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Final Report

on

Phosphate Glass Gamma-Radiation Dosimeter

Under Contract No. NObsr-49257 with

Navy Department, Bureau of Ships
Electronics Division

Index No. NE-051559

November 30, 1952

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Research Department
730 Main Street
Cambridge 39, Massachusetts

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Table of Contents

Abstract

New Dosimeter

A new type of personal dosimeter for measuring cumulative exposure to gamma radiation has been developed. The new device, although only the size of a dollar watch, is rugged and accurate. It measures exposures as small as about 5 roentgens (which is harmless) or as large as 600 roentgens--usually fatal. It appears almost ideally suited for use by military or civilian personnel in any situation where it is feasible to use auxiliary reader instruments to show what the dosimeters read.

The device performs well under almost all circumstances. For example, it readily records radiation received instantly, as from an air-burst bomb; also it accurately records radiation received over a prolonged period, as from contamination produced by an underwater burst.

The device resists temperature extremes well and has a useful life of perhaps 5 to 50 years. It uses little or no strategic materials, is well adapted to mass production, and should cost only of the order of $1 when produced routinely in large quantity.

The heart of the new dosimeter, known officially as the DT-60 (XN-3)/PD Radiac Detector, is a small square of special glass. This glass, discovered by scientists at Pennsylvania State College and the Naval Research Laboratory, contains a small amount of silver phosphate, and has the remarkable property of becoming permanently fluorescent when exposed to gamma radiation. Since the intensity of fluorescence is essentially proportional to the dose, it is a simple matter to evaluate the fluorescence directly in terms of roentgen dose.

Special Reader

Besides the dosimeter itself, a standard laboratory-type reader for evaluating the dosimeter's response has been designed and produced. The reader contains a UV lamp for exciting the dosimeter's fluorescence; also a photomultiplier tube for measuring the intensity of fluorescence. The result is indicated on a large meter, calibrated directly in roentgens and provided with two ranges: a low range extending from 0 to 200 r, and a "casualty" range extending from 0 to 600 r. Thus any dose of military significance, from harmless to fatal, may be measured.

The reader is compact, reasonably rugged, and easy to operate. It weighs 45 lbs. complete with carrying case, and operates off any 60-cycle, 110-125 volt line. Dosimeters may be read quickly--at a rate of one every 5 to 15 seconds.

Before using a reader routinely, its overall sensitivity must be checked. This is easily done with the aid of a "standard" which has the same general size and shape as a dosimeter, but has a known, fixed fluorescence. Suitable designs of standards were worked out.

Production

Under the present research and development contract, only token production was attempted. A thousand dosimeters were produced; also six readers and several hundred standards.

Separate programs have been established at Polaroid and elsewhere for true mass production. Large quantities of dosimeters are being produced; likewise a large number of readers especially designed for field use. These matters, however, are outside the scope of the present contract.

Assisting Other Groups

During the last year, we have assisted various other Navy and Navy contractor institutions by (1) showing them how to get the best performance from the readers we had furnished to them, (2) providing freshly-calibrated standards, and (3) advising them as to optimum design specifications, performance specifications, and test methods. Also we served as the central clearing house for insuring uniformity among readers and standards.

Further Improvements

We have developed schemes which would make it possible to obtain better performance and at the same time reduce the size and cost of the dosimeter. One improvement consists of providing "all-around" shielding, so that the response to radiation entering the dosimeter from the side would be the same as that from radiation entering the front or back of the device. Another improvement consists of making the glass piece much smaller and at the same time improving the utilization of fluorescent light.

A model of the improved device ("Type H-Xb design") was submitted to Buships, and recommendations for adopting this design were submitted.

Part I. Purpose, Factual Data, Conclusions

Section 1. Purpose

A. General Purpose.

The general purpose of this contract was to develop a new kind of personal dosimeter for measuring cumulative exposure to gamma radiation from atomic bombs. The new device was to employ a special kind of glass, namely a glass which becomes permanently fluorescent when exposed to gamma radiation.

The program involved studying the glass, designing a dosimeter around it, and designing a photoelectric device to "read" the dosimeter.

B. Purpose as Regards Special Glass.

It was intended that first attention be given to studying the special glass itself. Its "radiophotoluminescent" property had been discovered only a few years previously, and little was known as to the intensity of fluorescence, or the effects of temperature, light, heat, moisture, age, etc. Some uncertainty remained as to the optimum formula to use in making the glass, and little information existed as to the uniformity of the glass from batch to batch.

C. Purpose as Regards the Dosimeter.

When and if we found that the glass had satisfactory properties, we were to design a dosimeter employing such glass.

It was desired that the dosimeter be small, rugged, and inexpensive, so that it might be worn by all appropriate military personnel. The dosimeter was to measure cumulative exposure to gamma radiation either from an air-burst atomic bomb or from the radioactive contamination spread by an atomic bomb exploding underwater or underground.

The dosimeter was to respond essentially equally to all wavelengths of gamma radiation, from 0.15 Angstroms (80 kev) to 0.0025 Angstroms (5 Mev). It was to be able to detect a dose as small as 10 roentgens, which is relatively harmless, or as large as 600 roentgens, which is usually fatal. It was to operate over a wide range of temperature, and to be waterproof, shock-resistant, and easy to decontaminate. Other requirements are listed in Specification MIL-R-15239 (Ships), dated 15 March 1950.

These requirements posed many problems as to size, shape, and finish of the glass; also methods of shielding, mounting, and housing.

D. Purpose as Regards the Photoelectric Reader.

A special reading device was needed to read the dosimeter's dose. Dose could be read only in terms of intensity of fluorescence exhibited by the dosimeter; and to find the intensity of fluorescence required (1) exciting the fluorescence in the dosimeter by means of a beam of UV light, and (2) measuring the fluorescent output by suitable means.

At first it was hoped that the eye could be used in measuring the intensity of the fluorescent light; but it was soon found that this was impractical unless a very large piece of glass was used, or a very powerful UV lamp.

Consequently we were required to put major effort into developing a photoelectric type of reader. Designing such a device called for a knowledge of (1) optimum wavelength of the exciting UV radiation, (2) wavelength distribution of the emitted light, (3) background fluorescence found even in glass pieces never exposed to gamma radiation. Choices had to be made among many types of UV lamps, various UV-pass filters, various systems for collecting the fluorescent light and filtering out any UV light mixed therewith, various kinds of photoelectric detectors of fluorescent light. Attention had to be given to speed of loading and measuring the samples; also to the overall linearity and stability of response. Finally, fixed standards had to be devised for showing whether the level of sensitivity in the photoelectric reader had been set properly, so that the absolute accuracy of the readings would be high.

E. Miscellaneous Purposes.

During the later stages of the work several companies were preparing to mass produce dosimeters and readers. We were asked to assist these companies by advising them on design matters, testing procedures, and standardization.

Also we were asked to periodically issue freshly-calibrated standards to the various laboratories engaged in testing dosimeters. We undertook also to repair and adjust the readers which had been issued to those laboratories.

Section 2. General Factual Data

A. Relation to Other Types of Personal Dosimeters.

There are, of course, many other types of personal dosimeters. Conventional film badges have been used very successfully, but are not well suited to field use. They have to be developed and fixed, requiring specialized equipment which often would not be readily available.

Electrometer type devices, called pocket chambers, pocket dosimeters, etc., have been used also. These must be recharged periodically; they provide no permanent record of the dose; their cost is high ($20 to $50).

Color-changing liquids and color-changing crystals have been tried, but suffer from several limitations relating to stability and sensitivity; doses less than about 50 r are difficult to detect, and some drift may occur.

Self-developing film badges are being tested extensively; although successful in many respects (notably sensitivity, range, low cost, and elimination of any need for a photographic darkroom), they have shelf-life and storage limitations to be expected of photographic materials generally.

The present device—the glass dosimeter—is outstanding in many respects, including:

Small size: About the size of a dollar watch.

Wide range: From approximately 5 r to 600 r and beyond.

High Accuracy: 5 r or 10% typically.

Long Shelf-life: Little or no change up to one year; perhaps good for 5 to 50 years.

Always ready: No charging or servicing. Usable repeatedly; can be used, read, reused, etc., repeatedly and cumulatively, presumably for years.

Low cost: Should cost only about $1 in routine mass production.

A more complete list of properties is presented in a later section.

The present device, in common with most other personal dosimeters, is intended to measure gamma radiation, and is not suited to measuring alpha-radiation, beta-radiation, or neutron radiation. Also, it is intended only to measure the dose received by the dosimeter; this may be appreciably less than the dose received by the user if the user's body intervenes between dosimeter and radiation source.

B. Relation to Other Contracts on Glass Dosimeters.

The initial work on silver phosphate glass was done at Pennsylvania State College and at the Naval Research Laboratory. The radiophotoluminescent property of the glass was discovered by Weyl, Schulman, Ginther, and Evans. See Reference N-1.

The Naval Research Laboratory has advised and assisted in the glass dosimeter program since the outset. Its advice and encouragement has been most valuable.

The National Bureau of Standards has assisted the program in several ways. It studied the wavelength dependence of the dosimeters; also the directionality of the device, the effect of various changes in lead shielding, and other matters.

The Bausch and Lomb Optical Company provided most of the melts of silver phosphate glass used in the early stages of the work. More recently, operating under contract with Buships, it has been studying different formulations, etc., of radiophotoluminescent glasses. Also, it has been most helpful in making trial melts of special glasses, including manganese glasses, suitable for use in the fixed standards needed in checking the sensitivity of the photoelectric readers.

The Materiel Laboratory at the New York Naval Shipyard (Brooklyn) assisted in evaluating and testing the glass dosimeter, as did the Naval Radiological Defense Laboratory at San Francisco.

Small-scale production of laboratory-type readers was undertaken at Polaroid Corporation under separate Navy contracts NObsr 57040 and NObsr 57500.

A small production lot of glass dosimeters was produced by Polaroid Corporation under Navy contract NObsr 57501. Polaroid Corporation is now engaged in a large scale mass production program (on glass dosimeters) under NObsr 52704.

Large scale mass production of silver phosphate glass and the glass dosimeter is underway at the Corning Glass Works.

The Admiral Corporation, Chicago, Illinois, is undertaking mass production of photoelectric readers for field use.

An experimental model of an extremely small field-use reader was developed during the spring of 1952 by Mr. G.Work of the Naval Radiological Defense Laboratory.

Successful large scale production of the silver phosphate glass was worked out by the Pittsburgh Plate Glass Co., a principal supplier of special glass for the Polaroid Corporation's mass production program on dosimeters.

Pilot Chemical Co. of Waltham, Mass., also supplied some of the special glass to Polaroid Corporation. Pilot Chemical Co. produced glass having the highest sensitivity we have encountered, the sensitivity being about three times the sensitivity now regarded as standard.

