STUDIES ON GLASS DOSIMETERS
Final Report for the Period July 1, 1954
through June 30, 1955

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Cambridge, Massachusetts

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by
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INTRODUCTION

There is a growing possibility that in the future certain foods, drugs, and biological materials may be treated by ionizing radiations on a production-line basis. The problem of insuring accurately known doses in these irradiation processes, therefore, assumes paramount importance from both practical and legal viewpoints. For solution of this problem, suitable and practical dosimeters must be found to measure and check these doses. The requirements for a suitable dosimeter for this purpose have been listed by Schulman (1) and may be summarized as follows:

1) The dosimeter should conveniently measure doses from about $10^4$ to $10^7$ r.

2) Readings independent of dose rate should be possible.

3) The dosimeter should not be "erased" or altered in the reading process.

4) Simple, rapid, and reproducible measurements should be possible with the dosimeter.

5) The dosimetric reading should last indefinitely after irradiation.

6) Manufacture of the dosimeter should be possible in large quantities, at low cost, and with good reproducibility.

A seventh desirable requirement is that the readings on the dosimeter should be independent of the energy of the radiation.

Investigations at the Naval Research Laboratory by Schulman and his associates (1, 2, 3) and at the Department of Food Technology, Massachusetts Institute of Technology (4), have indicated that the silver-activated phosphate glass, originally developed at the Naval Research Laboratory to
measure low irradiation doses to which personnel may be exposed (5, 6, 7), has good potentialities for fulfilling these requirements. The present investigation is concerned primarily with an independent evaluation of this silver-activated phosphate glass for the measurement of the higher doses likely to be encountered in the applications mentioned above.

The use of glass as a dosimeter has several advantages that make it especially attractive for these applications. These include (1) chemical inertness, (2) rigidity, (3) insolubility, (4) small size, and (5) permanence. Various other potential advantages and disadvantages of this dosimeter are investigated and discussed in this report.

The glasses used in the present investigation were all manufactured by the Conning Glass Company and were identified by the number #9761. The composition of the glasses is that originally specified by the group at the Naval Research Laboratory, namely, 50% Al(PO₃)₃, 25% Ba(PO₃)₂, and 25% KPO₃, to which about 8% AgPO₃ has been added.

**THEORETICAL ASPECTS**

The property of the glass enabling its use as a dosimeter for high-energy ionizing radiations is that reproducible changes in absorption of light by the glass upon irradiation are produced in the visible and near ultraviolet region of the spectrum. The formation of active centers in the glass by the ionizing radiations is responsible for this induced optical activity. Schulman (7) attributes the increased number of active centers (in addition to those originally
resulting from impurities and natural defects of the structure) to the presence of the silver.

In the non-irradiated glass the silver may be considered to be present in the ionized form, $\text{Ag}^+$. When the glass is irradiated, photoelectrons set free in the glass migrate to these ions, neutralize them, and produce $\text{Ag}^0$ (neutral silver atoms) by the reaction:

$$\text{Ag}^+ + e \rightarrow \text{Ag}^0 \quad (1)$$

The neutral silver atoms can then absorb light, by virtue of excitation processes, to produce characteristic absorption and luminescent properties of the glass. For $\text{Ag}^0$ an excitation band is observed that extends into the visible wavelengths and produces an orange luminescence. This orange luminescence is measured when the glass is used as a personnel dosimeter. The linearity of the luminescent response to dose holds up to at least 500 r. The absorption spectrum of the exposed glass, corrected for the absorption of the non-exposed glass, shows a peak at about 3200 Å. The absorption falls off at longer wavelengths but is measurable up to at least 8000 Å. At wavelengths shorter than 3200 Å, the absorption of the non-exposed glass increases rapidly and sets a practical limit on use of absorption measurements in this region.

The phenomenon called fading involves the disappearance of some of the active centers (produced by irradiation) when the glass is exposed to light or increased temperature or even when it is allowed to stand at room temperature. Fading has been observed in various dosimeter glasses, including silver-activated phosphate glass (1-4), Vycor (Corning) glass (8), and a cobalt-silicate (Bausch and Lomb) glass (9).
exact mechanism is not known, but fading is possibly caused by disappearance of the active centers in the glass in a mechanism such as the reverse of reaction (1), the mobility of the electrons being increased by photo- or thermal stimulation.

**APPARATUS AND METHODS**

**Source.** The source of gamma radiation used in all experiments presented in this report was a multi-curie Cobalt-60 source (10) with a dose rate of about 1400 rep per minute. The doses used were based upon experiments and calculations employing physical dosimetric methods and the ferrous-ferric dosimeter (10). The doses correspond to values obtained by calibration of the source using a specific yield of the ferrous-ferric reaction of $15.4 \mu\text{H Fe}^{++}/1/1000 \text{ rep}$. The results of recent physical dosimetry in this Department, as yet unpublished, support this value in preference to the higher value ($20.2 \mu\text{N Fe}^{++}/1/1000 \text{ rep}$) previously supported.

**Irradiation.** Three to six replicate glasses were used in each determination, the glasses being stacked horizontally one on top of another in a cylindrical glass ampoule (diameter 1/2 inch, height 1-1/4 inches) with stopper. All ampoules were filled with water and irradiated in fixed positions in special sample holders, previously used, to match geometry and absorber characteristics as closely as possible to those used in the calibration of the source.
Measurements. All optical density measurements were made in a Beckman spectrophotometer (Model DU) using a special metal sample holder with four matched apertures to accommodate three glasses and a "blank" (Figure 1). The aperture dimensions were 0.80 cm. x 0.80 cm. Separate experiments showed that the amount of light passing through the four apertures was constant within detectable limits. The "blank" aperture is used as the 100% transmission reference, and the absorbancy index* is calculated by dividing the observed optical density by the measured thickness of the glass. Slit widths used were from 0.4 to 0.5 mm., and each glass was measured at the four wavelengths: 3500, 4000, 4500, and 5000 Å.

A special photomultiplier attachment (Beckman #4300) was used to increase the measuring range of the spectrophotometer approximately two optical density units, in order to obtain more measurements on glasses exposed to the higher doses.

Each glass was inspected carefully, and those with obvious flaws were not used in the experiments. Before each measurement each glass was carefully cleaned with special lens paper. The glasses were coded and marked on their edges with soft lead pencil.

*The absorbancy index (A.I.) is related to the absorption coefficient (A.C.) by the factor \( \log_{10} 10 = 2.3 \). Thus, A.C. = \( 2.3 \times \text{A.I.} \). Figure 1 given in the previous publication on glass dosimetry from this laboratory (4) lists values as "absorption coefficients"; these, however, are actually absorbancy indexes.
Glasses were first sorted with respect to thickness, so that the average of the optical density values of the replicate glasses could be divided by thickness. It was found that the absorbancy indexes of the non-irradiated glasses were fairly constant in each lot, and that each glass need not always be measured before irradiation. The values for non-irradiated glasses can then be obtained from the average value for several glasses in each lot. The reported absorbancy index is the absorbancy index of the irradiated glass minus the absorbancy index of the non-irradiated glass.

