. Rev.* **112,** 1940 (1958).
3. T. H. Maiman. *Nature* **187,** 493 (1959).
4. A. Javan, W. R. Bennett and D. R. Herriott. *Phys. Rev. Letters* **66,** 106 (1961).
5. F. J. McClung and R. W. Hellwarth. *Proc. I.E.E.E.* **51,** 46 (1963).
6. C. S. Naiman, J. Schwartz, M. Y. DeWolf and I. Goldblatt. Abs., 7A-6, 1966 International Quantum Electronics Conference, Phoenix, Arizona (April 12–15, 1966).
7. W. T. Ham, Jr., R. C. Williams, W. J. Geeraets, R. S. Ruffin and H. A. Mueller. *Acta Ophthalmologica,* Suppl. **76,** 60 (1963).
8. F. H. Verhoeff and L. Bell. *Proc. Am. Acad. Arts & Sci.* **51,** 630 (1916).
9. Reference 7 and W. T. Ham, Jr., R. C. Williams, H. A. Mueller, D. Guerry, A. M. Clarke and W. J. Geeraets, *Trans. N.Y. Acad. Sci.,* Feb. 1966.
10. L. R. Solon, R. Aronson and G. Gould. *Science* **134,** 1506 (1961).
11. W. J. Geeraets, R. C. Williams, G. Chan, W. T. Ham, Jr., D. Guerry, III, and F. H. Schmidt. *A.M.A. Arch Ophth.* **64,** 606–615 (1960). Also: ibid. *Invest. Ophth.* **1,** 340–347 (1962).
12. Bergqvist, Tore, Kleman, Bengt and Tengroth, Bjorn. Retinal Lesions Produced by Q-switched Lasers. Personal communication to the authors; submitted for publication to *Acta Ophthalmologica.*
13. J. C. Kaufman. *Microwaves.* April 1966, pp. 38–45.
14. G. W. Flint. Martin Marietta Corp., OR 8336 (May 1966).
15. T. Lubensky. Ref: 2720. 01/02, Hughes Aircraft Co. (August 1965).

16. W. E. Froemming. Personal communication to the authors. Guidelines for Safe Operation of Laser Systems (June 1966).
17. *Proceedings of the First Conference on Laser Safety*, sponsored by Martin Company, in cooperation with the U.S. Army, Surgeon General's Office, Orlando, Florida, 19–20 May 1966.
18. Symposium on Physiological Effects and Hazards of Laser Radiation, J.O.S.A. 1964 Spring Meeting Program, WI1–WI16, 1 April 1964, Washington, D.C.
19. *Federation Proceedings* **24**, No. 1, Part III, Suppl. No. 14, Jan.–Feb. 1965.

DISCUSSION

J. E. McLaughlin (*U.S.A.*):

I notice your proton spectra fall rapidly with energy and were quite smooth. Could you comment on:

1. The effect of local radiations from the space vehicle on these results.
2. The effect of energy resolution of the spectrometer on the spectra.

M. C. Chapman:

The proton spectral data were taken using phaswich scintillation detectors. These detectors use CsI as the energy detector, and plastic scintillators as a guard counter. Thus all spacecraft-produced protons are rejected by the guard counter. Four channel analysis, with 12% energy resolution, is performed on all acceptable events.

The smooth spectral shape is consistent with data obtained by other experimenters, and is consistent with our three or four energy determinations.

R. E. Simpson (*U.S.A.*):

Have you made comparative measurements between your scintillator (plastic) and an LET proportional counter? If so, what kind of agreement?

M. C. Chapman:

Concerning the comparison of Rossi-type ion chambers and the scintillator dosimeter, tests of this type are planned and will be accomplished shortly. Results should begin to be available in a month or several weeks.

D. Nachtigall (*Euratom*):

In den Wänden von gewebeäquivalenten Ionisationskammern ist normalerweise O durch C ersetzt. Wie weit sind die Wirkungsquerschnitte hochenergetischer Partikel für O und C bekannt, so dass man sagen kann, dass diese Kammern auch im hochenergetischen Bereich tatsächlich gewebeäquivalent sind?

Die Rückstossprotonen, die von Neutronen mit Energien kleiner als 20 keV in gewebeäquivalenten Kammern ausgelöst werden, ionisieren nicht mehr und werden deshalb nicht mehr nachgewiesen. Wie gross schätzen Sie den Fehler ein, der dadurch bei den gegebenen Spektren entsteht?

F. E. Holly:

We use two separate types of ion chambers, both constructed of shonka tissue-equivalent plastic and the types, mixtures, and proportions of gases varies depending upon the purpose. A report exists, which I can give you, describing their use, calibration, and tissue equivalency. About the neutron sensitivity and the error estimate, we have both neutron and neutron-insensitive chambers. These are described in the paper previously referred to.