Throughout the entire glass dosimeter program, the encouragement and leadership by Buships Code 854 has been of central importance. That agency initiated the major programs, gave continuing counsel as to design and performance specifications, and generally coordinated the research, development, and production programs. We believe that Buships is to be congratulated on having perceived (as early as approximately three years ago) the unique possibilities inherent in the silver phosphate glass, and in having pushed the program through to a successful conclusion. The program should be of value to all branches of the Armed Services, and to the civil defense effort also.

The program covered by this final report is the central program of specifying the particular grade of glass desired, helping determine the design of the dosimeter, developing a photoelectric reader, and finding suitable calibration standards. Thus the present report summarizes the foundation on which the various current production programs rest. It attempts to tell not only what designs were arrived at, but why they were chosen, how successful they have proved to be, and what additional improvements lie within reach.

C. Contract Dates, Ammendments, etc.

The present contract, NObsr-49257, Index No. NE-051551, was initiated June 30, 1950, and was intended to be completed by June 30, 1952.

The contract was ammended from time to time, additional funds were provided, and the termination date was extended to December 31, 1952. There were five ammendments in all.

D. Previous Reports.

The work performed under this contract has been reported in twenty-seven individual Monthly Reports, starting with the report for August 1950. These reports are listed in the bibliography appended to the present final report.

E. Technical Personnel.

During the period from August 1, 1950 through November 30, 1952, the following technical persons worked on the contract to the approximate extents indicated below:

Name	Hours
E. H. Land, President and Director of Research	No charge made
E. R. Blout, Associate Director of Research	No charge made
W. A. Shurcliff, Senior Physicist; Project Leader	2259
P. D. Bartlett, Engineer	211
E. G. Byrnes, Physicist	1858
A. G. Carpenter, Model Shop Supervisor	788
J. DeYoung, Electronics Engineer	257
M. N. Fairbank, Mechanical Engineer	104
L. Farney, Plastics Engineer	30
S. W. Haskell, Optical Designer	22
R. D. Hay, Mechanical Engineer	895
A. S. Makas, Physicist	362
C. H. Matz, Electronics Engineer	1562
C. O. Rolando, Mechanical Engineer	64
A. P. Sutton, Supervisor of Photometer Operation	83
E. W. Treuenfels, Chemical Engineer	1008
G. W. Trumbour, Control Test Engineer	65

Section 3. Detailed Factual Data

Introduction.

Section 3 consists of several subdivisions, as follows:

Section 3-A: Properties of Silver Phosphate

Section 3-B: Dosimeter Design Considerations

Section 3-C: Non-Feasibility of Using a Visual-Type Reader

Section 3-D: Photoelectric Reader Design Considerations

Section 3-E: The Problem of Providing Fixed Standards

Section 3-F: The DT-60(XN-3)/PD Dosimeter

Section 3-G: Other Specific Designs of Dosimeter

Section 3-H: The CP-95(XN-3)/PD Reader

Section 3-I: Other Specific Designs of Reader

Section 3-J: Designs of Fixed Standards

Section 3-K: The M-Std. Pool

Section 3-L: Future Possibilities

Section 3-A. Properties of Silver Phosphate Glass

A. Introduction.

The uniquely valuable property of silver phosphate glass was discovered about five years ago by Weyl, Schulman, Ginther, and Evans (Ref. N-1). They found that if the glass was exposed to gamma radiation, it acquired the ability to fluoresce when later exposed to ultraviolet radiation. Intense orange-colored fluorescent light resulted if the gamma-ray exposure amounted to several hundred roentgens. Furthermore, the intensity of fluorescence seemed proportional to the gamma-ray dose received. Thus it became clear that the glass might be used as the sensitive element, or detecting element, of a gamma-ray dosimeter. The possibility was brought to the attention of the Bureau of Ships, and the present development program was soon launched.

Detailed exploration of the properties of the glass confirmed the hopes that a new and unparalleled detecting element was at hand. The range of fluorescence, the linearity, and stability, and the homogeneity proved to be excellent.

Some points of weakness were found. These include: (1) variation in sensitivity of the glass, from one batch to another, unless suitable precautions are taken by the glass manufacturer; (2) variation in the initial, or background fluorescence, unless suitable precautions are taken; (3) tendency of the fluorescence to change somewhat depending on the temperature at the time of exposing the glass and also the temperature at the time of measuring the fluorescence; (4) tendency of the glass to respond to long wavelength gamma radiation more than short wavelength gamma radiation, unless appropriate shielding is used.

Altogether 30 or more different characteristics of the glass have been explored. These are summarized briefly below.

B. Formula of the Glass.

Silver phosphate glass is usually used at the so-called "8%" concentration. The 8% glass has the following formula, according to References N-1, N-2, and N-3.

50 parts by weight aluminum metaphosphate, $Al(PO_3)_3$

25 parts by weight potassium metaphosphate, KPO_3

25 parts by weight barium metaphosphate, $Ba(PO_3)_2$

8 parts by weight silver metaphosphate, $Ag(PO_3)$

C. Preparation of the Glass.

According to Reference N-3, the glass is prepared by melting the constituents together at 1200°C. in a fused silica crucible, casting the melt into a metal mold, annealing it, and then cutting, grinding, and polishing pieces of desired size.

Presence of certain impurities, such as iron, titanium, chromium, and perhaps several other elements, may cause considerable change in the initial fluorescence of the glass ("pre-dose fluorescence") and in the fluorescence resulting after exposure to gamma radiation ("post-dose fluorescence").

Bubbles, strains, etc. may be found in the glass unless suitable precautions are taken. Also, devitrification may occur unless the glass is cooled appropriately and rapidly.

Much additional information of preparation of the glass has been accumulated during the last year by the various glass manufacturers concerned. Presumably the Bausch and Lomb Optical Company is very familiar with the situation, since they are working under a Buships contract specially focused on the technology of silver phosphate glass and related glasses. The Pittsburgh Plate Glass Co. and the Corning Glass Works have also acquired much experience in this field. Pilot Chemicals, Inc. is familiar with the production of small melts of very high sensitivity.

Information may be obtained also from References N-1 and N-3.

D. Transmission of the Glass.

The 8% glass, before being exposed to gamma radiation, is essentially clear, colorless, and transparent. Transmission curves for the UV and visual regions of the spectrum are shown in the Monthly Report for September 1950 (Ref. P-2). The internal transmittance is essentially 100% for visible light, but falls to 50% at 350 millimicrons (for a path-length of 1 cm.) and to 1% just below 300 millimicrons. In other words, the glass has a smooth UV cut-off typical of common kinds of glass.

When the glass is exposed to gamma radiation, the transmission curve changes. The transmission for light of wavelengths near 400 millimicrons decreases; and the greater the dose of gamma radiation, the greater the decrease in transmission. When the dose reaches several hundred r, the decrease in transmission for the 400 millimicron (blue) light is sufficient to give the glass a slightly yellowish appearance. When the dose amounts to 50,000 r, the glass appears strongly yellow colored. Illustrative transmission curves of dosed pieces are shown in Ref. P-2.

If, for each wavelength of light, the optical density of the glass in pre-dose condition is subtracted from the density existing after dosing, a curve is obtained which represents the spectral absorption of the new "colorant" produced by gamma radiation. As shown in Ref. P-9, the absorption maximum of the new colorant is found at about 340 to 360 millimicrons.

E. UV Excitation of the Glass.

Whether dosed or undosed, the 8% glass emits a feeble bluish-white fluorescent light when exposed to UV radiation of wavelength below 350 millimicrons. The mercury 254-mμ line, for example, excites some bluish-white fluorescence.

After the glass has been gamma-irradiated, the situation is very different. A strong fluorescence is observed whenever UV radiation near 360 millimicrons is incident, and the color of the fluorescent light is very different, being orange.

The situation is summarised in Table 1.

Table 1

Intensity and Color of Fluorescent Light

	Kind of UV Exciting Light Used		
Condition of Glass	Far UV	Near UV	Visible
Never exposed to gamma rays	Weak bluish-white fluorescence	Very weak bluish-white fluorescence	None
Exposed to 1000 r of gamma rays	Weak bluish-white fluorescence	Strong orange fluorescence	None

As indicated in Ref. P-9, the orange color is excited by wavelengths from about 310 to about 410 millimicrons. Wavelengths near 360 millimicrons are perhaps more effective than other wavelengths if the glass has been exposed to a large dose; wavelengths near 340 millimicrons may be the most effective if the dose has been small.

F. Pre-Dose Fluorescence.

The pre-dose fluorescence (fluorescence which the glass exhibits before being exposed to gamma radiation) is usually small. A typical batch of 8% glass has a pre-dose fluorescence amounting to about 1/3 of the fluorescence created by a dose of 100 r of 1.3 Mev gamma radiation. This figure assumes that the UV excitation has the spectral energy distribution normally used in the laboratory-type reader specified in a later section. It assumes also that the measuring device (photocell) is covered by an orange filter, so that only the orange component of the fluorescent light is measured.

The pre-dose fluorescence would appear considerably stronger if shorter-wave UV excitation were used, or if the blue and green components of the fluorescent light were measured along with the orange component.

The intensity of pre-dose fluorescence is about the same as that of a standard pyrex glass (Corning #7740). It is only about 1/4 that of typical window glass or plate glass. It is between 1/100 and 1/1000 that of a typical uranium glass and typical commercial plastics.

The color of the pre-dose fluorescence is probably whitish or bluish-white; the intensity is so low that the color cannot be evaluated visually, and indirect methods must be used.

G. Post-Dose Fluorescence.

As indicated above, when the glass has been exposed to 100 r of 1.3 Mev gamma radiation, it becomes fluorescent. More exactly, it acquires a permanent fluorescence-ability, i.e., the ability to fluoresce steadily when illuminated steadily with UV light.

To express the amount of fluorescence is not easy. A rough estimate has been made of the absolute efficiency of fluorescence in Ref. P-7; it is estimated that of the order of 10^{-7} watts of fluorescent light is produced per watt of near UV radiation incident, assuming certain typical experimental conditions. There is no doubt that the fluorescence, even when referred to as "strong," is actually very weak as compared with commercial fluorescent screens, commercial fluorescent glasses, etc.

For convenience, fluorescence intensity measurements are usually made on glass samples exposed to just 100 r of 1.3 Mev gamma radiation.

The fluorescence is orange in color; spectral radiance curves have been presented by Schulman and others. (References N-1 and N-3). The fluorescence includes, besides orange light, some yellow light, much red light, and a little near-IR light.

Of course, once a dosimeter design has been frozen, and once routine manufacturing and testing procedures have been arrived at, it is logical to define a response scale, or post-dose fluorescence scale, such that a 100 r dose increases the fluorescence by just 100 units. (See a later section.)

It is a remarkable property of the 8% glass—not only that it becomes fluorescent when gamma-irradiated—but also that the fluorescent light lies in a band well separated from the exciting band. For nearly all other fluors known, the situation is quite different, the bands lying very closely adjacent and even overlapping to the extent of perhaps 25 to 50%. Having the two bands well separated is a great benefit to the present project, simplifying the problem of obtaining a strong signal (orange light) essentially free from noise (UV exciting light).