Special experiments have shown that the non-exposed glass may be used as the 100% transmission reference instead of the blank aperture. The observed optical density then represents the difference in the optical densities of the exposed and non-exposed glasses. (An exposure of the non-exposed glass to 3,500 Å for ten hours in the Beckman DU instrument produced no detectable change in the glass absorption properties.) This procedure eliminates the necessity for separate measurement of non-exposed glass and reduces the calculation time. The different glasses should show good reproducibility in non-exposed absorption properties and have the same thickness, if this procedure is to be employed successfully.
EXPERIMENTAL RESULTS

Effect of Storage at Refrigerator Temperature

Previous research in this laboratory (4) has shown that the temperature of storage has an observable effect upon the fading characteristics of Corning #9761 glasses when the glasses are not heat-treated after irradiation with a dose of about $10^5$ rep. No differences were detected between the fading characteristics during storage at $20^\circ$ C. and those during storage at $37^\circ$ C. (except for a small difference at 4000 Å), but differences were observed when comparisons were made after storage at $20^\circ$ and $55^\circ$ C. for wavelengths of 4000, 4500, and 5000 Å.

In an extension of these previous experiments, additional experiments were conducted to determine the effect of storage at refrigerator temperature ($2^\circ$-$4^\circ$ C., i.e., $35^\circ$-$39^\circ$ F.). Six glasses were irradiated with a dose of $1.30 \times 10^5$ rep. Sixty minutes after irradiation, measurements were taken and the glasses were then stored in the refrigerator. Further measurements were made 6, 12, 24, 48, 96, 1280, and 2570 hours after the end of the irradiation, to examine fading behavior. Figure 2 shows the values obtained, expressed as relative percentages of the absorption coefficient one hour after irradiation (considered to represent 100%) and plotted as a function of the natural logarithm of the time of storage. The data for the glasses stored at room temperature are the same as those in Figure 2 previously reported (4) but include an added measurement at 4300 hours.
Differences between the two sets of glasses held at the two storage temperatures are evident in all the measurements made at the four wavelengths. These differences attain a maximum of about 10\% (in the case of the measurements at 4500 Å) after about three weeks but appear to approach zero after about four months of storage.

**Stability of Absorption Properties of Glass when Exposed to Light**

No separate experiments were performed to determine the stability of the absorption properties of the glass when exposed to light. It has been reported, however, that this glass is sensitive to light (7). In all the experiments reported herein the glasses were exposed as little as possible to light during handling, stored in envelopes, and the optical measurements were conducted in such a way as to reduce excessive exposure of the irradiated glasses to the light in the spectrophotometer.
Effect of Heat Treatment after Irradiation

Previous research by Schulman (1), the results of which were later confirmed by this laboratory (4), has indicated the value of short periods of heating after irradiation as a method of eliminating some of the unstable centers in the glasses and thus reducing appreciably the rate of fading during storage. It may be possible to apply heat for a definite, short period of time to stabilize the reading.

By means of a small precision furnace, glasses irradiated with a dose of $3.70 \times 10^5$ rep were heated, 60 minutes after irradiation, to temperatures of $130^\circ$ and $150^\circ$ C. Temperatures were measured by a thermocouple placed close to the glasses. Glasses were also heated to $100^\circ$ C. by insertion into boiling water. Figure 3 presents the absorbancy indexes at 3500, 4000, 4500, and 5000 Å observed (a) immediately after heating for 5, 10, 15, and 20 minutes at the different temperatures and (b) after 1, 2, 4, and 8 days of storage at room temperature. The data at each temperature indicate:

1. that the light absorption at the four wavelengths decreased with time and temperature of heating,
2. that the curves begin to flatten out after ten minutes of heating,
3. that there was little additional decrease in light absorption after about 15 or 20 minutes of heating at the three temperatures, and
4. that the fading at room temperature was reduced considerably after the heating process, decreasing from about 8% after eight days in the $100^\circ$ C. experiment to about 4% after eight days in the $150^\circ$ C. experiment.
Additional experiments in which glasses were heated to 175° C. indicated an additional decrease in absorption in the initial heating process, but the relative amount of fading after 8 days was not greatly decreased in comparison with the 150° C. experiment.

Figure 4 compares graphically data obtained with glasses heated at 100° C. after a dose of 1.30 x 10^7 rep and additional data obtained with glasses given a dose of 1.30 x 10^6 rep and also heated at 100° C. The percentage of fading appears to have been about the same at the two dose levels after 20 minutes of heating at 100° C. However, the percentage of fading that occurred in the 8-day interval following the heating was slightly greater in the glasses given a dose of 1.30 x 10^6 rep (5000 Å) than in those given a dose of 1.30 x 10^5 rep, even though the former glasses were heated for a total of 60 minutes rather than 20 minutes, as with the latter glasses.

These experiments indicate the usefulness of heating the glass to reduce the rate of fading after irradiation, although heating does not eliminate all fading in glass of this particular composition.

Calibration Curves Obtained with Heat Treatment

Because the application of short periods of heating considerably reduces the post-irradiation rate of fading, especially that observed in the first 24 hours, the desirability of obtaining calibration curves of the glass when irradiated and then heat treated becomes evident. Figure 5 presents calibration curves at 3500, 4000, 4500, and 5000 Å constructed from measurements of the optical density readings.

*The optical density readings in Figure 5 are normalized to correspond to glasses of 0.300 cm. thickness.
of glasses after irradiation at different doses (six glasses irradiated at each dose) from about $10^3$ rep to about $4 \times 10^6$ rep. The points shown are average values obtained when the glasses, 60 minutes after irradiation, were heated for 20 minutes at $100^\circ$ C. (in boiling water) and measured within 30 minutes after heating was completed. The use of $100^\circ$ C. is convenient, as this temperature is readily obtainable with boiling water. As has been shown in Figure 3, however, the use of higher temperatures is preferable to reduce the rate of post-heat fading.

Non-linearity of response of the glass to radiation became appreciable at doses above $3 \times 10^5$ rep, as shown by the curves at 4500 and 5000 Å. This characteristic of the glass parallels that of the non-heat-treated glass exposed to the same dose range (4). The considerable decrease in the slopes of the curves at these higher doses indicates that the accuracy in the use of the glass in this region is greatly reduced. The decrease in response does not preclude use of the glass after doses above $3 \times 10^5$ rep. However, it must be realized that good precision of experimental techniques and reproducibility of the glass characteristics become increasingly important in this region, to obtain accurate results. Furthermore, the doses corresponding to the broken portions of the curves (below an absorbancy index of about 0.1 cm.$^{-1}$) decrease in accuracy because of the decreased precision inherent in measuring optical density changes below 0.030. However, by use of the shorter wavelength (3500 Å) it is possible to measure down to as low as 2000 rep with reasonable accuracy.
Figure 6 shows calibration curves at 3500, 4000, 4500, and 5000 Å constructed from data obtained by irradiating glasses (six at each dose level) with doses ranging from about $1.3 \times 10^3$ rep to $7 \times 10^6$ rep. Sixty minutes after irradiation, these glasses were heated for 10 minutes at $130^\circ$ C. An extra minute was allowed for the glasses to reach the desired temperature after insertion into the oven. Following irradiation, measurements were taken before heating, after heating (within 30 minutes), and after 8 days of storage at room temperature. Figure 6 shows the three sets of measurements.

