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ANALYSIS OF THE EFFECTS OF 10.6 MICRON RADIATION ON SOME MATERIALS COMMONLY FOUND IN CO_2 LASER PROTECTIVE DEVICES

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Analysis of the Effects of 10.6 Micron Radiation on Some Materials Commonly Found in CO_2 Laser Protective Devices

Studies have been carried out on the hazards associated with the 10.6 μ radiation emitted by a CO_2 gas laser (1,2). Although radiation at this wavelength can cause severe skin burns and may ignite clothing and hair, injury to the eye is of primary concern, especially injury to the cornea which is the initial site of interaction with the eye (2). Injury to the cornea may heal by the formation of opaque scars, which can impede vision. Injury to the lens, without corneal perforation, has also been observed following 10.6 μ irradiation of the eye (2).

Protective devices which have not been specifically designed for use against radiation at 10.6 μ have been used by many investigators in the laboratory[1]. These devices include cellulose acetate goggles and face masks, and welder's goggles and masks with glass inserts. When the expected hazard is due to low power density radiation, some investigators rely on eyeglasses for protection.

This report contains the results of an examination of the materials contained in the above devices. This examination was performed to determine the degree of protection these materials furnish.

The examination of protective materials would have been considerably simplified if it had been possible to prepare a definitive list of the required properties of an adequate safety device. Unfortunately, a list of this type is difficult to prepare since the device could be employed under unforseeable circumstances, including unusual temperature and humidity conditions. There are some properties, however, which must be included in any such list.

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[1] Since this paper was initiated, a CO_2 laser safety goggle has become available from the American Optical Company. A consideration of this device is given at the end of this report.

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These are:

a) The protective material should not transmit intensities of CO_2 laser radiation that are injurious to the underlying region, i.e., the absorption coefficient should be high at 10.6 μ[2].

b) Materials which reflect radiation in sufficient power densities to be a hazard at 10.6 μ should not be exposed to the laser beam[3].

c) Any intense visible light generated from the protective materials which may constitute a hazard should be prevented from reaching the eye.

d) The materials employed should give an indication of being irradiated as a warning to the wearer before protection fails.

e) Materials which emit dangerous or unpleasant substances when irradiated should be avoided except when the emission is used as a warning (see (d) above).

f) The protection time should be sufficiently long.[4]

g) The material should give an indication if its protectiveness becomes inadequate under either use or storage.

h) The device should be comfortable, and not awkward.

i) The device should not impede communication.

j) The device should neither impede vision nor fog under normal use.

k) The device should protect at all angles of incidence.

l) Any destructive or hazardous reaction in the device initiated by CO_2 laser irradiation should stop when the irradiation ceases.

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2 The power densities necessary to cause long or short term threshold ocular injury are under investigation. However, materials of reasonable thickness are presently available which transmit virtually no radiation at 10.6 microns. Some of these materials may initially be employed in safety devices.

3 e.g. many metals are highly reflective at 10.6 microns, (16).

4 This time must be much longer than the human reaction time, usually taken as 0.1 sec. (A safety factor of 100 is considered minimal).

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Some of the safety devices presently employed have been studied with regard to the above specifications. For example, corrective glasses have metal rims or hinges which reflect the radiation. They do not protect more than the eye area, do not offer protection at all angles of incidence and may fog. Face masks usually protect the face and often the front of the scalp, but sometimes have exposed metal parts, are usually awkward, and impede both communication and peripheral vision.

Cellulose acetate goggles do not protect the hair and lower face, usually impede or distort vision, and may be uncomfortable.

Welder's goggles and masks often have heavily tinted glass inserts which impede vision. The goggles protect only the eye area; the masks are usually awkward, uncomfortable, and impede communication. The masks generally have large opaque areas which reduce the visual field.

Thus, it is apparent that each of the above devices, when used specifically for protection against CO_2 laser radiation, has one or more inherent disadvantages. However, these disadvantages do not preclude the use of these devices until a more specialized safety device is constructed, as long as the prospective hazards and disadvantages are recognized and adequate preparations are made to minimize them.