H. Sensitivity.

By "sensitivity" we mean: the increase in fluorescence per roentgen of gamma-radiation dose. It is customary to compute the sensitivity by (1) finding the fluorescence before exposure, (2) finding the fluorescence after a 100 r exposure, (3) subtracting the former from the latter, and (4) dividing the difference by 100. The absolute sensitivity is of the order of magnitude of 10^{-9} fluorescence-efficiency units per roentgen of exposure.

Of course, once routine manufacturing and testing schemes have been established, it is easy to specify sensitivity precisely. The sensitivity of a typical sample is then expressed as, say, 100 indicated roentgens per 100 actual roentgens exposure. See a later section.

I. Non-Migration of Fluorescence-Ability.

If only half of a piece of 8% glass is exposed to gamma-radiation, the other half being shielded by a thick block of lead, only the exposed half is made fluorescent. Even after storing such a specimen for a year in a desk drawer, one half will continue to have fluorescence-ability, while the other half remains essentially non-fluorescent. See Reference P-4. (This is in marked contrast to the situation found for sensitized alkali-halide crystals—where migration of the color proceeds rapidly.)

J. Fluorescence vs. Phosphorescence.

Cathode ray oscilloscope tests show that the fluorescence of dosed 8% glass ceases essentially immediately (within 0.01 sec. or less) after the UV illumination is cut off. Thus it is appropriate to refer to the luminescence as fluorescence, rather than phosphorescence. (As explained in a later section, some manganese glass samples used in fixed standards appear phosphorescent, rather than fluorescent. Such disparity could lead to errors if the time constants of the measuring instrument components were selected improperly.)

K. Additivity.

The 8% glass shows excellent additivity. For example, five separate exposures, each of 20 r, lead to essentially the identical fluorescence-ability as a single dose of 100 r. See Ref. P-6.

L. Non-Dependence on Dosage Rate.

The 8% glass shows excellent independence of the time-rate of dosage. Essentially the same fluorescence results whether a 200 r dose is delivered to the glass in 20 seconds or 20 hours. See Ref. P-7. Informal communications from others suggest that the performance is excellent even when the dose is received in a fraction of a second.

M. Linearity.

The 8% glass shows excellent linearity of response throughout the range of interest (0 to 600 r) and even beyond. In fact the linearity extends beyond 10,000 r. Throughout this enormous range, a given increment in dose produces the same increment in fluorescence. See Ref. P-3; also Appendix 1 of Ref. P-16.

N. Dosage Range Covered.

The fluorescence of the 8% glass continues to increase even when the dose exceeds 100,000 r, but the rate of increase ceases to be linear when the dose exceeds about 20,000 r. See Ref. P-16. Using special calibration charts, the glass could be used to measure doses up to 100,000 r (possibly 1,000,000 r).

It is obvious that the glass has a far greater range than is required in a 0-to-600 r personal dosimeter.

O. Temperature-During-Dosing Effect.

If a sample of 8% glass is gamma-irradiated when at elevated temperature, the resulting fluorescence-ability (measured subsequently, with the sample restored to room temperature) is found to be slightly greater than usual. A 1°C rise in dosing temperature causes a 0.3% increase in the fluorescence-ability. As shown in Appendix 3 of Ref. P-6, the fluorescence-vs-temperature curve is perhaps linear for temperatures near room temperature, but tends to flatten out at lower temperatures.

The exact value of the temperature-during-dosing coefficient has not been determined accurately, and there is indication that it varies somewhat depending on the quality of the particular melt of 8% glass under consideration.

The effect should not be confused with a different kind of temperature effect—discussed in the following paragraph.

P. Temperature-During-Reading Effect.

If a sample of dosed 8% glass is read while at room temperature, and is then re-read after being brought to a higher temperature, the fluorescence will be found to be slightly less. The temperature coefficient has approximately the value: -0.7% per ° C. The value may vary slightly from batch to batch of the glass. See Ref. P-3.

It will be noted that this effect is in the opposite direction from the temperature-during-dosing effect defined previously. Thus if a sample is dosed and read at high temperature, the two sources of error tend to compensate to some extent. (However, the temperature coefficient of the fixed standard employed affects the outcome also, as explained in a later section.)

Q. Build-Up Effect at Room Temperature.

If a piece of 8% glass is dosed very rapidly and then read immediately, it will read lower than if allowed to age for a few hours before being read. For example, if a piece receives 100 r in ten minutes, immediately thereafter it might then read 10 to 30% less than if allowed to age for four hours.

Practically any increase or "build-up" which is imminent will occur within the first four hours, assuming that the sample is stored at room temperature. A slight increase may perhaps occur during the next few days or weeks, but if such increase occurs at all, it is usually less than 5% and is therefore difficult to detect reliably.

If the dose is delivered in a few seconds instead of a few minutes the post-dose build-up may amount to a factor of 2. But again the difficulty is avoided by allowing the sample to age for a few hours.

In general, the phenomenon appears to have a relaxation constant of the order of 10 to 20 minutes, at room temperature.

If the dose is delivered over a 24-hour period, any build-up involved is practically complete by the time the exposure is terminated. The increase to be expected during the next four hours is perhaps only 5%.

If the dose is very small (less than 25 r), the build-up effect is negligible or even non-existent. The effect is appreciable only for large doses.

The effect depends strongly on the ambient temperature and on the concentration of silver phosphate glass, as explained in later paragraphs.

R. Build-Up Effect at High Temperature.

If the sample is stored at high temperature (immediately after the exposure to gamma radiation has been completed), the build-up occurs more rapidly.

S. Latent Fluorescence-Ability.

If a dosed piece of 8% glass is exposed to gamma radiation and is then heated to 150°C for several hours, the fluorescence tends to be slightly greater than if the sample had been stored at room temperature. Thus high temperature appears to bring out a small amount of "latent" fluorescence-ability. Since there is no expectation of using the dosimeters at such temperature, this effect is perhaps of no practical importance. See Ref. P-17 for further details.

T. Wavelength Dependence.

If exposed while entirely unshielded, the 8% glass shows considerable wavelength dependence. Typical pieces of the glass may respond roughly ten times as much to a given dose from a 150 kv x-ray machine as when exposed to an equal dose of 1.3 Mev gamma radiation from radio-cobalt. (See Ref. P-4, P-6, and P-20.) Depending on the exact thickness of the glass and the exact wavelength of the radiation, the error may be more or less than a factor of ten.

The error is large only for photon energies below about 150 kev. It is small and perhaps negligible for energies exceeding about 300 kev.

Thus in general the effect is small over the great majority of the photon energy range of interest: 80 to 5,000 kev.

The error existing for photon energies below 300 kev. is greatly reduced by use of appropriate shielding, as discussed in a later section concerned with the dosimeter as a whole.

U. Angle-of-Incidence Dependence.

A thin, flat sample of 8% glass tends to respond slightly differently, for a given wavelength of gamma radiation, depending on the obliquity of the incident gamma radiation. The obliquity angle determines the relative importance of the primary beam of gamma radiation and the secondary beam of Compton recoil electrons accompanying the primary beam.

The angle-of-incidence dependence is particularly important if the sample is thin and is provided with flat metal shields, as discussed in a later section. See also Ref. P-20.

V. Effect of Bubbles, Etc.

Available evidence indicates that presence of a few small (0.5 mm. dia.) bubbles in the glass sample is not harmful.

Sometimes small occlusions occur in the glass. These may fluoresce fairly strongly, and may be harmful.

Often the glass pieces contain pronounced frozen-in strains, as may be seen by placing the glass piece between crossed polarizers. This is usually not harmful.

W. Erasure of the Fluorescence.

If a piece of 8% glass is dosed, so that considerable fluorescence is produced, the fluorescence may be almost entirely erased by heating the glass to 350°C. and holding it at that temperature for several hours. The glass may then be re-used in normal manner.

Thus in principle, at least, the glass can be "erased" and re-used. Erasure is likely to be impractical for several reasons, including: nuisance, likelihood of melting the dosimeter shield and case, and likelihood of contaminating the glass surface.

X. Effect of Prolonged, Intense UV Irradiation.

If an undosed piece of 8% glass is exposed for many hours to intense UV radiation from a quartz mercury arc, some fluorescence-ability will be created in the glass.

The reverse effect may occur in a highly dosed sample. Thus if a piece of the 8% glass is exposed to 2000 r of gamma radiation and is then exposed to intense near-UV radiation, the fluorescence will decrease to a marked degree. It may decrease to a value corresponding to perhaps 200 r; but it will not vanish entirely. See graph presented in Ref. P-2.

Weak UV radiation, such as that provided in the photoelectric readers, has no detectable effect on the glass piece even if the piece is left in the path of the UV beam for many hours.

Y. Effect of Daylight.

If a dosed piece of 8% glass is exposed to bright daylight or direct sunlight for several hours, a slight decrease in fluorescence may occur. However, an hour's exposure is usually without detectable effect.

Exposure of several weeks may reduce the reading by 20 to 60%.

Z. Effect of Hot-Storage.

Storing undosed or dosed 8% glass at temperatures as high as 150°F. for considerable periods appears to be essentially without effect.

AA. Effect of Cold-Storage.

No appreciable effect has been found to result from storing undosed or dosed pieces of 8% glass at temperatures well below room temperature, provided the glass pieces are free—not cemented to anything.

BB. Effect of Hot Salty Water.

No appreciable effect, other than tendency for the glass surface to become slightly cloudy, has been found to result from immersing the glass for an hour in boiling salty water.

CC. Effect of Age.

Little or no change has been found in polished pieces of undosed and dosed 8% glass stored in darkness at room temperature for a year. The accuracy of the tests was less than ideal, and it may be, for example, that some slight decrease in fluorescence (5%, possibly) occurred.

Slight change may occur occasionally in pieces which have a coarse-ground finish. The change tends to take the form of a prompt (24-hour) increase in reading. However, the change is usually small and is probably to be attributed to the "curing" of the freshly-ground surface, rather than to any change within the body of the glass. Regrinding the surface tends to wipe out the increase.

DD. Effect of Fingermarks.

Contaminating the surface of a piece of 8% glass, as by pressing it firmly with a sweaty or greasy finger, tends to increase the apparent fluorescence by a small amount, such as 2 to 10 r. However, such contamination can be washed off readily.

EE. Explanation of the Fluorescence Induced by Gamma-Rays.

As explained in Appendix 2 of Ref. P-16, and also in Ref. N-1 and N-3, it is assumed by Schulman and others (1) that gamma radiation liberates electrons within the silver phosphate glass, (2) that these electrons migrate towards individual Ag^+ ions, and (3) that each loose union of electron and Ag^+ ion constitutes a fluorescence center. Such centers are capable of absorbing near-UV light and emitting orange light; they can do so repeatedly, almost indefinitely.

Ref. P-16 lists eighteen properties of the 8% glass and shows that nearly all of these may be explained simply by the above-stated mechanism.