As was observed in Figure 5, the slopes of the curves decrease appreciably above a dose of about $3 \times 10^5$ rep, and at the lower doses the broken portions of the curves (corresponding to optical density below about 0.1 cm.$^{-1}$) indicate the decrease in accuracy caused by small changes in optical density. The percentage of fading, both during the heating period and during the 8-day storage period, decreased significantly with the lower doses. In fact, fading at the four wavelengths after the heat treatment became almost negligible when the irradiation doses were below $4 \times 10^5$ rep.
Details of Fading Behavior of Glasses
Given Heat Treatment after Different Doses

Figures 7 to 12* show details of the decrease in absorbancy index at 3500, 4000, 4500, and 5000 Å observed after the glasses received doses of $1.21 \times 10^5$, $1.30 \times 10^5$, $3.66 \times 10^5$, $1.23 \times 10^6$, and $3.55 \times 10^6$ rep, respectively. The measurements shown were taken one hour after irradiation, after 10 minutes of heating at 1300 °C. (with the exception of those in Figure 8, where heat treatment was 5 minutes at 100 °C.) and at various periods up to 8 days of storage at room temperature after the heat treatment. Figure 7, 8, 9, and 10 also show data obtained from glasses irradiated or stored at different temperatures; these results are discussed elsewhere in this report.

It is evident that a fairly good approximation to account for fading for the first 8 days after irradiation is given by the formula:

$$A.I. = a \ln t + b$$

where A.I. is the absorbancy index observed at a time t after irradiation, and a and b are functions of the dose and wavelength but are constant for a given dose and a given wavelength.

These results show the large reduction in fading to be obtained if the heat treatment is applied after irradiation. In comparing Figures 2 and 7, for example, it is seen that the application of heat after a dose in the $10^5$ rep range reduces the fading of the initial absorption from about 25% (without heat) to about 6% (with heat) during an 8 day period (5000 Å).

*Points on these figures are displaced slightly on the horizontal coordinates to show them on the figures when they are coincident in the data.
Effect of Heating Glasses After Longer Periods of Time Following Irradiation

Experiments employing heat treatment described thus far in this report utilized the heat treatment between 1 and 1-1/2 hours after the irradiation. Application of this heat treatment in practice may not be convenient if it is necessary to apply it at a definite time after irradiation. A series of experiments was, therefore, conducted to study the behavior of the glass when it was heated after different time intervals following irradiation.

Twenty-one glasses were irradiated with a dose of 3.74 x 10^5 rep. The glasses were separated into seven groups of three each, and all were measured one hour after the irradiation. Over a period of 8 days, each of six groups was given the heat treatment for 10 minutes at 130° C., at different time intervals following irradiation, including 0.5 hours, 1 day, 2 days, 4 days, and 8 days, respectively. The seventh group was allowed to fade at room temperature without heat treatment. All the glasses were measured at various times after the heat treatment up to the eighth day following irradiation, including measurements immediately following the heat treatment.

Figure 13 presents the absorbancy index values, obtained as a function of time, at 3500, 4000, 4500, and 5000 Å, and includes previous data where heat treatment was made one hour after irradiation. It is evident that the absorbancy indexes immediately following the heat treatment drop to values approximately linear (broken line curve) with respect to the logarithm of the time, for all the time intervals between irradiation and heating (from 1 hour to 8 days) that were tested. However,
the absorbancy indexes of a *given group* of glasses *subsequent* to the initial measurement after the heat treatment have, in general, a different linear relationship with respect to time.

Fading following heat treatment proceeds at a lower rate than that shown by the curve based on measurements taken immediately following heat treatment applied at different intervals. This would seem to suggest that the heat treatment not only eliminates some of the more unstable centers but stabilizes some of the remaining centers so as to reduce their probability of fading. This is dramatically illustrated in the 3500 Å measurements, which show after 8 days that the glass heat-treated one hour after irradiation had an absorbancy index about 5% higher than the non-heat-treated glass.*

These results indicate that if heat treatment is to be applied at different time intervals following irradiation, one should not correct for the time interval by utilizing fading data following heat treatment one hour after irradiation (such as given in Figures 7 to 12). Rather, it would be preferable to employ actual curves obtained by heating glasses after different time intervals. These curves appear to be fairly good linear plots with the logarithm of the time, so that measurements after two widely spaced time intervals such as one hour and one week will yield data sufficient for fair approximations within this range.

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*A portion of the higher value is likely due to the higher initial reading (one hour after irradiation). However, the same phenomenon is observed at 4500 and 5000 Å where the initial readings are 'not' higher.*
Electron Beam Dosimetry

Work by this laboratory reported in the paper by Schulman, Klick, and Rabin (3) has shown the feasibility of using the silver-activated phosphate glass for determination of doses of 3 m.e.v. electron beams from a Van de Graaff accelerator. Since the intensity of ionization falls off much more rapidly for electrons than for gamma rays after they enter matter (the effective range for electrons is about 0.5 cm. for each m.e.v. of energy in a substance of unit density), it is of importance to determine the effect of placement of the glass when it is used as a dosimeter for electron beams, and the possible effect of variation of ionization density in the glass itself because of its appreciable thickness compared with the maximum range of the electron beam.

Use of a previous calibration of the silver-activated phosphate glass dosimeter is necessary for interpretation of the changes in absorption properties of the glasses after receiving doses of high energy electrons. The calibration of the glass by Cobalt-60 source, shown in Figures 5 and 6, can be used for this purpose. However, the relative times of irradiation must be taken into account. For example, the Van de Graaff accelerator delivers a million rep dose in about 10 seconds whereas the Cobalt-60 source, used for calibration, delivers the same dose of gamma rays in about 12 hours. The difference in fading during the two different irradiations must be taken into account. This has been done
in the following experiment by exposing more than one set of glasses to the same dose of electrons and measuring them at two different time intervals after irradiation.

Two groups consisting each of seven glasses of approximately 0.12 cm. thickness were stacked one on top of another, and the two piles were secured with Scotch tape. They were then irradiated with the surfaces of the glasses perpendicular to the direction of the beam. The energy of the electrons was 3 m.e.v., and the current of the beam was adjusted for both groups to deliver a dose of \(10^6\) rep in the region of maximum ionization density (at an average dose rate of \(3.6 \times 10^6\) rep/min.). After irradiation, the glasses were given heat treatment of 10 minutes at 130° C., group "B" receiving it one hour after irradiation and group "C" receiving it one day after irradiation. Measurements were taken of both groups of glasses immediately following heat treatment. Doses were determined from the calibration chart constructed from Cobalt-60 exposures (Figure 6), by using the values obtained immediately after heat treatment applied one hour after irradiation. Depth-dose curves were drawn from apparent doses received by the top six glasses in each group. The seventh and bottom glass in each group apparently was beyond the range of the beam, as it received no detectable dose.

The abscissae in Figure 14 are in terms of absorber thickness, obtained by multiplying the distance of penetration by the density of the material, so that materials of different density may be compared. The ionization density
curves for the glass show the characteristic rise to a maximum from its initial entrance value. After the maximum is reached, the curves fall off rapidly to a value close to zero. The "true" curve for glass should then lie between curves B and C. This is because the 1 hour and 1 day waiting periods for curves B and C are shorter and longer respectively than the irradiation times for corresponding doses involved in the Cobalt-60 calibrations.

Superimposed on Figure 14 is an ionization density curve at 3 m.e.v. energy obtained for aluminum (11), with the maximum at 10^6 rep. The three curves are similar in shape, and the maxima appear at the same absorber thickness. The maximum range in the aluminum is about 0.2 gm./cm. greater than in the glass. Furthermore, the ionization density in glass as determined by both groups of glasses remains appreciably lower than that in the aluminum shortly after the maximum values are exceeded. The explanation for these differences is not known, but the differences are likely caused by a difference in the scattering properties of the aluminum and glass.