A complete investigation of a safety device for CO_2 laser radiation must include a consideration of the interaction of the radiation with both the transparent and opaque materials within the device. Most of the materials employed in safety devices (e.g., cellulose acetate, fiberglass, rubber) interact with 10.6 μ radiation in a relatively simple manner by burning or melting. Some of these materials have been investigated and the results are presented below. Glass however does not react in a simple manner. It is well known that glass may fracture if heated non-uniformly, without showing evidence of melting or burning. Considerable attention was therefore directed towards interaction of CO_2 laser radiation with glass. Radiation at 10.6 μ is absorbed essentially at the surface of most types of glass. When irradiated by a CO_2 laser, there are three ways in which the surface of a glass plate may be non-uniformly irradiated:

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1) the laser beam may be non-uniform.
2) the beam may be smaller than the exposed glass, or, if the beam is larger, only a portion of the glass may be irradiated.
3) a portion of the glass in the safety device may be covered by other material.

Since the glass portion of most safety devices is supported by opaque material which covers the edges of the glass, non-uniform irradiation of the surface is the rule rather than the exception.

When glass is heated non-uniformly, thermal gradients result. These gradients introduce thermal stresses (8) which may lead to fracture (11,12). This type of fracture in glass is somewhat different from the types usually reported in the literature. Most of the existing literature on the fracture of glass is directed towards one or more of the following areas:

1) The interaction of glass with pulsed lasers which emit radiation at 6943A or 1.06 μ (4,5,14).

2) The reaction of glass to mechanical shock after specified uniform thermal treatment (7,9).

3) The mechanical flaws which contribute to glass fracture (3,6,11,12).

The first and second areas apply only marginally to C.W., CO_2 gas laser irradiation. The reported studies in the third area indicate that experimentation on glass fracture will lead, at best, to general results which are for the most part qualitative. An important conclusion which is drawn from the reports in the third area is that one of the most significant factors which influence the fracture of glass under any type of stress is the presence of microscopic flaws at the surface of the glass. These flaws may be caused either by the way in which the glass has been worked (i.e., polishing, grinding) or, in many instances, by the way the glass is normally handled in the laboratory. It is expected, then, that if the glass is not subject to special care, similar glass samples, tested in similar ways, may behave very differently. In general, we have found this to be

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the case. However, we have found that there were general recommendations that could be stated if glass was used as a part of a safety device. These recommendations are presented towards the end of this report.

Initial testing was carried out on crown glass microscope slides because they are similar in size and chemical structure, and new slides from the same package probably have similar histories with regard to production and handling. It was expected that these similarities would minimize the spread of the data.

In preliminary studies on microscope slides it was noted that when held by metal clamps, the glass would often fracture along a path from the irradiation site to the clamp, irrespective of near edges. However, when held by wax, samples of glass would usually fracture along a path that went from the irradiation site to the nearest two edges. The latter type of fracture was also noted when the glass was supported by string. Therefore, it was assumed that the metal clamp was grossly affecting the experiment and for that reason wax was used to support all subsequent samples.

In the first set of tests, the power density incident on the glass sample was held fixed at $20 w/cm^2$ while the diameter of the irradiating beam was varied. Table 1 summarizes the results on 1" x 3" x 1/25" microscope slides when the irradiation zone was centered at the center of the surface of the slide.

From the table, it is evident that the glass fractured more quickly as the diameter of the irradiation site increased. It was also observed that the samples always fractured across the 1" dimension, i.e., from the irradiation site to the nearest edge.

When 2" x 3" x 1/25" slides were irradiated, the slides were again observed to fracture more quickly as the irradiation diameter increased. Similar results were obtained on subsequent tests on protective glass, such as filter lens by Jackson products (4 1/2" x 5 1/4" x 1/8") filterweld plate by the American Optical Company (4 1/2" x 2" x 3/32") and (4 1/2" x 5 1/4" x 1/8") and AIRCO lenses 1 15/16" in diameter x 1/8" thick. Noting that the irradiation time necessary to fracture a sample increased as the spot size decreased, the spot diameter was reduced still further. A spot size was found at which the sample did not fracture during ten minutes of irradiation. In addition, smaller spot sizes would not fracture the glass within 10 minutes. The power was then varied and at each power, a spot size was found below which the sample would not

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fracture for long irradiation intervals. The above experiments were repeated with the irradiation site close to an edge of the samples; all samples that were irradiated in a manner which would previously fracture the glass, were observed to fracture in a shorter time interval. Furthermore, it was observed that at some power densities and spot diameters for which no effect was observed on central irradiation, the sample fractured when irradiated near an edge.