FF. Batch-to-Batch Variation in the Glass.

Especially in the early stages of the present program, much variation was found between different batches of glass. The intensity of pre-dose fluorescence varied typically by perhaps 5 to 10 r. Sometimes it amounted to more than 100 r.

The sensitivity fluctuated also, varying typically by 10 to 30%, and sometimes by 50% or more.

Much better uniformity was obtained when successive batches were made using the identical equipment and the identical lots of raw materials.

Now that control of raw materials and equipment has been greatly improved, the variations in question have been reduced to small fractions of the earlier variations. It appears likely that the manufacturers will be able to hold the variations to within 5 or 10% ordinarily.

Some batch-to-batch variation in temperature effects, build-up time, stability, etc., may perhaps occur. Few tests of this nature were performed during the course of the work reported here.

GG. Effect of Changing the Content of Silver Phosphate.

The effect of changing the concentration of silver phosphate is discussed at length in Ref. P-8.

The general conclusion is that the 8% concentration is probably about the best compromise. It has a low pre-dose fluorescence, good sensitivity, and a rapid build-up of the fluorescence.

Glass of lower concentration, such as 6%, has the attractive property of exhibiting an even lower pre-dose fluorescence. It has the added attraction of consuming less silver phosphate, which is the most expensive ingredient. However, the 6% glass seems to have a slower build-up, and perhaps performs somewhat poorly when gamma-irradiated at low temperature.

A glass of higher concentration, such as 15%, may have slightly greater sensitivity, and shows a quicker build-up; presumably it performs slightly better than 8% glass when the dose is received at low temperature. However, the 15% glass tends to have a high pre-dose reading and consumes an unnecessarily large amount of silver phosphate.

Section 3B: Dosimeter Design Considerations

A. Introduction.

The heart of the dosimeter is, of course, the piece of 8% silver phosphate glass. But to produce a complete dosimeter we need also a mounting and casing which will perform the following functions:

Protection: Protect the glass from shock, light, dirt, etc.

Handling: Permit handling the glass without danger of dropping it, getting fingerprints on it, etc.

Shielding: Provide shielding for reducing the wavelength dependence.

Identification: Carry identifying symbols (designation, serial No., etc.)

Attaching: Provide a loop for the cord or chain attaching the dosimeter to the user.

B. Protection.

The glass piece could be protected against shock, light, dirt, etc. by keeping it inside a case of rubber, plastic, or metal. Plastic is probably most favorable because of its long life, amenability to low-cost mass production, and its non-use of strategic materials.

If plastic is used, a tough, flexible, plastic material must be selected. Ethyl cellulose is perhaps ideal. Materials such as Tenite II were tried, but were found to be too brittle.

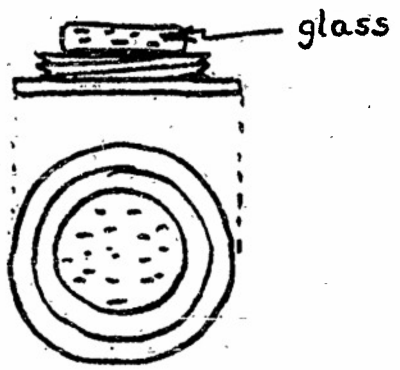
To exclude light, dirt, etc., in business-like manner—even if the dosimeter is immersed in muddy water—requires making the housing waterproof. This can be done by providing a screw cap which closes against a waterproof, compressible gasket. It is difficult to conceive of any other economical method of producing a water-tight seal between plastic members subject to some slight cold-flow and warping.

If the screw-cap is to be easily and quickly screwed up or unscrewed, it must have a heavy, coarse thread. At least 2/3 of one revolution thread engagement is necessary; one full revolution engagement would be preferable, as it would leave no part of the screw-cap's periphery unsupported.

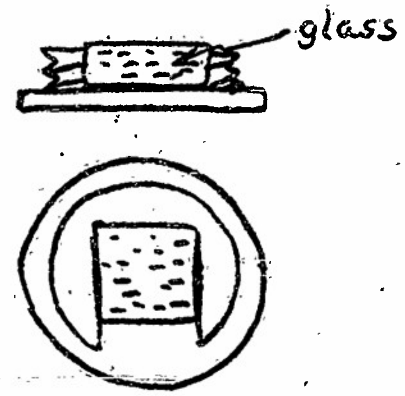
C. Handling.

The glass piece is small enough so that, if unattached, it might easily slip out of the fingers and become lost; also, it would almost surely become fingermarked promptly.

To avoid these difficulties, the plastic piece may be attached permanently to a larger, more easily handled, object. A plastic piece projecting out around the glass piece, and cemented to it, is presumably indicated. See the following sketches.



glass not recessed



glass recessed

D. Shielding.

Extensive tests have been made by Polaroid, National Bureau of Standards, and other institutions to see what shielding material and what shield thickness is optimum for reducing the glass piece's wavelength dependence.

1. Shielding suitable for special situation. In most tests, the assumption was made (at the request of Buships, Code 854) that only the upper and lower faces of the glass piece would be shielded, and that only radiation incident perpendicularly on the shields should be considered. Acting in accordance with a suggestion made by NRL advisers (See Ref. P-6) each shield was made in the form of a lead plate having a small central opening, the latter being intended to let through a little of the very soft (long wavelength) radiation that otherwise would be cut off almost entirely by the lead.

Tests carried out by Polaroid with the assistance of the National Bureau of Standards, the High Voltage Engineering Corp., and the Deaconess Memorial Hospital indicated that the energy dependence was corrected to a considerable degree using lead shields 1 mm. thick and containing a central hole 0.07 inches in diameter.

Tests carried out later by other groups, but again with the help of the National Bureau of Standards, showed that a slightly greater thickness of lead—approximately 0.045"—gave better performance under the special conditions established by Buships Code 854.

2. Shielding suitable for more general situations. We showed in January 1952 (Ref. P-18) that perpendicular incidence of the radiation was far from typical; simple calculations indicate that one radian (57 degrees) from the perpendicular is the typical angle prevailing when rays of all directions strike a flat shield. Rays incident at 57 degrees pass through the lead shield obliquely, experiencing a greater pathlength. Accordingly we pointed out that a thinner lead shield would be more appropriate with respect to typical rays; a thickness of 0.03" would appear to be close to optimum.

Appendix 6 of Ref. P-18 shows that this general conclusion is valid for radiation from an air-burst atomic bomb (point-source situation) and also for radiation from contamination (omni-directional situation). The conclusions is valid, moreover, whether the man wearing the dosimeter (on his chest) is standing, sitting, or lying down. For each of these situations a slightly different "typical angle of incidence" is arrived at, the values ranging from about 45 degrees to about 80 degrees from the perpendicular. A value of 57 degrees (or roughly 60 degrees) from the perpendicular is very representative.

Thus for a great majority of field situations, a lead shield thickness of 0.03" would give better results than the 0.045" shield. Also, it would save weight and cost.

3. Shielding suitable to the most general situation. In September 1951, and March 1952, (Ref. P-15 and P-20) we showed that a further improvement in shielding was needed—to take into account radiation striking the glass piece from an "edge" direction. When rays approach the dosimeter from all directions with equal probability, half of the rays strike at an angle of more than 57 degrees from the perpendicular. Approximately 25% of all rays strike the dosimeter in directions which are practically "edgewise" directions.

If no shielding is provided for these edgewise rays, large errors can result. For example, tests reported in Ref. P-20 show that a dosimeter not shielded on the edges will read approximately five times too high if irradiated edgewise with 100 kev. x-rays.

These same tests showed that the error is almost entirely eliminated by providing lead shielding on the edges, as well as the faces, of the glass piece. (See sketches on a later page.)

Of course, the spectrum of gamma radiation from an atomic bomb is a very broad spectrum. Thus the errors resulting from omission of the edge shielding may be small in those field situations where little soft radiation is involved. But where much soft radiation is involved, edge shielding appears highly desirable.

(As explained in a later section, the present "H-47" type of mass-production dosimeter DT-60()/PD employs no edge shielding. We have proposed a type H-50b which includes complete, omni-directional shielding; see a later section.)

E. Identification.

Besides its general designation symbol, each dosimeter should carry a serial number. This makes it possible for each man to know which dosimeter is his.

The serial number should be attached either to the glass itself or to something else that is permanently attached to the glass. The obvious solution is to apply the serial number to the plastic base piece to which the glass is cemented.

Presumably a man could scratch his name or initials on the plastic piece also.

F. Attaching.

The dosimeter may be carried on a ribbon or chain hung around the neck; or perhaps it might be carried in the pocket. In any case, it appears desirable to provide in the dosimeter a pierced ear for attaching a ribbon or chain.

G. Tamperproofing.

The dosimeter is likely to last longer, and give more accurate readings, if handled and opened as little as possible. Since the device can be read only by means of an auxiliary reader—which is ordinarily not immediately at hand—there should be no occasion for the dosimeter wearer to open the device himself, or to inspect it himself. (It should be opened and inspected only by the man authorized to operate the reader.) This means that the dosimeter should be constructed so as to be reasonably tamperproof.

Tamperproofing is easily accomplished by recessing the plastic base slightly, so as to leave no convenient hand-hold, and by providing two small holes—which may be engaged by a special wrench fastened to the photoelectric reader. While not fully tamperproof, such a device would greatly discourage unauthorized opening of the dosimeter.

Dosimeter designs have been proposed in the light of the general functions discussed above. Additional questions have arisen, however, and these are discussed below.

H. Size of the Glass Piece.

The glass piece should be large enough so as to be capable of producing enough fluorescent light to be measured readily. At the time of a Buships conference in January 1951, it was generally felt that a glass square 1" x 1" x 3/16" would be the minimum satisfactory size. Later, however, (February 1951) it was decided that a smaller square (3/4" x 3/4" x 3/16") would be adequate. An engineering drawing presented in Ref. P-12 shows the tolerances proposed for such a square. Such squares are used in the DT-60()/PD dosimeters now in mass production.

Later, however, as our understanding of the glass and the readers improved, we found that an even smaller glass piece would be adequate—for example, a disk 5/8" in diameter and 5/32" thick. (Ref. P-20; Type H-50b design.)

Probably even smaller pieces could be used—if there were some advantage to using smaller pieces. Unfortunately, the smaller the glass piece, the smaller are the permissible tolerances. Also, mounting very small pieces may be inconvenient, and positioning them accurately may be difficult. It is probable that the 5/8" diameter, 5/32" thick piece represents approximately the optimum size.

I. Shape of the Glass Piece.

If the glass piece is large, the cost of fabricating it is perhaps lowest if it is rectangular—square, for example. The straight cuts can be made quickly and cheaply using a glass cutter. (Square pieces are used in the mass-produced dosimeter.)

If the pieces were to be very small, then the tolerances would be small also, so that cutting might be impractical and grinding, or grinding and polishing, might be necessary. In such case, a disk might be the optimum shape.