C. A. Adams (*U.K.*):

Dr. Vogt's emphasis on hazards did not appear to correspond with their order of importance in the releases which could occur from nuclear reactors. In general our analysis shows that inhalation is the dominating hazard. In particular I understood him to say that ^{131}I could give an ingestion risk greater than the inhalation risk. This would be understandable if there were an area of crops, with no individual present on the land or its neighbourhood. However, if an individual is present I should like to know the circumstances in which deposition could give a risk to him greater than that to which he would be subjected by inhalation of the cloud. Could Dr. Vogt give an example of the circumstances he had in mind?

J. K. Vogt (*Germany*):

Bei der Freisetzung von ^{131}I kann tatsächlich die Strahlenbelastung durch Ingestion die Inhalationsbelastung erheblich überwiegen, wenn es zu Ablagerungen aus der radioaktiven Wolke über landwirtschaftlich genutzten Flächen und damit zu einer Kontamination der Nahrungskette kommt. Im Einzelfall hängt die Gefährdung durch Ingestion natürlich von den Ernährungsgewohnheiten ab. Bei einem Milchkonsum von 1 Liter pro Tag kann die Ingestionsbelastung durch ^{131}I zwei bis drei Zehnerpotenzen über der Inhalationsbelastung liegen, wenn der gesamte Bedarf an Milch und Milchprodukten aus dem Aufkommen gedeckt wird, das auf kontaminierten Weideflächen erzeugt wurde.

B. W. Emmerson (*U.K.*):

Under actual accident conditions I consider that the nomograms presented by the speaker would require considerable time in estimating the actual hazard from the release plume. Has any attempt been made to produce simplified nomograms in terms of the two major release hazards, namely, inhalation and deposition. At Bradwell nuclear power station we have produced simple nomograms on which the minimum evacuation time for various levels of airborne activity, and the degree and types of agricultural foodstuff banning for given levels of deposited activity, can be read directly from two main nomogram charts.

K. J. VOGT (*Germany*):

Ausser den hier anhand von Beispielen gezeigten allgemeinen Unterlagen für die Abschätzung der Umgebungsbeeinflussung bei Freisetzung radioaktiver Abluft haben wir für einzelne Emittenten wie die Reaktoren spezielle Unfallanalysen erarbeitet. Dabei wurden für bestimmte hypothetische Unfälle in Karten die Bereiche eingetragen, in denen die äussere Bestrahlungsdosis und die durch Inhalation und Ingestion von ^{131}I sich ergebende Schilddrüsendosis für Erwachsen bzw. Kinder die zulässigen Unfallbelastungen überschreiten können, so dass Evakuierungen und Lebensmittelrestriktionen erwogen werden müssen. Die zur Verfügung stehenden Aktionszeiten können aus Kurven abgelesen werden.

A. P. HULL (*U.S.A.*):

This sort of analysis is quite commendable and useful for hazards analysis, but I wonder if this degree of sophistication is applicable to the accident situation in which one seldom has a very accurate estimate of either source term or of prevailing meteorology.

K. J. VOGT (*Germany*):

In aktuellen Unfallsituationen wird es tatsächlich oft schwierig sein, einigermassen sichere Angaben über die Quellstärke zu erhalten. Dagegen entstehen bei der Bestimmung der meteorologischen Bedingungen keine Probleme, wenn die Anlage über eine meteorologische Beobachtungsstation verfügt. In der Kernforschungsanlage Jülich werden die für die Bestimmung der Diffusionskategorie erforderlichen Beobachtungen des Temperaturgradienten und des Windgeschwindigkeitsprofils, sowie der Windrichtungsschwankungen und der Strahlungsbilanz an einem 120 m hohen Turm durchgeführt.

E. W. JACKSON (*U.K.*):

I am a little doubtful about the policy of including data on downwind concentrations following the release of a radioactive cloud. In my view the data obtained by calculating on the basis of a release at ground level should suffice in practice. If the release in fact occurred above ground level the information obtained in this way would be pessimistic which would perhaps not be a disadvantage.

G. COWPER (*Canada*):

Would Prof. Ham tell us what has been the incidence of permanent or temporary damage from lasers?

W. T. HAM:

I cannot give any real statistics on injury today from lasers, but I can assure you that at least in the United States there has been a considerable amount of damage in this field. As you can well understand the various companies which are doing the laser radiation and making applications from laser research have had accidents on numerous occasions, but these involve legal matters and do not often see the light.

Dr. Milton Zaret, an ophthalmologist in New York City, is a consultant to many of these companies and Dr. Zaret has come in contact with a good many cases of damage due to laser radiation. I cannot give you any exact figures as to how great this hazard is at the present time, but damage which is caused is of course permanent; the type of damage I am speaking about is an irreversible damage to the retina and does not heal. Does this answer your question?