Although in all the above experiments, there were no alterations of the irradiated glass sample which could be seen on direct visual examination until fracture occurred; at higher power densities (of the order of 100 w/cm^2) the glass was observed to alter at the irradiation site. This was first noted as a distortion of objects seen through the sample. At these higher power densities, the glass did not fracture on irradiation, unless the irradiation site was very close to an edge. However, the sample frequently cracked on cooling. In general, it was found that for a given irradiation site and spot diameter, samples which would fracture at power densities insufficient to cause observable change previous to fracture, would either not fracture at higher power densities or would take longer to fracture at higher power densities. However, the glass which did not fracture on irradiation at the higher power densities would frequently crack on cooling.

The observed changes in the samples which were irradiated at the higher power densities indicate that the glass within the altered region had reached a temperature beyond its annealing point. This annealing temperature is dependent primarily on the composition of the glass.

When glass has been heated to beyond the annealing point, all thermal strain within the annealed region is relieved, but permanent residual strain is formed when the glass subsequently cools. For a given ambient temperature, this residual strain increases as the temperature reached beyond the annealing point increases (12). It appears that sufficient permanent strain had been instituted to crack the cooling glass in some cases, but not in others. The samples that reached a lower annealing temperature on irradiation at lower power densities did not usually crack while those irradiated at the higher power densities usually did.

When the annealed samples that had not cracked on cooling were examined, a distortion was usually noted when objects were viewed through the irradiation site.

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These samples usually exploded violently after a short period if re-irradiated near the old irradiation site, even at power densities that would not normally fracture the sample. In particular, normal eyeglass lenses were markedly explosive under these conditions.

It is well-known that thermal strain induces stress patterns in glass samples during irradiation. Stress patterns due to residual strain can result post-irradiation if annealing had occurred. The development of these patterns was followed photographically and visually using polarized light. In all samples examined under polarized light, these stress lines were observed to form at the irradiation site and to expand in an outward direction. One of the following four processes was observed:

1) The lines eventually reached a stationary configuration. Direct observation of the sample gave no evidence that irradiation was taking place. The lines disappeared post-irradiation. No evidence of the irradiation could be detected in the sample after it had cooled.

2) The lines eventually reached a stationary configuration. The glass cracked during cooling. Residual lines were still present in the region surrounding the cracks which indicated that some residual stress was still present.

3) The lines reached a stationary configuration. The glass did not fracture on cooling, but the stress pattern did not altogether disappear when the glass cooled. This phenomenon was sometimes accompanied by an observable depression in the anterior surface of the glass after cooling.

4) The glass fractured during irradiation while the stress lines were expanding or after they appeared to become stationary.

The samples which did not lose all the induced stress post-irradiation were more likely to fracture or even to explode during re-irradiation.

Furthermore, it was observed that for those samples in which the stress lines were confined within the edges, the sample did not usually fracture on irradiation, while if the stress lines reached the edge, the sample was more likely to fracture. This observation

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indicated that the reason the smaller spot diameters and center irradiation experiments discussed earlier usually did not cause fracture, while the larger spots and edge irradiation did, was that in the latter case, the stress lines were more likely to reach the edges of the sample.

However, as mentioned above, some samples were observed to fracture during irradiation even though the stress lines were confined to well within the edges, and the irradiation site appeared to anneal. This phenomenon seems to be somewhat clarified by the observation that was noted earlier in this report, i.e., that the surface condition of the glass may strongly influence the result of irradiation. The samples that fractured under conditions that did not normally cause fracture may have had surface defects. Scratches were shown to result in fracture under irradiation conditions which would not normally cause fracture. Samples which did not fracture were irradiated for $\sim$ 10 min. at an arbitrary power density which caused annealing at the irradiation site. A scratch was then made on the rear surface with a steel stylus without otherwise perturbing the experiment. The samples always fractured shortly after being scratched. Samples were also scratched prior to irradiation. At power densities that caused annealing, these samples invariably fractured.

At sufficiently high power densities, all glass samples were observed to emit a bright white light and a small jet of flame. The flame appeared to be emitted from both sides of thin samples (1/25"), and from the front only of thicker samples (1/8"). These emissions were accompanied by a fine powder or smoke. The light emissions were studied with regard to the possibility that they were intense enough to be hazardous.

Since the maximum power output of the CO_2 laser employed was 20 watts, studies on secondary light emission were carried out using a focused beam. When glass samples were placed at the focal point of an IRTRAN II lens, an intense white light was produced from the irradiation site. This light was painful to observe at a distance of 3 feet from the source, and appeared to result in temporary impairment of visual acuity and persistent after-images (scotomatic glare) in a portion of the visual field. As expected, clear glass appeared equally bright when viewed from front or back; tinted glass transmitted less light as the optical density increased. Only a dull red glow was observed at the back when shade #6 glass[5] was irradiated under the above conditions.