If the glass pieces could eventually be made by a molding operation, disks would probably be a favored shape.

J. Finish of the Glass Piece.

Tests reported in Ref. P-11 show that it is not necessary to use glass pieces having polished faces. Rough-ground faces are adequate, and the amount of fluorescent light reaching the detector is almost the same for polished or rough-ground pieces.

Rough-ground surfaces have some minor disadvantages, however. They tend to lessen the precision of readings, especially for very small doses. When a large number of polished pieces are prepared from a given melt of 8% glass, their pre-dose readings seldom vary by more than 1 or 2 r; and the readings remain remarkably constant from month to month. If a number of rough-ground pieces are prepared from a given melt, the variation is likely to be greater--perhaps 2 to 4 r. Furthermore some increase in reading often occurs in the first day or two after the rough surfaces were prepared, suggesting that some short-term "surface curing" occurs; further slight increase may perhaps occur in the subsequent weeks. (Such increases may be wiped out by re-grinding the glass surfaces, indicating that the effect is a surface effect only.)

In general, rough surfaces are probably best when the glass pieces are generously large (large volume-to-surface ratio), or when economy is important. Polished surfaces are preferable if the glass piece is very small, or if high accuracy is necessary even in measuring small doses.

K. Painting the Glass.

If the UV light is incident on the glass piece on one face only ("UV entrance face"), and if the fluorescent light measured is limited to light issuing from one edge only ("exit edge") the remainder of the surface ("unused surface") may be painted.

Painting the unused surfaces white may double the amount of fluorescent light emerging from the exit edge; but two disadvantages may result also. (1) The paint itself tends to fluoresce; such fluorescence tends to increase the pre-dose reading, handicapping the dosimeter in measuring small doses. (2) The reflectivity of the paint may perhaps change with time; this would change the dosimeter's pre-dose reading and its sensitivity also, interfering with the measurement of all doses, whether small or large. (See Ref. P-7.)

Use of black paint, rather than white paint, has much merit. The reflectivity of black paint is not likely to change appreciably, and the fluorescence of such paint is very slight indeed. A glass piece that has been painted black on the unused surfaces has a very low pre-dose reading and is excellently suited to measuring very small doses (as well as large doses). Furthermore, the black paint prevents the surfaces in question from being contaminated by fingermarks, etc. Finally, black-painted surfaces can be cemented to plastic holders, or the like, with a minimum chance that the holder itself, or the cement, will contribute to the fluorescence.

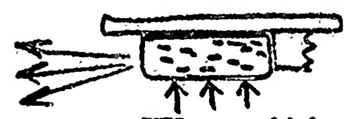
Experience has indicated that a black paint should be applied to all unused surfaces which are rough, or are to be handled appreciably, or are to be cemented.

Many kinds of black paint are suitable. Sea-Lac Black Lacquer (Duralac Chemical Corp., Newark, N.J.) appears particularly satisfactory. It shows almost no fluorescence.

L. The Plastic Base Piece.

It is obvious that the glass piece may be mounted on top of the (ethyl cellulose) plastic base piece, or may be recessed in it, as indicated in the sketch shown on a previous page. The relative advantages of these two schemes are listed briefly below.

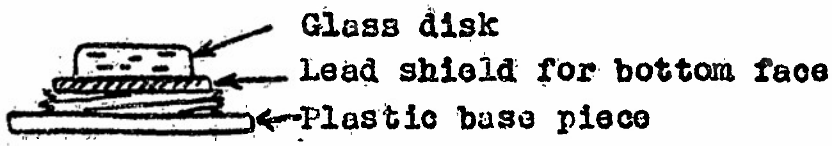
1. Recessed Mounting. Mounting the glass piece in a recess has the advantage of saving space; the resulting dosimeter is thinner. Using such a scheme it is necessary, of course, to cut away the plastic material by one edge, so that the fluorescent light may emerge; see the following sketch.

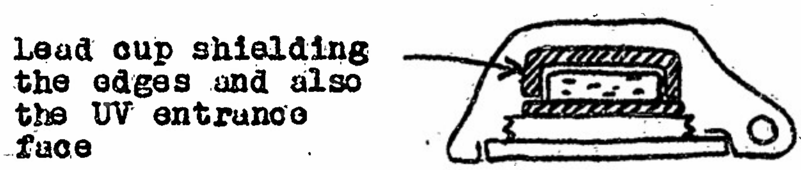


Also, it is necessary to paint all the unused surfaces of the glass piece; otherwise the reflectivity and fluorescence of the enclosing plastic regions will play a part and will introduce error.

The disadvantages of the scheme are as follows: (1) the thread is interrupted (by virtue of the region cut away to permit egress of the light); this means that the closure of the device is less secure—especially if the plastic used is flexible. (2) It becomes difficult to provide shielding for the four edges of the glass piece.

2. Non-Recessed Mounting. The glass piece may be mounted on top of the plastic base piece, as shown in the following sketch.





The advantages of this scheme are as follows: (1) The thread is not interrupted; thus the closure is positive over the entire 360°. (2) The edges of the glass piece are "free," and need not be painted at all; this saves one operation, and doubles the amount of fluorescent light emerging. (3) It is a simple matter to provide shielding for the edges of the glass piece as well as for the faces (see sketch); the plastic base piece no longer gets in the way of the edge shield.

There is a slight disadvantage, namely that the overall thickness of the device tends to be slightly greater. But the glass piece does not need to be more than 5/32" thick, so that the overall thickness of the entire dosimeter would still be only about one half inch.

M. Cementing the Components of the Base Assembly.

The base assembly consists of the plastic base piece, a lead shield, and the glass piece. These may be attached by any of various cements. In the work done under the present contact, the cements used were (a) "Miracle Type M" cement produced by the Miracle Adhesive Co., and (b) "Cement Type EC-1022" produced by the Minnesota Mining and Manufacturing Co. (See Ref. P-13). However, later work showed that these cements were not entirely satisfactory as regards shock resistance and resistance to low temperature.

N. The Plastic Cap.

The plastic cap is a cup-shaped plastic piece, also of ethyl cellulose, which holds and covers the base assembly. The plastic cap contains a lead shield (cemented in); a pierced ear for the carrying ribbon; also a gasket. The gasket, which is waterproof and compressible, assists the closure between base assembly and cap. It is essential that the gasket be somewhat compressible in view of the fact that the plastic parts may not be perfectly formed, and may tend to distort slightly with passage of time. The gasket is cemented in place. Several types of gaskets were tried; 0.020" thick polyvinyl chloride was found to be moderately satisfactory. (See Ref. P-13)

O. Color of Dosimeter.

A black color to the dosimeter seems preferable, primarily because black material is least likely to fluoresce and is least likely to reflect stray light. These considerations may be of importance if the optical design of the photoelectric reader is imperfect.

A gray color would have two advantages: (1) the absorption of thermal energy, as from an air-burst atomic bomb, would be reduced, and (2) the conspicuousness of the dosimeter would be reduced.

Until more is known about the field readers and the trouble which might be encountered therein from unwanted fluorescence and unwanted reflections, black seems to be the safest choice of color.

P. Miscellaneous Considerations.

The dosimeter case is given a smooth finish in order that it may be cleaned and decontaminated readily. For the same reason it should be reasonably free from cracks, crevices, etc.

If the plastic base assembly is to be mounted in the photoelectric reader in a certain orientation, locating pins or holes may be provided to insure correct orientation.

Section 3C: Non-Feasibility of Using a Visual-Type Reader

A. Introduction.

The contract called for a study of the feasibility of producing a reading device which would contain no photocell, but would rely on the human eye to make the measurement. In principle, visual-type readers could operate using either of two kinds of measurements: (a) measurement of the darkening produced in the glass by the exposure to gamma radiation, and (b) measurement of the fluorescence produced.

For the reasons explained below, neither of these schemes proved practical.

B. Visual Reader Which Measures Darkening.

As explained in a previous section, the silver phosphate glass tends to become darker—yellower—when exposed to gamma radiation. By judging the extent of darkening, or "tenebrescence," we can evaluate the exposure.

It was soon found, however, that the amount of darkening was too slight to detect visually unless the dose was of the order of 500 r (assuming a glass piece about one inch long). If the glass piece were several inches long, if a well-designed visual photometering system were provided, and if a source of blue light were available, perhaps a dose as small as 25 to 100 r could be detected visually; but the equipment involved would be somewhat complicated, and far less precise than a photoelectric reader.

C. Visual Reader Which Measures Fluorescence.

A small reader built at the Naval Research Laboratory in 1950 demonstrated that the fluorescence of silver phosphate glass could be measured with some degree of success using the eye as the measuring device. Using an H-4 high pressure mercury arc as source, and using "test" and "comparison" glass pieces two inches long, this device permitted visual detection of doses as small as about 25 to 50 r.

However, the scheme entailed considerable equipment, required use of long, polished, glass pieces, and afforded much less sensitivity than was to be expected using a photomultiplier tube as detector.

It was concluded that visual-type readers were less promising than photoelectric readers. Visual readers would undoubtedly be successful in measuring moderate or large doses received by long pieces of the special glass; but photoelectric devices should be far more sensitive, and would permit use of smaller glass pieces.

All subsequent effort on reader design was devoted to photoelectric readers. The following section summarizes the principal considerations governing design of photoelectric readers.

Section 3D: Photoelectric Reader Design Considerations

A. Introduction.

Several different kinds of photoelectric readers have been made by the various institutions concerned in this program:

1. The Naval Research Laboratory built a small, simple photoelectric reader in 1950, to demonstrate that such readers were feasible.

2. Polaroid Corporation, under the present contract, produced several types of photoelectric readers. The latest and most successful type, called the CP-95(XN-3)/PD radiac computer indicator, or "laboratory-type reader," has been in routine use in many industrial and military laboratories. This reader is described in detail in a later section. Some readers of this type have been adjusted with great care, and have been provided with components conforming to very close tolerances. Such readers, intended for use in the most accurate quality control testing of dosimeters, are sometimes referred to as "high-precision laboratory-type readers."

3. Admiral Corporation is making a reader which is to be mass produced for use in the field.

4. A small, battery-operated reader has been designed at the Naval Radiological Defense Laboratory. Because of its simplicity and small size, this device might be very useful as a field reader.

The present section summarizes the principal considerations governing the design of readers in general and the CP-95(XN-3)/PD laboratory-type reader in particular.

B. General Requirements of the Laboratory-Type Reader.

During the early stages of the present contract, no distinction was drawn between reader designs suited to laboratory-testing of glass, dosimeters, etc., and reader designs suited to routine field use. It was assumed that one design would serve both purposes.

Later, however, (February 1951; see Ref. P-7) the difference between laboratory-use function and field-use function was recognized. We were then asked to design a laboratory-type reader CP-95(XN-3)/PD which, besides being well suited to use in laboratory tests, would be useful in certain other applications also. In all, four different types of functions were to be served by this laboratory-type reader, as follows:

1. It was to be excellently suited to routine quality control testing of complete dosimeters; also to routine testing of glass melts, i.e., testing small, unmounted pieces of glass.