These experiments illustrate the applicability of this glass for electron beam dosimetry and stress the importance of placement and geometry of the dosimeter system in interpreting correctly the dose received by the material being irradiated.
Energy and Dose Rate Dependence

A dosimeter that can respond with constant sensitivity to equal doses of radiations of different energies or to such doses applied at different rates is highly desirable. Studies of the dependence of the dosimeter on the energy level of the radiations and the dose rate are, therefore, of great interest.

Schulman, Ginther, and Klick (7) have reported the luminescent output from the silver-activated glass as a function of equal roentgen doses of various effective energies. They have found that the output remains fairly constant from about 1.2 m.e.v. (Cobalt-60 gamma rays) down to about 125 k.e.v. (X-rays), increases at 65 k.e.v. to a value about eighteen times that at 1.2 m.e.v., and then decreases rather sharply at 50 k.e.v. to a value about seven and one-half times that at 1.2 m.e.v. (Figure 15 is reproduced from reference (7).)

No similar energy dependence study of the optical absorption properties of the glass has yet been made. Schulman (1) feels that the absorption properties and the luminescent properties as functions of energy are similar. The energy dependence of the luminescence when the glass is used as a personnel dosimeter has been compensated to a certain extent by application of special shielding. It appears possible that the same techniques may be applied when the absorption properties of the glass are used in dosimetry at high energy levels. The relationship between
the energy level of ionizing radiations and the absorption coefficients of the silver-activated phosphate glass has not yet been studied by us.

Schulman, Klick, and Rabin (3) have found no significant differences in the sensitivity of the glass at dose rates of 10,000 and 730,000 rep per hour. They also quote experiments at MTR that show no differences in results at dose rates in excess of $10^7$ rep per hour.

The experiments described herein in relation to electron beam dosimetry support the viewpoint that dose rate has no direct effect upon the response of the glass since the Van de Graaff and Cobalt-60 sources had the widely varying dose rates of 3.6 x $10^6$ rep/min. and 1.5 x $10^3$ rep per minute (a ratio of about 2,000:1).
Determination of Precision Limits

Because of the large number of glasses whose optical densities were measured under identical conditions in this investigation, it has been possible to compile sufficient data for statistical analysis of the reproducibility characteristics of #9751 glass. Table I presents the optical density measurements, at 5500, 4000, 4500, and 5000 Å, of 48 glasses used in experiments extending over a period of about two months. These glasses all originated from the same lot supplied by the manufacturer, and all received a dose in the #4 position of the Cobalt-60 source (10) corresponding to an exposure for 90 minutes. All measurements of optical density were made within 60 ± 5 minutes after the end of irradiation.

Because of the decrease (about 2%) in the dose rate of the source over a 2-month period, numerical corrections were applied to the original optical density readings based on the known decay rate of Cobalt-60. Therefore, the readings as recorded in Table I have been normalized to the same day (November 10, 1954) with respect to the dose received in 90 minutes. Small numerical corrections were also applied to the readings to correct for differences in thickness of the individual glasses (within ± 1%), so that the readings have also been normalized for a constant thickness of 0.314 cm.

Measurements on the six individual glasses irradiated in the ampoule during each loading of the #4 position in the source have demonstrated differences (4 to 7%) in the
dose rates received by the individual glasses. These six glass positions in the ampoule have been designated by letters from A to F, proceeding from the bottom to the top of the ampoule. The data in Table I have been accordingly segregated so that the readings for any given position in the ampoule can be compared. This segregation eliminates variations in readings that might arise from actual differences in dose because of variations in positions of glasses in the ampoule.

From the data in Table I, the arithmetic mean and the standard deviation of the optical density measurements on each set of glasses irradiated in a different position in the ampoule have been calculated for the different wavelengths and are shown in Table XII. To utilize all the data in a determination of the statistical limits of error, the standard deviations of the data for the different positions at a given wavelength can be normalized to the mean value obtained for the six positions. Table XII also shows these normalized standard deviations. Based on all the data for each wavelength, standard deviations are then calculated according to the formula:

$$\sigma_{\text{total}} = \sqrt{\left(\sigma^2_A + \sigma^2_B + \ldots\right)/(n-1)/n-1}$$

*The average of these six measurements of dose rate is usually employed when comparisons are made with doses measured by physical or chemical means, since these previously used physical and chemical dosimeters occupy the same total volume as the six glasses.*
where \( \sigma_A, \sigma_B, ... \) are the normalized standard deviations for the different positions A to F, \( n \) is the number of measurements in each position, and \( N \) is the total number of measurements for all the positions.

Table III summarizes, for each wavelength and for a single glass irradiated in the #4 position of the source, the probable percentage limits of error in the optical density measurements calculated at different probability levels, namely, 68% (\( \pm 0 \)), 99% (\( \pm 2.576 \sigma \)), and 99.7% (\( \pm 3 \sigma \)). If the mean of three replicate glasses is taken, the limits of error are decreased by the factor \( 1/\sqrt{3} \). These limits are also shown in Table III.

It may be concluded from this analysis that the limits of error in optical density measurements on individual glasses from the same manufactured lot given equal doses (about \( 10^5 \) rep) and measured under identical conditions will, on the 99.73% probability level, range from \( \pm 3.8\% \) (at 3500 Å) to \( \pm 6.3\% \) (at 5000 Å). On a 99% probability level, the error limits will range from \( \pm 3.3\% \) (at 3500 Å) to \( \pm 5.4\% \) (at 5000 Å). When the mean readings for three replicate glasses are used, these ranges of error are reduced by a factor of \( 1/\sqrt{3} \).

The cause of the increase in the error limits between the wavelengths of 3500 and 5000 Å is not known at the present time. A portion of the increase, however, may be attributed to an increase in reading error at the higher wavelengths, because of numerically smaller absorption values.

Optical density measurements on nineteen non-irradiated
glasses from the same lot were also analyzed statistically. The following ranges of values were calculated at a 99.73% probability level:

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Optical density (glasses 0.505 mm. thick)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500 Å</td>
<td>0.103 ± 0.011</td>
</tr>
<tr>
<td>4000 Å</td>
<td>0.343 ± 0.007</td>
</tr>
<tr>
<td>4500 Å</td>
<td>0.743 ± 0.003</td>
</tr>
<tr>
<td>5000 Å</td>
<td>0.343 ± 0.006</td>
</tr>
</tbody>
</table>

It may be concluded that no appreciable increase in precision is obtained if individual glasses are measured before irradiation with doses of \(10^6\) rads or greater. The mean values of a few non-irradiated glasses from the same lot will suffice for the pre-irradiation absorption corrections. However, at the lower dose levels, where the pre-irradiation readings represent a larger percentage of the irradiation readings, individual pre-irradiation measurements are advisable.
Fading Corrections on Glass Measurements

The experiments described herein have demonstrated that fading of the glass occurs after irradiation, whether the glass is heated or not (although the extent of fading is reduced appreciably by the heat treatment). The possibility of applying corrections to the glass measurements to compensate for fading is evident if a relationship between the rate of fading and the time after irradiation can be developed. Figures 7 to 12 show that fading proceeds approximately in accordance with an equation of the type:

\[ \text{A.I.} = (a \times \log t) + b \]

where A.I. and t are the absorbancy index and time after irradiation, respectively, and a and b are constants for a given dose and wavelength.