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[5] Optical density between 1.93 and 2.36, transmission peak in the green.

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There appear to be hazards associated with this source of intense visible radiation. If this source were near the eye, as in a normal protective device, an appreciable fraction of the light would be transmitted through the glass (unless adequately filtered) and enter the pupil. This might result in a hazardous power density at the retina. Kohtiao, et al., (15) have reported findings which indicate that a retinal power density of 54 w/cm^2 incident on the retina due to direct viewing of the sun through a 3mm pupillary aperture is hazardous. Lesions have been observed in retinal studies on people who have given a history of direct viewing of the sun (17).

To determine the power density on the retina caused by the emission from glass, the following procedures were carried out.

The laser beam was focused on the surface of a glass sample to a small spot size. This caused visible light to be emitted. A magnified image of this secondary source was obtained and the size of the source was determined to be 0.2 mm. This was done by inserting a lens and a screen behind the source. The lens formula was then utilized to find the source diameter when the image diameter was measured on the screen.

A 7 mm aperture was placed 2 cm behind the secondary source. This aperture was used to simulate the dark adapted pupillary aperture. The light passing through this aperture was collected by a lens and focused. The power at the focal point was 15 mw. The retinal power density produced by 15 mw entering the eye and focused to 0.2mm is approximately 50 w/cm^2. This power density is similar to that which has been indicated to be hazardous (15).

As previously mentioned, other protective materials have been considered. A 1/4" thick piece of cellulose acetate placed at the focal point of an IRTRAN II lens was penetrated in about 0.8 seconds by a 15 watt CO_2 beam. It smoked and appeared to melt, gave off an acrid odor, but emitted no evident visible light. At lower power densities, correspondingly longer times were required for penetration. For example, at about 10 w/cm^2, penetration occurred after 15 sec, with little or no odor or smoke. At lower power densities, the material melted and was slowly "ablated" from the surface in a manner that might not be observed unless the irradiation site were in direct view. This indicated that at low power densities, irradiation of this type of protective shield might not be noticed until after the protection failed. Fiberglass welders' masks acted in a similar way at low power densities, but at high power density a flame appeared at the irradiated site.

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RECOMMENDATIONS

If glass is used as part of a safety device, the following guidelines should be observed.

1) the dimensions of the glass should be large in comparison with the dimensions of the beam.

2) the edges of the glass should be covered for several centimeters by opaque material to prevent irradiation close to the edge of the glass.

3) the glass should be checked for stress by polarized light before being used.

4) care should be taken to minimize surface scratches and bruises by rough handling.

5) the glass should be sufficiently tinted (or a tinted back-up plate should be employed) to reduce both scotomatic glare and the possibility of retinal burns due to secondary emissions.

A safety goggle produced by the American Optical Company for use with CO_2 lasers was studied. It consists of 3 sections: (1) a mask consisting of a rubber frame supporting quartz (Vycor) and plastic plates (2) an adjustable plastic headband (3) two spring loaded metal connecting units between the mask and headband to support the mask. The transparent section of the mask is made of quartz plate and a plastic back-up plate with an air space between them.

The quartz was irradiated at all power densities, spot diameters, and locations which had fractured glass plates of similar dimensions. Although the anterior surface of the plate was scarred by high power densities ($\sim 10^3$ w/cm^2) fracture could not be induced. The sample remained intact even when the posterior surface was cooled with liquid freon while the anterior surface was being irradiated.

Observation under polarized light during irradiation yielded stress pattern formations identical to those found in glass under similar circumstances. Post-irradiation observations

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showed that residual stress was formed in the quartz but the patterns were always much smaller than those noted in glass, indicating that the stress was more localized than that found in glass. Although residual stress lines were present, re-irradiation of the quartz (Vycor) did not result in fracture.

Light emission under high power density irradiation was noticeably less than that observed with glass.

The rubber portion of the mask was then examined with regard to protection against CO_2 laser radiation. The material was a flexible rubber mold, reinforced with a metal strap to hold its shape. This metal is not normally exposed to the beam. The rubber smoked, emitted a strong odor, and was eventually penetrated when irradiated at the following power densities.

1) For a 1.5 cm irradiation diameter ($\sim$9.5 w/cm^2), the rubber was penetrated in 24 seconds.

2) For a 2.5 mm irradiation diameter ($\sim$565 w/cm^2), the rubber was penetrated in 5 seconds.