2. It was to be suited to research studies of reader performance, interchangeability of reader components, etc.; also to assisting in the selection of filters, photomultipliers, etc., required in building additional readers.

3. It was to serve as the general basis of design of a field reader--to be designed in detail by Admiral Corporation.

4. It was to be reasonably suited to field use--in the interim period prior to the availability of regular field readers.

C. Specific Requirements of the Laboratory-Type Reader.

It was desired that the laboratory-type reader CP-95(XN-3)/PD meet the following specific requirements:

Range: 0 to 600 r (high range); also 0 to 200 r (low range).

Linearity: Reasonably linear throughout this range.

Sensitivity: It was hoped that the reader would be sensitive to perhaps 2 to 5 r for dosimeters exposed only slightly, and perhaps 2 to 5 percent for dosimeters which had been exposed heavily.

Accuracy: It was hoped that when properly adjusted, the reader would provide absolute accuracy of perhaps 5 to 10 r, or 5 to 10%, whichever is greater.

Flexibility of scale: It was desired that the reader be able to accommodate almost any level of pre-dose fluorescence which might later be adopted, and almost any degree of glass sensitivity which might be adopted. In other words, the zero setting and sensitivity setting should be adjustable over wide ranges.

Direct reading: Readings were to be made directly in roentgens.

Ease of loading: The design was to be such that dosimeters could be loaded readily, and would automatically locate themselves properly in the reading station.

Ease of verifying the accuracy: Provision was to be made whereby fixed standards could be measured periodically in place of the "unknowns," to make sure that the instrument was performing properly.

Electrical supply: 110 to 120 volts, 60 cycles.

Ease of operation: It was desired that the controls be few and simple; also that the positioning of the samples in front of the UV lamp should be semi-automatic; also that exclusion of ambient light should be essentially automatic and should be complete enough so that the instrument would operate properly even in direct sunlight.

Miscellaneous: The device was to be simple, light, rugged; it was to use only JAN-approved electrical parts.

D. Selection of Optical System Components.

The individual components of the reader's optical system were selected after weighing many alternatives. Fluorescence measurements are notoriously difficult, and large errors may enter from apparently minor changes in the UV excitation system and the fluorescent-light measuring system. Selection of optimum components is essential (a) to insure reproducible performance from one reader to another, (b) to provide the maximum output of fluorescent light--in order to maximize the signal-to-noise ratio, and (c) to avoid need of establishing fantastically close tolerances as to spectral response, position, angle, etc., of the various parts.

The principal components of the optical system are discussed separately below.

1. UV Lamp. The RP-12 cockpit lamp, a small fluorescent lamp containing some mercury and a small amount of rare gas, has been found to be very satisfactory. It serves excellently as the source of UV radiation for exciting fluorescence in gamma-irradiated pieces of 8% silver phosphate glass. This lamp, recommended to us by NRL scientists, consumes only about 5 watts, yet gives out much radiation in the near UV region of the spectrum. It has a life of 1000 hours or more. Starting and stopping it does no harm. It warms up in a few seconds. It starts easily, ordinarily; some lots, however, were found to be difficult to start. It is not critical as to voltage; a wide variation in voltage changes the spectral energy distribution only very slightly. Its output changes appreciably with temperature, however. If cold air is blown across the lamp, the intensity falls appreciably. Also, the lamp must be wired up so that the correct polarity is observed.

Other lamps have been tried. The H-4 mercury arc is extremely rich in near-UV light; but unfortunately it dissipates much heat, and requires more power. Ordinary incandescent lamps could be used, but produce relatively little near-UV light, as compared to visible light.

2. UV-Pass Filter. It is necessary to block off the orange light issuing from the lamp: such light would tend to obscure the orange-colored fluorescent light originating within the glass piece. A UV-pass, orange-excluding filter must be placed between lamp and glass piece.

The 5-mm-thick Corning filter #5860 has been found almost ideal for the purpose. As shown in Refs. P-14 and P-22, it has a pass-band centered near 360 mμ, and transmits almost no visible light. Use of a 2.5 mm. thickness might be even better; it would pass twice as much UV.

But it might possibly pass enough light near 600 mμ to hurt the signal-to-noise ratio. Also, it would pass a little UV radiation near 310 mμ, which tends to increase the amount of fluorescence originating even in undosed glass; this also would hurt the signal-to-noise ratio.

Various other Corning filters have been tried; but they transmit less UV, or transmit too much light near 310 mμ or near 700 mμ.

We have found that different melts of #5860 filter glass vary somewhat in concentration of colorant. Thus to obtain a given transmission at 360 mμ we have had to adjust the thickness slightly; in some instances a thickness of 4 mm. was used, rather than 5 mm. In general, we have regarded it as a good precaution to adjust the thickness so that the transmission of 360 mμ light will be approximately 33% (more exactly: 33% plus or minus 8%, for a typical laboratory-type reader, and 33% plus or minus 4% for a high-precision laboratory-type reader).

The UV-pass filter is usually placed close to the lamp, and is housed carefully so that no radiation can pass around the edges. As an added precaution the filter edges are painted black.

The filter appears very stable. No appreciable change occurs in 1000 hours of use.

3. System for Collecting the Fluorescent Light. Fluorescent light issuing from the glass piece issues, of course, from all the exposed surfaces. It seems best, however, to collect only the fluorescent light issuing from the edges (i.e., the slender lateral surfaces) of the glass piece. This has three advantages: (1) very little UV radiation is collected, since little emerges here; any that did emerge might produce fluorescence elsewhere, and might hurt the signal-to-noise ratio. (2) Very little visible light is collected; this too would hurt the signal-to-noise ratio. (3) The incident UV beam does not overlap the beam of fluorescent light collected, so that the diaphragming problems, etc., are cleanly separated.

The light to be collected could be collected by a concave mirror, a lens, a light-pipe, or merely by placing the detector itself very close to the glass piece's exit edge.

A concave mirror seems best from many viewpoints. A concave, rear-surface, glass mirror of 2" radius of curvature and large aperture is very inexpensive. It collects light over a large solid angle. If used slightly off-axis, it can be made to deliver its light effectively to the detector, at unit magnification, and with little distortion.

Such mirror has one disadvantage, however. It actually images the glass piece's exit edge onto the detector, e.g., onto the photocathode of the photomultiplier. Thus if the light emerging from the exit edge is non-uniform in intensity, as is likely to be the case, the illumination of the photocathode is non-uniform also. But the sensitivity of a typical photocathode varies from point to point over the photocathode, with the result that the photomultiplier's output signal may be slightly too great or slightly too small depending on the exact nature of the non-uniformity of the light emerging from the exit edge. If the concave mirror is slightly out of focus, or is oriented slightly incorrectly, the error in question may be accentuated.

Another excellent means of collecting light is simply to place the detector very close to the glass piece. This makes for economy and has the further advantage that the glass piece's exit edge is not imaged on the detector. There are three disadvantages, however; (1) Less light is collected—especially when it is impractical to situate the photocathode itself very close to the exit edge itself. (If the photocathode is too close to the exit edge, the least variation in distance from exit edge to photocathode may alter the efficiency of light collection by, say, 5%, which produces a 5% error in the reading). The amount of light collected is typically about 1/3 to 1/10 as great as when a concave mirror is used. (2) Rays emerging from the exit edge in oblique direction tend to miss the photocathode altogether. This means that an error will result whenever a sample has an exit edge which is especially diffusing or is tilted slightly. (3) Trouble is likely to arise by virtue of the fact that the sensitivity distribution over the photocathode is often non-symmetric.

Instead of using a concave mirror, we could use a lens. But 2-inch-diameter lenses of large numerical aperture tend to be expensive. (If a lens of plastic is to be used, it is essential that the orange-pass, UV-excluding filter is placed ahead of the lens; otherwise the plastic itself will receive some UV and will fluoresce, hurting the signal-to-noise ratio.) Fresnel lenses might be used, but tend to collect dust. Light-pipes offer some advantages.

4. <u>Orange-Pass Filter</u>. It is essential to use an orange-pass, UV-excluding filter between glass piece and detector, to prevent passage of any of the UV exciting radiation to the detector.

A 3-mm-thick Corning #3482 filter has been found ideal. Here again some melt-to-melt variation has been found, but the desired spectral cut-off can be achieved by adjusting the thickness of the filter.

As shown in Refs. P-13 and P-23, the #3482 filter has a sharp cut-off, eliminating all light of wavelength less than about 530 mμ and transmitting freely light of wavelength exceeding about 570 mμ. We have regarded a filter as being ideal if its transmission at 550 mμ is 53% plus or minus 16% (for laboratory-type readers), or 53% plus or minus 8% (for high-precision laboratory-type readers).

Determining the transmission at 550 mμ with sufficient accuracy is difficult, since the transmission curve is very steep here. It is essential that the determination be made with a specified, narrow band-width of radiation, and with accurate wavelength calibration, all as explained in detail in Ref. P-23.

Attempts have been made to use filters having cut-offs at shorter wavelength. This was found to be undesirable, as it passed some of the bluish-white fluorescence produced even by the undosed glass, and thus increased (a) the pre-dose reading, and (b) the variation in pre-dose reading. Moving the cut-off wavelength towards longer wavelengths, on the other hand, tended to cut off some of the orange fluorescent light, thus reducing the signal strength.

The #3482 filter appears essentially unchanged after 1000 hours' use. It is well known that this filter's cut-off wavelength changes slightly when the filter's temperature is changed drastically; but a 20°F. change in temperature was found to affect the reader's performance only negligibly.

5. Detector. A photomultiplier tube has invariably been used as the detector. In the early stages of the project, the indications were that other types of detectors would probably be insufficiently sensitive. Later, improved UV lamps were obtained, as well as improved filters and improved light collection systems, so that it might now be possible to use a vacuum phototube instead of a photomultiplier.

The photomultiplier used is the 931-A tube (G.E., R.C.A., or Westinghouse) with the usual S-4 photocathode. This tube was adopted because it was a common, inexpensive photomultiplier, and because it had good (although not peak) sensitivity to orange light.

Not all 931-A photomultiplier tubes purchased were found satisfactory. A few showed insufficient sensitivity, or were microphonic.

By far the greatest difficulty, however, was the difficulty of selecting photomultipliers having the desired shape of spectral response curve.

Most of the 931-A tubes have slight or negligible sensitivity to red light, as compared to blue light. For some of the tubes, however, the sensitivity to red light is abnormally high. As explained in Refs. P-13 and P-15, such abnormal spectral response is harmful in two ways: (1) it causes readings made on undosed dosimeters to be too low, relative to readings of dosed dosimeters, since undosed dosimeters emit mainly bluish-white light whereas dosed dosimeters emit mainly orange light. (2) It causes readings made on fixed standards to be in error, since those standards seldom give off light of just the same color as the light from dosed dosimeters.