A simple method for utilizing this logarithmic relationship graphically is illustrated in Figure 1. In the lower portion of Figure 6 is a logarithmic time scale of arbitrary size extending from 0 to 8 days. The change of the optical density (fading change) between 0 and 8 days after irradiation (area between the curve for readings after 10 minutes of heating and the curve for readings after 8 days of storage) can be estimated from the fractional portion of the time scale corresponding to the time elapsed between irradiation and measurement. Linear interpolation of the logarithmic scale is sufficiently accurate at small time intervals.

An example can best illustrate this use of the scale. Assume that an optical density of 1.00 (3 mm. glass) is
obtained at 4500 Å, three days after the irradiation (glass was heated, 60 minutes after irradiation, for 10 minutes at 130° C.). The time scale shows that 3 days represents about four-fifths of the distance to 8 days. An optical density reading of 1.00 intercepts the fading area between the two curves at doses corresponding to the dose range of 4.70 x 10^5 to 5.30 x 10^5 rep. However, it intercepts the fading area four-fifths of the vertical distance between the fading curves, at about 5.15 x 10^5 rep. The total dose is, therefore, 5.15 x 10^5 rep.

Use of Figure 6 for a calibration curve when other sources or dose rates are used must take into account fading during irradiation, if the exposure is for an appreciable period of time. The extent of fading that takes place during irradiation is not known. However, the use of the heat treatment after irradiation will reduce appreciably the effect of the amount of time that elapses after irradiation, since it apparently eliminates the centers that are most unstable and that have a high probability of fading in the initial periods. For greatest accuracy, the calibration curves should be constructed so that the doses are delivered in time periods comparable with those to be encountered during future use.
Erasure and Reuse of Exposed Glasses
by Application of High Temperature

Preliminary experiments showed that exposed glasses may be "erased" (i.e., removal of the coloration caused by irradiation) by application of high temperatures in the region of 400° - 500° C. Further experiments were then conducted to determine whether the sensitivity of the glass remains constant with repeated erasures and whether the number of erasures possible on a piece of glass is limited.

Fifteen minutes of exposure to a temperature of 450° C. was found sufficient to erase these glasses after exposure to doses up to $5 \times 10^6$ rep. However, after repeated erasures, the initial absorptions at 3500 and 4000 Å were observed to increase slightly but significantly over the absorption of the non-exposed glass not previously erased. These absorptions could not be reduced to the original values by prolonged heating of the glass. It became necessary, therefore, to measure the pre-exposure absorption in these erasure studies and subtract the values from the post-exposure values.

Figure 16 shows the arrangement for erasing glasses. A Coors porcelain pipette rest (glazed except bottom) with thermocouple attached was allowed to come to temperature in the oven. With the use of tongs, the clean glasses were then laid on the curved surfaces of the rest so that they were supported only on their edges, in order to avoid damage to the glass surfaces. At the end of the period at high temperature, the porcelain rest and glasses were removed without disturbing the glasses, and all were allowed to cool on an
asbestos pad outside the oven. This arrangement avoids cracking of the glasses by sudden temperature changes when they are removed from the high-temperature region.

Table IV shows the results obtained after five successive exposure-erasure cycles, where the dose given in each exposure was $1.24 \times 10^5$ rep and the glasses were measured one hour after irradiation. The observed absorption values at 3500, 4000, 4500, and 5000 Å are close to those predicted from the calibration chart but have a larger dispersion than expected from the studies on reproducibility. However, this greater dispersion is not certain since a much greater number of measurements would be needed for a valid statistical analysis. It is evident, however, that there was no definite increase or decrease in sensitivity of the glasses with repeated exposure-erasure cycles.

A series of ten successive exposure-erasure cycles was conducted in the high dose region, doses being chosen randomly in the region of $2.5 \times 10^5$ to $5 \times 10^6$ rep. The values obtained at 4500 and 5000 Å are plotted on curves determined for non-erased glass from the same lot (Figure 17). The points on the curves are marked to show the chronological order of the exposure-erasure cycle. Again it is evident that the glass behavior remained essentially constant even after ten successive erasure-exposure cycles. Furthermore, the fading behavior observed in cycles 8, 9, and 10 remained unchanged from that of the original glass.

The slight deviation in the measurements of the erased glasses from those of the non-erased glasses in the higher
dose region cannot be said to be significant, as the non-erased measurements are not sufficient in number for statistical comparison. As in the lower dose erasure studies, it may be said, however, that there was no consistent gain or loss of sensitivity of the glass with repeated erasure cycles. Hence there is a strong possibility that these glasses can be re-used after erasing at high temperature. This re-use will add considerably to the value of the glass as a dosimeter.
Effect of Freezing Temperatures during Irradiation

The application of ionizing radiations to biological materials for purposes of sterilization frequently produces undesirable chemical and physical changes. It has been found in certain cases that freezing the material can inhibit these changes markedly. The question then arises of what happens to the silver-activated phosphate glass dosimeter when it is used in a material that is frozen while being irradiated.

Figure 8 shows the results of an early experiment where a group of glasses were frozen in water during irradiation (1.30 x 10^5 rep), measured after irradiation, and then heated for 5 minutes at 100°C. Dry ice was used as the refrigerant. The temperature was below -20°C and is believed to have been in the range -20°C to -40°C. Following the heat treatment, the glasses were measured, stored at room temperature, and subsequently measured again during a period of 8 days. These results are compared in Figure 8 with results obtained with glasses treated identically but irradiated at room temperature. No differences were discernible between the two groups of glasses.

Figure 9 shows the results of a comparable experiment where the glasses were given a dose of 3.66 x 10^5 rep, heated for 10 minutes at 130°C, and stored at room temperature. At this higher dose level, significant differences are apparent, the glasses irradiated at the freezing temperature showing consistently lower readings. Therefore, a genuine effect
of temperature of irradiation is probable where the color
center formation is favored by the higher temperature,
since an effect of fading during the irradiation would favor
lower readings for the glasses held at the higher tempera-
tures.

The conclusion is that if the silver-activated phosphate
glass dosimeter is to be used in frozen materials, a
correction factor should be applied to calibration charts
constructed from results of irradiation at room temperature,
or that special calibration charts should be constructed
from data obtained from glasses irradiated at freezing
temperatures.
Use of Heat Treatment
to Minimize Effect of Storage Temperature

The previous report from this laboratory (4) on glass dosimeters has shown that fading without previous heat treatment is dependent on the storage temperature. However, between 20° and 37° C. no such dependence was observed except at the wavelength of 4000 Å. These previously reported experiments were based on an irradiation exposure of about $10^5$ rep.

Figure 7 indicates the results obtained in an extension of the earlier experiments. In the more recent experiments the glasses, after receiving an irradiation dose of about $10^5$ rep, were given heat treatment for 10 minutes at 130° C. and were stored at 42° C. Comparison of the results obtained after storage at room temperature and at 42° C. indicated no dependence of fading on storage temperature.

Figure 10 shows the data obtained when three groups of glasses, each group consisting of three glasses, were irradiated with $3.66 \times 10^5$ rep. One hour after irradiation the glasses were measured and then given the heat treatment for 10 minutes at 130° C. They were measured again after heat and thereafter were stored in a refrigerator (2°-4° C.), at room temperature (22°-26° C.), and in an oven maintained at 43° C. Measurements were taken during an 8-day period on the three groups held at the different temperatures.