3) At best focus of the IRTRAN II lens, ($\sim$10,000 w/cm^2), 3 seconds elapsed before penetration.

The characteristics of the American Optical Company safety goggle can now be compared with the requirements for protective devices listed at the beginning of this report.

A) all material in the mask itself has a high absorption coefficient at 10.6 as required.

B) the metal connecting units located at the temples and used to support the mask are exposed to the beam and may be reflective at this wavelength. However, the hazards due to the reflected beam may be reduced by the shape of the reflecting surfaces.[6]

C) there is an untinted piece of plastic behind the quartz which together with the intervening air space acts as a heat insulator. This does not, however, affect the secondary light which is emitted from the quartz under high power density irradiation.

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D) the rubber smokes and yields an odor under irradiation, affording a warning of irradiation; the quartz will exhibit a local change in index of refraction, and may glow, under sufficient power density, thus providing a warning. However, there will be no warning provided at low power density.

E) the smoke emitted from the irradiated rubber does not seem to contain hazardous materials.

F) although the quartz insert offers excellent protection for protracted periods of time, consideration should be given to increasing the protection time of the rubber frame.

G) the protection time provided by the Vycor (quartz) was adequate under the conditions of irradiation. However, the rubber charred and blistered and was penetrated under irradiation.

H) the device is quite comfortable, and not awkward.

I) there is no communication impediment.

J) "tunnel vision" only is possible. Redesign of the mask may permit extension of the "visual field".

K) the eye protection afforded by the quartz appears, under preliminary investigation, to be adequate for use with a 20 watt CO_2 laser. The rubber mask can be penetrated in 3 seconds with the highly

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[6] A preliminary investigation of the reflection of 10.6 μ radiation from a flat glass plate and a flat quartz plate was performed. Both samples were irradiated with an $\sim$ 1.5 cm beam containing 12 watts power at an angle of incidence of 45°. No reflection was observed from the quartz plate using Thermofax paper. No heat was felt by an experimenter when he passed his hand through the air at the expected location of reflected radiation. In contrast, the flat glass plate was observed to reflect enough of the radiation to both darken the Thermofax paper and cause a sensation of heat. It is estimated that 0.2 - 0.5 w/cm^2 was reflected under the conditions described above from the glass plate.

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focused beam and may not be adequate under all circumstance. Protection at all angles of incidence is assured by total enclosure of the protected area. The protected area is approximately that covered by a skin diver's facemask, leaving the rest of the head and hair unprotected which, as was previously noted, may represent a hazard.

L) all reaction in the material appears to stop when irradiation ceases. However, there is residual stress in the quartz.

SUMMARY

A consideration of glass, plastic, and quartz has been made with regard to their relative effectiveness as protection against CO_2 laser radiation. It is shown that both plastic and glass can be made ineffective as safety materials either by penetration of the beam, or by fracture upon irradiation with a 20 watt CO_2 laser.

Furthermore, glass can be stressed, with little or no visible indication, in such a way that it will explode violently under otherwise "safe" irradiation. Glass can undergo irradiation without giving visual indications which would otherwise serve as a warning. It may emit hazardous white light due to incandescence when irradiated by high power densities. It may reflect hazardous amounts of radiation.

Vycor, on the other hand, could not be made to fail under irradiation with a 20 watt CO_2 laser. It would not fracture nor be penetrated, nor retain sufficient stress to fracture upon re-irradiation at these power levels. It reflected less radiation than glass during a preliminary study. Although it would become incandescent under high power density irradiation, the emitted light was much less bright than that emitted from glass on similar irradiation.

A rubber mask, made to hold the quartz plate was also tested. It afforded some protection and considerable warning of irradiation by smoking and yielding an acrid odor. However, if is felt that this type mask should have its protection properties improved.

Cellulose acetate and fiberglass of the kind found in chemical goggles and welders' masks, respectively, acted much like the rubber discussed above.

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TABLE I.

Occurrence of Fracture on Irradiation of 1" x 3" x 1/25" Microscope Slides at Constant Power Density With Various Irradiation Diameters

Power (watts)	Power Density (watts/cm^2)	Diameter (cm)	No. of Tests	Time Interval During Which Fracture Occurred (sec)	
12	20	0.9	5	7.4 - 18.5	8.1 sec(average)
7.7	20	0.7	10	8 - 15	10.6 "
5.6	20	0.6	10	15 - 29.6	21 "
3.2	20	0.55x0.4	6	27 - 64	47 "

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