Part of the difficulty is eliminated, or at least reduced, by the use of the orange filter referred to on the previous page. This filter simplifies the situation by eliminating all of the blue light. However, a little green light gets through, and much yellow light--in addition to orange and red light.

The difficulty could be reduced further--in principle, at least--by placing just in front of the photomultiplier a sharp-cut-off, wide-angle, filter transparent to orange light but opaque to red light. If such a filter were used together with the orange filter, the shape of the photomultiplier's response curve would be almost irrelevant. Unfortunately, no such red-eliminating filter is known.

To reduce the difficulty, advantage was taken of the fact that many 931-A photomultipliers appeared to have very little response to red light. It was found, for example, that in a lot of 32 photomultipliers, only about half had appreciable sensitivity to red light; by rejecting these tubes, we were left with a group all of which had roughly the sample spectral response, and in particular, very little red response.

Sensitive, non-microphonic 931-A tubes having low response to red light were given the name "Group 1 photomultipliers." The exact criteria used in selecting Group 1 tubes are explained in Ref. P-15. Selecting these tubes is one of the most important steps in producing readers which will read alike for any given dosimeter, whether dosed or undosed.

Some lots of 931-A tubes have been found to be largely unsatisfactory; which adds to the expense of finding good tubes.

The need for obtaining tubes having the correct spectral response is partially reduced as better standards are found; if we could find fixed standards giving out orange light of just the color emitted by dosed dosimeters, the tolerances on the photomultipliers could be eased somewhat. They could be eased further if sharper-cutting orange filters were found, or if a sharp-cutting minus-red filter could be found.

Other types of photomultipliers could be used. Some of the newer "end-on" photomultipliers might be very convenient, especially as no auxiliary light-collecting means would then be needed.

It might be advantageous to use a photomultiplier having a flat response curve in the orange part of the spectrum. (The 931-A Group 1 tube has a response curve which drops rapidly at wavelengths exceeding 500 mμ.) However, there are no commercially available photomultipliers having peak response in the orange or red part of the spectrum; we understand that experimental lots of tubes of this type have been made but have appreciable dark current and short shelf-life.

The typical 931-A Group 1 tube performs excellently and lasts 1000 hours or more. Its output is very sensitive to change in voltage, but this is not serious since (a) considerable voltage regulation may be built into the electrical supply system, and (b) if the sensitivity should change, periodic re-measurement of the fixed standards reveals the error and permits re-adjusting the sensitivity control knob.

The 931-A tubes also exhibit various photo-fatigue effects, as explained in Ref. P-22 and P-26. But by designing the reader properly, so that the photocathode is at all times shielded from intense ambient light, excellent performance is achieved.

E. Selection of Electrical Components.

It is necessary that the electrical supply system for the photomultiplier be matched to the maximum current to be drawn from the photomultiplier. If the supply system if inadequate, a large voltage drop may occur when large current is drawn from the photomultiplier; if this happens, intensely fluorescent samples may produce readings smaller than those produced by less fluorescent samples. The danger of overloading the photomultiplier's supply system is reduced by making sure that the UV lamp intensity is not too great, and that the sensitivity of the photomultiplier itself is not too great. In measuring extremely fluorescent samples it may be worthwhile to place a mask over the UV lamp, to reduce the amount of UV light reaching the sample. (See Ref. P-24.)

If, for example, the electrical circuit includes a full-wave rectifier employing a 6AL-5 double diode, special precautions may be necessary if overall electrical linearity is to be maintained. It may be desirable to operate the tube at abnormally low heater current; negative feedback may be necessary; it may even be necessary to select double diode tubes so as to retain only those which are found empirically to give essentially "0" reading when measuring a completely non-fluorescent sample. If adequate precautions are taken, linear operation may be maintained even for samples showing only half the fluorescence exhibited by a typical, undosed dosimeter. (See Ref. P-22.)

For most purposes, the indicating meter is adequate if it has a scale 3 inches long and if the deflection-vs-current relationship is linear throughout the scale to within about 3% of full scale. For readers to be used in precision testing, however, it is preferable to use a meter having a scale at least 6 inches long and have linearity better than 1% of full scale. (See Ref. P-25.)

In general, it is desired that rugged, standard, JAN-approved electrical parts be used.

F. General Mechanical Design.

It is desired that the reader components be arranged compactly, and so that the principal controls are accessible at the front of the instrument.

The samples—and especially the fixed standards—should be mounted preferably facedown, so that dust cannot collect on the UV entrance faces. A UV-illumination diaphragm should be included, to standardize the size of the illuminated area of the glass piece. An opaque barrier should be provided which will prevent scattered UV light from reaching the detector.

Provision should be made for leaving the fixed standards more or less permanently housed within the instrument, protected from dust, yet ready at any moment to be swung into the instrument station to check the overall performance of the instrument.

Samples and standards should preferably be mounted on a swinging sector, since this entails less friction and less play than a straight-sliding holder.

To provide two ranges with only one meter, it is necessary to have a range-change switch, and to provide the meter with two scales.

A suitable housing should be provided. It should contain louvres or grilles to permit some circulation of air and to prevent the temperature rise from exceeding about 20°F. In precision test work, an electric fan should be used to keep the temperature rise below 10°F.

The reader should be provided with an electric supply cord, an on-off switch, a key to open the (tamperproof) dosimeter, an instruction manual, adequate signs warning of danger from electrical shock if the instrument is opened, and a carrying case.

A later section describes the actual designs used. The present section has been concerned only with design principles.

Section 3E: The Problem of Providing Fixed Standards

A. Introduction; Need for Fixed Standards.

The entire glass dosimeter program depends on having suitable fixed standards available, meaning objects which are similar in form to dosimeters but which fluoresce with fixed, known intensity.

Fixed standards are necessary because the photoelectric readers are, in fact, only comparators. They can compare the fluorescence of an "unknown" sample against the fluorescence of a "known" sample. But they cannot make absolute determinations in the absence of any fixed standard.

The need for fixed standards derives from these circumstances: (1) The UV output of UV lamps varies slightly from lamp to lamp and probably from day to day also—especially if the ambient temperature changes. (2) The sensitivity of photomultiplier tubes varies widely from tube to tube, and varies somewhat from day to day, depending on variations in line voltage, etc. (3) Various other components of the reader may vary. To evaluate these changes is impractical. The easier course is to adjust the overall sensitivity of the instrument by trial and error until the correct reading is obtained for a sample whose fluorescence-ability has been evaluated previously.

B. Permanently Fixed vs. Semi-Fixed Standards.

Fixed standards may be permanently fixed or semi-fixed. By permanetly fixed standards we mean standards whose fluorescence remains essentially constant for years, regardless of whether they are exposed to gamma radiation, daylight, etc. By semi-fixed standards we mean standards that remain essentially unchanged if kept in the laboratory and protected from gamma radiation, intense daylight, etc., but are subject to some change otherwise. Obviously, field-use readers should be provided with permanently fixed standards. But laboratory-use readers may perform excellently using semi-fixed standards, if suitable precautions are exercised.

C. Classes of Standards.

The most important standards are those whose fluorescence corresponds to that of a typical dosimeter exposed to, say, 100 to 200 r; such standards are called "medium-fluorescent standards," or "M-Stds." A less important class of standards is the class whose fluorescence resembles that of a typical, undosed dosimeter; such standards are called "low-fluorescent standards," or "L-Stds." In addition, there are various special types of standards which may be used for special purposes, as in selecting reader components, revealing reader defects, etc.

These three classes of standards are discussed separately below.

D. M-Stds.

1. Purpose. An M-Std. is used from minute to minute and from day to day in adjusting the overall sensitivity of a reader. It is inserted in the reader in place of the unknown dosimeter, and the meter reading is noted; the overall sensitivity is then adjusted until the meter reading has the value known to be correct for the standard in question. The unknown dosimeter may then be evaluated with confidence.

2. Design Requirements. M-Stds. must be designed so as to have approximately the same size and shape as a typical dosimeter; thus minor variations in reader geometry, etc., will be of little consequence.

The M-Stds. are designed to emit light of essentially the same color as that emitted by dosed dosimeters—a dull orange color. Such similarity is essential if different readers have photomultipliers of unlike spectral response.

The M-Stds. are designed also so as to have roughly the same UV spectral excitation curve as a typical dosed dosimeter. Using such standards, variation in the spectral output of the UV lamp, or in the spectral transmittance of the UV filter, will be of little consequence.

The M-Stds. are designed to have roughly the same transparency for UV light that dosed dosimeters have. This insures that the geometry of production of fluorescent light within the standard will be comparable to that within the typical dosimeter.

The transparency of the M-Std. for the fluorescent light produced within it is designed to be comparable to the situation in a glass dosimeter, so that fluorescent light will in each case emerge with essentially equal ease and similar angular distribution.

The temperature coefficient of fluorescence of the M-Stds. is intended to resemble that of the dosed dosimeter so that variations in room temperature will not greatly change the relative response of standard and dosed dosimeter.

The M-Stds. are intended to be as stable as possible with respect to exposure to gamma-radiation, X-radiation, daylight, UV radiation, heat, age, etc.

Finally, the M-Stds. are intended to have an amount of fluorescence corresponding to between half and full scale deflection on the meter (using the 0 to 200 r range); such a deflection makes it easy to adjust the overall sensitivity of the instrument accurately.

If the fluorescence were stronger, the meter indicator would go off-scale. If the fluorescence were weaker, errors due to dirt or finger-prints on the standard would be relatively more harmful.

3. Kinds of Glass Available. Many different kinds of glass have been tested in the hope of obtaining an almost ideal M-Std. The work has been summarized in Ref. P-16, where eleven different types of glass are compared with respect to the ten major criteria of excellence.

The best types of glass for use in M-Stds. appear to be several types (E-9530, E-9686, E-9272, E-9631, and C-1109) formulated and prepared specially for this purpose in 1951 and 1952 by Dr. N.J. Kreidl of the Bausch and Lomb Optical Company. Previously, several less-satisfactory types had been used, as follows:

> Pittsburgh Plate Glass Co.'s commercial "flesh tint" glass. This emits light which is much too reddish in color.
>
> Water white plate glass. This emits light which is too whitish in color. The amount of light tends to be too little, and depends critically on the amount of UV light in the wavelength region below 330 mμ.
>
> "S-4L" glass, which is a manganese-containing glass prepared by B and L; slightly too reddish; moderately opaque to its own fluorescent light. See Ref. P-14.

The E-9530 glass proved to be superior to the glasses listed above. It emits light of approximately the desired color and in approximately the right quantity. Its principal weakness is its tendency to undergo small surface-changes, so that the fluorescence may change by 5 or 10% over a period of several months. Also, its transparency to its own fluorescent light is somewhat low. This glass contained a small amount of manganese, and probably a small amount of iron also, to partially quench the overly-intense fluorescence of the manganese. See Ref. P-16 for further details.

The E-9686 glass is very similar to the E-9530 glass, having the same good and bad features.