Figure 10 indicates that there was no significant difference between any of the different groups held at different temperatures (except at the eight-day measurement when a small lowering in readings for the glasses held at
43° C. was detected) when the dose was $3.66 \times 10^5$ rep and measurements were taken during an 8-day period. It may be concluded that an additional value in heat treatment after irradiation lies in the considerable decrease of the dependence upon storage temperature of readings made a considerable period of time after irradiation. The range of values encountered at "room temperature" is certainly adequate to insure constant fading properties after heat treatment.
SUMMARY

On the basis of results of experiments given in this report and in the previous report from this laboratory (4), and on the basis of results by other investigators, the following summary may be made of the behavior and use of silver-activated phosphate glass (Corning #9761) or other glasses with similar composition.

Selection and Treatment of Glasses
Prior to Irradiation

Glasses should be inspected before use, to select those free from obvious flaws, cracks, and surface abrasions. It may be argued that these defects in the glass are compensated for in the correction for the non-irradiated glass. However, in cases where the light beam in the reading instrument is narrow relative to the glass area, the non-irradiated glass will have a reading dependent upon the interception of the light beam by the defect. Therefore, the non-irradiated glass reading will be dependent upon the orientation of the glass in the holder. This is an inconvenient restriction upon reading of the glass.

Glasses should be carefully wiped with special lens paper before each measurement, to clean off fingerprints, condensed water vapor, and other contamination that might increase the readings. For best results glasses should be handled with tweezers or grasped by the edges between thumb and index finger.

Glasses can be numbered or coded on their edges by means of a soft lead pencil.
Thickness should be measured with a micrometer, and glasses separated into thickness ranges if this has not been done previously. This separation increases the ease of calculation in the determination of doses.

Irradiation of Glasses

Because of the relative chemical inertness and insolubility of the glasses, their use need not be restricted to any particular position in the object being irradiated, except for the following considerations.

The most effective use of a dosimeter results when the geometry and absorber characteristic approximate most closely those that prevailed in calibration of the dosimeters. This is especially important for the glasses, because their optical properties are greatly affected by the energy of ionizing radiations below 100 k.e.v. The safe situation is to avoid arrangements in calibration and routine use where scattered radiation of degraded energy might have an important effect. However, if scattered radiation cannot be avoided, the glasses should be calibrated under geometrical and absorber conditions identical with those encountered in routine measurements.

In the case of X-rays or gamma rays of energies likely to be encountered in sterilization processes, the placement of the dosimeter in relation to the radiation beam (e.g., radiation beam normal to face or normal to edge) is not of great importance, because the absorption of the incident beam in the glass is not appreciable. However, where use is made of cathode rays or radiation the ionization intensity of which
falls off rapidly in substances, the dose registered by the dosimeter will depend upon its placement relative to the beam. As a matter of fact, it is advisable to use thin glasses (1 mm. or less) for cathode rays, to avoid great variation in the dose within the glass itself. The placement of the glass relative to the beam will require careful examination of geometry and absorber characteristics in each application.

For special applications such as field mapping, smaller glasses can be used, and there seems to be no reason why these cannot be prepared in any shape and size desired.

**Measurement of Optical Properties of Glasses**

Optical measurements of each of the glasses before irradiation are not necessary, since it has been found that absorption coefficients of non-irradiated glasses in the same lot do not deviate appreciably. However, if highest precision is desired, especially for doses where low optical density readings are involved, individual glasses should be measured before the irradiation.

The Beckman spectrophotometer, Model DU, can conveniently handle three glasses at one loading, in addition to a provision for a blank measurement. This can be accomplished by use of a special holder with four matched apertures. If convenient, precision is increased by using three replicate glasses for each dose measurement. These three glasses can be measured in a period of time only slightly longer than that required to measure one glass, since readings will be in the same range and the spectrophotometer controls need not be reset for the individual glasses.
For glasses of 3-mm. thickness, the effective measuring range at 3500 Å extends from about $10^3$ to $10^5$ rep, whereas at 5000 Å it extends from about $10^4$ to above $10^7$ rep. Measurements corresponding to doses above $10^6$ rep can be obtained on the Model DU spectrophotometer at both 4500 Å and 5000 Å. These ranges can be extended by use of a photomultiplier attachment. However, at these higher dose levels the sensitivity of the glass to radiation dose decreases considerably because of the saturation of the glass that occurs at these higher doses. Glasses of different thicknesses can also be used in changing the range or precision of measurement.

Other instruments than the Beckman Model DU spectrophotometer can profitably be employed for measurement of these glasses. Although the DU Model has been used for these particular experiments, a simpler type of instrument employing filters rather than a monochromator can be used to measure optical properties of the glass. Choice of an instrument should be dictated by degree of precision and versatility desired.

**Time of Measurement and Heat Treatment**

Because of the tendency of the glass to exhibit fading after irradiation, certain procedures must be observed regarding the time after irradiation when the measurement is made. In cases where the glasses are not heat-treated, the interval of time between irradiation and measurement should be long compared with the period of time required for irradi-
ation. The object is to minimize the influence of fading that might occur during irradiation and thus eliminate an auxiliary effect dependent on dose or dose rate.*

Measurements made within one hour after irradiation should be avoided, as the rate of fading is pronounced during this period and, although the fading characteristics during this hour may be accurately known, it is usually difficult to make a measurement at an exact time, especially when measurements are to be made at several wavelengths.

The percentage rate of fading after irradiation appears to be slightly dependent upon dose. Correction can be made for this by applying to an average rate of fading a factor based on the approximate dose received or by use of a calibration curve such as shown in Figure 6, where extent of fading has been determined at different doses.

The necessity of waiting a long time after irradiation before measurement of the glass can be avoided by heating the glass for a short period after irradiation at a temperature in the region of $100^\circ$ to $150^\circ$ C. This appears to eliminate the unstable centers that ordinarily tend to disappear within a relatively short time after being formed, either during irradiation or shortly thereafter.

After heating has continued for about 10 minutes, the extent of fading caused by the heating is not critically dependent upon length of heating. However, increasing the temperature will increase the extent of fading and also decrease the subsequent rate of fading at room temperature.

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*The dose rate effect is actually an indirect one. Since doses delivered at high dose rate involve a shorter time of irradiation, less fading will occur during the irradiation than if the same dose were delivered at a low dose rate.
Heating the glasses in boiling water (100° C.) is convenient because it is not necessary to have a precision oven on hand that has been previously brought up to temperature. Moreover, there is no uncertainty in the time required for the glass to reach 100° C. and no great fluctuation in the temperature of the water when the glass is introduced, as is the case in the temperature of an oven when the door is opened to insert the glass.

Precautions should be taken to avoid cracking or breaking of the glasses by preventing motion of the glasses in the boiling water.

Heating the glasses at temperatures higher than 100° C. requires the use of a method for accurately maintaining the higher temperature, such as a precision oven. There is also the possibility of using a constantly boiling liquid to provide a constant temperature. Subject to the limitations just discussed, raising the temperature above 100° C. has an advantage in that the rate of fading during storage is reduced even further. A 10-minute period of heating at 130° C. at a time 60 minutes after irradiation has been found to give desirable results. Raising the temperature to 150° C. and higher will reduce the rate of fading at room temperature even further. However, flattening of the calibration curves will increase at these higher temperatures and reduce accuracy of measurement in the mega rep dose region.
Temperature of Storage

The rate of fading of the glass during storage is dependent on the temperature of the environment, if the glass is not heat-treated. If the glass is heat-treated this dependence is appreciably reduced. However, the temperature dependence is not critical within the range usually classified as room temperature, and good results can be obtained with glasses stored in the laboratory without benefit of a constant temperature device, whether the glass is heat-treated or not.

Appreciable changes in fading rate will occur if the glasses are not heat-treated and are stored at more extreme temperatures, as in a refrigerator or in high-temperature incubators. Storage in a high-temperature incubator (e.g., 55°C) will increase the fading to such a degree as to make measurements meaningless unless the fading has been calibrated accurately with respect to time at the particular temperature.

Storage in a refrigerator reduces fading significantly. Glasses irradiated with $10^5$ rep and heat-treated for 10 minutes at 130°C show a fading of only 3% after 8 days in a refrigerator. A combination of heat treatment and storage of the glass at refrigerator temperature, therefore, will minimize loss in precision caused by fading effects and avoid the necessity of precise timing in measurement.

Calculations

It has been found that optical measurements of the glasses are conveniently obtained as optical densities. If the glasses have been previously segregated into groups having definite thicknesses, the optical densities of replicate dosimeter glasses can be averaged and divided by the thickness to obtain
the average absorbency index. The difference between this value and the absorbency index of the non-irradiated glass (the latter obtained from the same glasses or other glasses in the lot) is taken as a measure of the dose. This value is independent of the thickness of the glass and may be compared with absorbency index values obtained with other glasses of different thicknesses. Absorption coefficients may be obtained by multiplying absorbency index values by the factor 2.3.

Alternatively, calibration figures may be made directly in terms of optical density vs. dose where the optical density is for a definite thickness of glass. This procedure is most useful when a single thickness of glass is used all the time.

Recommended Procedure for Use of #9761 Glass

Optical measurements of the glasses can be made on the Beckman spectrophotometer, Model DU, or other colorimeter or densitometer instruments by referring optical density measurements of the glass to an equivalent air path. The choice of the thickness of the glass and the choice of the wavelengths used for measurement depend upon the irradiation dose to be measured and the desired precision of measurement.

Experimental results have shown that for a glass 3 mm. thick, measurements at 3500 Å give highest sensitivity to dose and are possible in the dose range from $10^3$ to $10^5$ rep. Measurements at 4000 Å will extend this range up to about $2 \times 10^5$ rep. with a slight decrease in sensitivity. Measurements corresponding to doses above $2 \times 10^5$ rep. usually have
to be taken at the longer wavelengths of 4500 and 5000 Å. Measurements corresponding to lower doses can also be made at these higher wavelengths, but with corresponding loss in sensitivity to dose.

The following procedure may be employed in use of the glasses:

1) Inspect glasses and select only those free from obvious flaws, cracks, and surface abrasions.

2) Measure the glasses with a micrometer and separate into groups of equal thickness within a range of 1%, if this has not already been done. Code the glasses by marking on the edge with a soft lead pencil.

3) If doses are to exceed $10^5$ rep, pre-irradiation absorption measurements need not be made for all individual glasses. Mean values of pre-irradiation absorption measurements of three glasses from the same lot can be used, or a piece of non-irradiated glass may be used as the 100% reference in the optical density measurements. This latter method eliminates need for correction of the optical density measurements of irradiated glasses but is regarded as lower in precision.

4) Insert glasses at points of interest in material to be irradiated. For cathode rays or other radiation where depth-dose variation is appreciable, the glasses should be oriented with respect to the source of radiation so that the glass faces are normal to the direction of the radiation. Otherwise orientation is of no importance.
5) Sixty minutes after irradiation, heat the glasses for 10 minutes at 130°C. If it is inconvenient to heat glasses 60 minutes after irradiation, heating may be done at different time intervals following irradiation. In this case a calibration chart (see step #8) should be used where at least two measurements have been taken covering the desired time interval. Heating should be done immediately before each measurement, and a log (t) interpolation can be made of this time interval. Fading data, as in Figure 6, should not be used in this procedure, as the measurements are all based on heating one hour after irradiation. Heating may also be done in boiling water (100°C.) for 20 minutes, if no suitable oven is available. The decrease in absorption values for 100°C. is slightly different from that at 130°C., and an appropriate calibration figure should accordingly be used.

6) Absorption measurements of the irradiated glasses may be made at different times following the irradiation. Avoid exposure of the glasses to light or extremes in temperature. Record time elapsed between irradiation and measurement.

7) Subtract values for optical densities of the glasses before irradiation from the values obtained after irradiation.

8) Determine doses from a calibration chart, such as Figure 6. Correct for fading, based on time elapsed between irradiation and measurement.
CONCLUSIONS

In the opinion of the authors, the silver-activated phosphate glass dosimeter holds great promise of being a simple, inexpensive, versatile dosimeter for routine use.

The properties of inertness, insolubility, and rigidity possessed a priori by glass are highly desirable. The additional properties possessed by the silver-activated phosphate glass, namely, good sensitivity to radiation, ease of measurement, permanence of reading, and possible re-use after high temperature erasure, add considerably to its value as a dosimeter.

The restrictions in the use of the silver-activated phosphate glass dosimeter, such as avoidance of extreme temperatures and excessive exposure to light, are not difficult to fulfill in practice.

The properties of fading during exposure and during storage after exposure, and the energy dependence at energies below 200 k.e.v. are disadvantages, but these apparently can be minimized by various techniques and do not detract appreciably from the value of the dosimeter.

There is an appreciable decrease in sensitivity of the silver-activated glass dosimeter as the million rep dose is exceeded. This decreased sensitivity does not preclude use of the dosimeter in the megarep region. It is necessary, however, to apply careful experimental techniques to attain
the precision in the megarep region that is readily available with lower doses. The degree of precision desired is variable with different needs and the latter should dictate the experimental methods used in the high dose region.

The merits of glass dosimetry, both present and potential, are so attractive that continuous research should be conducted on the post-irradiation properties of the glass with respect to the effects of variations in the different components of the glass and the proportions of these components. Such research is desirable for the development of glass dosimetry to its fullest potentiality.
TABLE I

Optical Density Measurements* of Glasses in Different
Positions in Ampoule Irradiated in
#4 Position of Cobalt-60 Source

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*Measurements have been normalized to a glass thickness of 0.314 cm., to a dose received in 90 minutes on the same date (November 10, 1954).
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<tr>
<th>Glass No.</th>
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*Measurements have been normalized to a glass thickness of 0.314 cm., to a dose received in 90 minutes on the same date (November 10, 1954).*
### TABLE II

**Arithmetic Means (\(\bar{X}\)) and Standard Deviations (\(\sigma\)) of Optical Density Data in Table I**

<table>
<thead>
<tr>
<th>Position in ampoule</th>
<th>3500 (\bar{X})</th>
<th>(\sigma)</th>
<th>4000 (\bar{X})</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\bar{X})</td>
<td>(\sigma)</td>
<td>(\bar{X})</td>
<td>(\sigma)</td>
</tr>
<tr>
<td>A</td>
<td>1.907</td>
<td>0.0354</td>
<td>1.180</td>
<td>0.0201</td>
</tr>
<tr>
<td></td>
<td>(0.0367)</td>
<td></td>
<td>(0.0208)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.939</td>
<td>0.0398</td>
<td>1.199</td>
<td>0.0204</td>
</tr>
<tr>
<td></td>
<td>(0.0304)</td>
<td></td>
<td>(0.0208)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1.970</td>
<td>0.0268</td>
<td>1.217</td>
<td>0.0234</td>
</tr>
<tr>
<td></td>
<td>(0.0269)</td>
<td></td>
<td>(0.0235)</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.992</td>
<td>0.0188</td>
<td>1.229</td>
<td>0.0168</td>
</tr>
<tr>
<td></td>
<td>(0.0187)</td>
<td></td>
<td>(0.0167)</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2.026</td>
<td>0.0256</td>
<td>1.253</td>
<td>0.0233</td>
</tr>
<tr>
<td></td>
<td>(0.0250)</td>
<td></td>
<td>(0.0227)</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>2.037</td>
<td>0.0206</td>
<td>1.250</td>
<td>0.0211</td>
</tr>
<tr>
<td></td>
<td>(0.0200)</td>
<td></td>
<td>(0.0206)</td>
<td></td>
</tr>
<tr>
<td>Mean value of all positions in ampoule</td>
<td>1.979</td>
<td>1.221</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Continued)

The standard deviation shown in parentheses is the original value normalized to correspond to the mean optical density for all the positions.
TABLE II (cont'd.)

Arithmetic Means ($\bar{X}$) and Standard Deviations ($\sigma$) of Optical Density Data in Table I

<table>
<thead>
<tr>
<th>Position in ampoule</th>
<th>$4500 \AA$</th>
<th></th>
<th></th>
<th>$5000 \AA$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{X}$</td>
<td>$\sigma^*$</td>
<td></td>
<td>$\bar{X}$</td>
<td>$\sigma^*$</td>
</tr>
<tr>
<td>A</td>
<td>0.540</td>
<td>(0.0094)</td>
<td></td>
<td>0.251</td>
<td>0.0046</td>
</tr>
<tr>
<td>B</td>
<td>0.550</td>
<td>(0.0106)</td>
<td></td>
<td>0.255</td>
<td>0.0075</td>
</tr>
<tr>
<td>C</td>
<td>0.557</td>
<td>(0.0128)</td>
<td></td>
<td>0.260</td>
<td>0.0077</td>
</tr>
<tr>
<td>D</td>
<td>0.561</td>
<td>(0.0094)</td>
<td></td>
<td>0.253</td>
<td>0.0052</td>
</tr>
<tr>
<td>E</td>
<td>0.569</td>
<td>(0.0120)</td>
<td></td>
<td>0.262</td>
<td>0.0072</td>
</tr>
<tr>
<td>F</td>
<td>0.566</td>
<td>(0.0093)</td>
<td></td>
<td>0.263</td>
<td>0.0050</td>
</tr>
<tr>
<td>Mean value of all positions in ampoule</td>
<td>0.557</td>
<td>(0.0094)</td>
<td></td>
<td>0.258</td>
<td>(0.0049)</td>
</tr>
</tbody>
</table>

*$^*$The standard deviation shown in parentheses is the original value normalized to correspond to the mean optical density for all the positions.
<table>
<thead>
<tr>
<th>Wavelength</th>
<th>One glass</th>
<th>At probability level of:</th>
<th>Three glasses (mean)</th>
<th>At probability level of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68% 99% 99.7%</td>
<td></td>
<td>68% 99% 99.7%</td>
<td></td>
</tr>
<tr>
<td>3500</td>
<td>± 1.3 ± 3.3 ± 3.9</td>
<td>± 0.8 ± 1.9 ± 2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>± 1.6 ± 4.2 ± 4.9</td>
<td>± 0.9 ± 2.4 ± 2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td>± 1.8 ± 4.7 ± 5.5</td>
<td>± 1.0 ± 2.7 ± 3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>± 2.1 ± 5.4 ± 6.3</td>
<td>± 1.2 ± 3.1 ± 3.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE III**

Probable Percentage Limits of Error for Corning #9761 Glasses, Calculated on Basis of 48 Separate Irradiations in #4 Position in Cobalt-60 Source for 90 Minutes.
<table>
<thead>
<tr>
<th>Dose No.</th>
<th>3500 Å</th>
<th>4000 Å</th>
<th>4500 Å</th>
<th>5000 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.40</td>
<td>3.35</td>
<td>1.45</td>
<td>0.604</td>
</tr>
<tr>
<td>2</td>
<td>5.65</td>
<td>3.44</td>
<td>1.43</td>
<td>0.600</td>
</tr>
<tr>
<td>3</td>
<td>5.80</td>
<td>3.48</td>
<td>1.41</td>
<td>0.585</td>
</tr>
<tr>
<td>4</td>
<td>5.55</td>
<td>3.46</td>
<td>1.45</td>
<td>0.610</td>
</tr>
<tr>
<td>5</td>
<td>5.76</td>
<td>3.46</td>
<td>1.46</td>
<td>0.625</td>
</tr>
</tbody>
</table>
REFERENCES


Fig. 1--Holder for silver-activated phosphate glasses when optical measurements are made.
Percentage Decrease in Absorption Coefficients of Silver Phosphate Glass (Corning) as a Function of Time of Storage at Different Temperatures

DOSE: $1.30 \times 10^5$ rep Cobalt-60 Gamma Rays

Storage:
- Refrigerator temperature 35-40°F
- Room temperature 70-80°F

Fig. 2—Effect of temperature of storage on irradiated silver-activated phosphate glasses not given heat treatment.
Fig. 3--Effect of time of heating at different temperatures on irradiated silver-activated phosphate glasses stored at room temperatures.
Fig. 4—Effect of time of heating at 100°C on silver-activated phosphate glasses given two different irradiation doses and stored at room temperature.
Fig. 5—Calibration of silver-activated phosphate glass irradiated with Cobalt-60 gamma rays and then heat-treated for 20 minutes at 100°C.
Fig. 6—Fading corrections and calibration of silver-activated phosphate glass irradiated with Cobalt-60 gamma rays, measured before heating, after heat treatment for 10 minutes at 130°C., and after 8-day storage at room temperature.
Fig. 7--Fading characteristics of silver-activated phosphate glass given dose of 1.21 x 10^5 rep and stored at two different temperatures after heat treatment for 10 minutes at 130° C.
Effect of Temperature During Irradiation on Absorption of Silver Phosphate Glass (DOSE: 1.30 X 10^5 rep)

Fig. 8--Fading characteristics of silver-activated phosphate glass given dose of 1.30 x 10^5 rep at two different temperatures, heat-treated for 5 minutes at 100°C, and stored at room temperature.
Fig. 9--Fading characteristics of silver-activated phosphate glass given dose of $3.66 \times 10^5$ rep at two different temperatures, heat-treated for 10 minutes at $130^\circ$ C., and stored at room temperature.
Fig. 10--Fading characteristics of silver-activated phosphate glass given dose of $3.66 \times 10^5$ rep, heat-treated for 10 minutes at $130^\circ$ C., and stored at three different temperatures.
Fig. 11--Fading characteristics of silver-activated phosphate glass given dose of $1.23 \times 10^6$ rep, heat-treated for 10 minutes at $130^\circ$ C., and stored at room temperature.
Fig. 12--Fading characteristics of silver-activated phosphate glass given dose of $3.55 \times 10^5$ rep, heat-treated for 10 minutes at 130° C., and stored at room temperature.
Fig. 13—Effect of heating glasses for 10 minutes at 130° C. after different time intervals following dose of $3.74 \times 10^5$ rep.
Fig. 14--Effect of irradiation of silver-activated phosphate glass with 3 m.e.v. electrons and comparison of depth dose curves with that of aluminum.
Fig. 15--Energy dependence of silver-activated phosphate glass (Schulman, Ginther, and Klick (7)).
Fig. 16--Arrangement for heating and erasing glasses at elevated temperatures.
Fig. 17—Comparison of optical densities of nonerased glasses and glasses subjected to ten successive exposure-erasure cycles.