The E-9272 glass, discussed in detail in Ref. P-16, was found to be satisfactory in all respects except one: it fluoresces much too strongly, corresponding to about 1500 r. Unless stopped down suitably, it gives readings which are off-scale and even tend to over-load the photomultiplier system. But by covering the glass square's

UV entrance face with a suitable mask, it is a simple matter to reduce the intensity of fluorescence to approximately 150 r. Standards of this type are described in a later section.

The E-9631 glass is very similar to the E-9272 glass, having the same excellent features.

The C-1109 glass also is very similar to the E-9272 glass and has the same excellent features; melt C-1109 has the added advantage of being a large melt—400 lbs, sufficient to make several thousand standards if this should be desired.

Of course, a dosed dosimeter (dosed to, say, 150 r) may itself be used as an M-Std. of semi-fixed type. Such device is ideal in that it "automatically" resembles a dosed dosimeter in all principal respects. However, it is by no means stable with respect to gamma radiation and various other influences.

Finding a glass well-suited for use in M-Stds. has been one of the major difficulties of the entire project. The three glasses mentioned in the three preceding paragraphs represent excellent, although not quite perfect, solutions to the problem. It seems likely that even more ideal glasses could be formulated if necessary.

4. Requirements as to Uniformity. It is convenient, although not essential, that all M-Stds. made from a given melt of glass have the same fluorescence. In the various groups of M-Stds. made to date, such uniformity has not be achieved; variations of perhaps 10% have been found. Such variations are of little consequence, however, if each of the M-Stds. is evaluated separately and marked accordingly.

5. Calibrating the M-Stds. The M-Stds. must be calibrated by a central group serving as a "standards laboratory" for the entire glass dosimeter program.

If it is thought that the standards may change somewhat from month to month, the standards should be re-calibrated at suitable intervals, such as every month. Alternatively, the old standards may be discarded and new ones used in their place.

The standards laboratory responsible for calibrating standards must have two basic tools: (1) a master reader, and (2) a master pool of M-Stds. ("M-Pool"). The master reader must be that one reader which is declared to be "perfect" as regards spectral properties of photomultiplier, filters, UV lamp, and in all other respects also. The M-Pool must be the best available collection of M-Stds. representing a variety of glass types, assembly methods, etc. (so that it is not necessary to assume blindly that any one type of glass or any one type of assembly will give complete constancy from month to month and year to year.)

By assuming the M-Pool values to be known and constant, by assuming the master reader to be perfect, and by comparing the M-Pool readings with the readings obtained for the M-Stds. to be calibrated, the desired calibration is effected.

It is a basic weakness of the present program that no means exists at present for demonstrating whether the M-Pool itself remains constant. This pool, which has been maintained by the Polaroid Corporation' Research Department for the better part of a year, has perhaps changed by no more than 5 or 10% per year; but it is at present impossible even to estimate just how great the change has been, or in which direction. (See Ref. P-21, P-26)

To provide a sound, fixed basis for calibrating M-Stds., an absolute fluorimenter must be built. General designs of such fluorimeter have been proposed (Ref. P-26), and construction of such an instrument has been urged (Ref. P-26). An absolute fluorimeter is one of the greatest needs of the entire glass dosimeter program.

Even assuming that the present M-Pool is perfect, some difficulty remains in calibrating M-Stds. The reproducibility of mounting and reading the M-Stds. is perhaps no better than about 3% (for the two-sigma variation). Also, some slight changes in the master reader are occasionally unavoidable, as when the photomultiplier fails and must be replaced by another photomultiplier—which is almost certain to have slightly different spectral response.

E. L-Stds.

1. Purpose. L-Stds. ("low-fluorescent standards") may sometimes be needed. Such a standard may be needed, for example, in finding whether a reader reads correctly when measuring dosimeters which are undosed, or have received only small doses. The need for an L-Std. is great in two situations: (1) the reader is not linear, or (2) the spectral response of the optical system is incorrect.

As regards non-linearity: The earliest of the CP-95(XN-3)/PD readers were linear over most of the 0-to-600r range, but were somewhat non-linear near the low end of the range. Thus it was not sufficient merely to achieve the correct general level of sensitivity in the reader; it was necessary also to adjust the "zero knob" by trial and error so that an L-Std. of known, fixed fluorescence would read properly. (The readers produced after November, 1951, employ an improved electrical design, using negative feedback; they are almost perfectly linear. For such readers, L-Stds. are superfluous ordinarily.)

As regards spectral response: If for example the photomultiplier used in a particular reader had a slightly too-low response to short-wavelength light, undosed dosimeters would tend to read too low. To compensate for such tendency, the operator could insert an

L-Std. of known, fixed fluorescence, and adjust the zero knob until the correct reading was obtained. Such compensation would be required also if the spectral properties of the filters, UV lamp, etc., were incorrect. (In readers produced since November 1951, especially great care was taken in verifying the properties of all principal components. Thus the need for L-Stds. was greatly reduced.)

L-Stds. may find some use also in adjusting readers so that they will read directly in roentgens. A typical, undosed dosimeter exhibits some fluorescence; but by adjusting the zero knob appropriately this fluorescence can be virtually cancelled out, so that an undosed dosimeter will read zero (0 r). (There is, however, a better method of accomplishing this end, as explained in Ref. P-24, Appendix 1. That method requires no L-Std.)

2. Design Requirements. It is required of an L-Std. that it resemble an undosed dosimeter in all principal respects, but must be unaffected by gamma radiation, light, age, etc. It is especially important that it resemble the undosed dosimeter as regards: spectral excitation curve, spectral emission curve, and amount of fluorescence. Other desired properties are indicated in Ref. P-20.

3. Kinds of Glass Available. Very few types of glass are available for use in L-Stds. since few types exhibit as little fluorescence as undosed 8% silver phosphate glass. Ordinary window glass and ordinary plate glass, for example, were found to fluoresce several times as strongly as the 8% silver phosphate glass.

However, two kinds of glass were found to be generally satisfactory: Pyrex glass of Corning type 7740, and 0% silver phosphate glass. The pyrex glass was tried out fairly thoroughly and found to meet the requirements of an L-Std. glass rather well, as explained in detail in Ref. P-20. The glass tends to fluoresce somewhat too little; but it was found that the fluorescence may be increased slightly, as desired, by exposing the glass for several hours to the intense UV radiation from a Hanovia Luxor quartz mercury arc situated at a distance of a few inches.

Probably the 0% silver phosphate glass would make an excellent L-Std. glass also. This glass, which has the same formula as the 8% glass but contains no silver phosphate, has a very low fluorescence and is reasonably stable with respect to most influences, including gamma radiation.

Of course, undosed dosimeters can be used as L-Stds; but they can scarcely be said to be stable against gamma radiation or prolonged exposure to UV light.

4. Calibration of L-Stds. The L-Stds. must be calibrated using the master reader, and with respect to the M-Std. pool. For best results, they should be re-calibrated frequently.

5. Fundamental Weakness of L-Stds. It seems clear that L-Stds. have the fundamental weakness of instability. Fingermarks, for example, may increase the reading by perhaps 2 to 10 r. Aging of the glass surface may increase the reading by 0 to 10 r if the glass surface is rough--and if it is not rough, it is scarcely comparable to the glass squares ordinarily used in dosimeters. Aging of the black paint, and perhaps some tendency for the cement to diffuse through to the (back) surface of the glass, may cause an increase in reading.

The point is that such increases are relatively serious in a sample resembling an undosed dosimeter; they may represent increases of 5 to 50% in the reading. (For an M-Std., an increase of 2 to 10 r is far less serious.)

Thus it appears unwise to place any long-term reliance on L-Stds. It is better to use an M-Std., and rely on the linearity of the electrical circuit to interpolate to small readings.

Even if an elaborate L-Pool were set up, it is likely that the pool itself would show considerable drift and thus would fail to perform a useful function.

F. Miscellaneous Types of Standards.

Various other types of standards may be useful in special circumstances.

H-Stds. (highly-fluorescent standards) corresponding to about 500 r may be useful in verifying the performance of readers near the upper limit of their high range. If highly-dosed dosimeter tend to saturate the photomultiplier system, or if the range-change system associated with the meter is imperfect, an H-Std. may prove helpful. No formal standards fulfilling this function have been made, but they undoubtedly could be made readily using the E-9272 glass referred to on the previous page.

Probably the glass piece would have to be masked down somewhat, to prevent its giving an off-scale reading.

An opaque standard (for example, small square of aluminum painted black) permits verifying that the reader performs properly when no light at all issues from the standard.

Standards differing in fluorescence by exactly 3 to 1, say, permit determining whether the reader is linear. It is only necessary to measure both of the standards using various different sensitivity settings, and see that for each setting the resulting readings are exactly in the ratio: 3-to-1. Such standards are useful also in verifying the correctness of the 3-to-1 range-change mechanism.

Standards having very abnormal spectral excitation or spectral emission characteristics may be useful in revealing any abnormality in spectral response of the reader. We have found it useful to use (a) a "WW" standard, consisting of a square of water-white plate glass and emitting a bluish-white light and (b) an "FTS" standard, consisting of a square of flesh tint glass and emitting a very reddish light. If, for example, the ratio of the readings of these two standards is near 1.5 to 1.6 for a given photomultiplier, this constitutes evidence that the photomultiplier has a typical spectral response; a ratio of only 1.0 indicates that the photomultiplier is too red-sensitive and should be rejected.

To verify the focal setting of the light-collecting concave mirror, it is convenient to use standards having (1) highly polished exit edges and (2) very rough exit edges. If the mirror setting is correct, the ratio of readings of such standards will have a certain value; but if the setting is incorrect, the ratio will be abnormal.

Section 3F: The DT-60(XN-3)/PD Dosimeter

A. Introduction.

Plate 1 shows the appearance of the DT-60(XN-3)/PD dosimeter, or radiac detector. This design, sometimes referred to as the H-47 design, is the design according to which several hundred dosimeters were produced and shipped to Buships for test. Furthermore, this design closely approximates the design of the DT-60()/PD glass dosimeters now in mass production by two different manufacturers (Polaroid Corporation and Corning Glass Works). (A later section describes a smaller, better design, known as the H-50 design, worked out subsequently to the H-47 design.)

B. Design.

The DT-60(XN-3)/PD design was based on considerations discussed in previous sections.

The device employs 8% silver phosphate glass such as was produced in 1950 by the Bausch and Lomb Optical Co. The sensitivity level of the glass was chosen arbitrarily and is perhaps 30 to 60% greater than that typical of the dosimeters now being mass produced. The pre-dose fluorescence of the glass is perhaps comparable with that of the dosimeters now being mass produced.

The glass piece is a square approximately 3/4" x 3/4" x 3/16", and has a matt finish on all sides. The unused surfaces are painted black with Sea-Lac black lacquer. See Refs. P-8 and P-12 for further details.

The square lead shield is 3/4" x 3/4" x 0.034", and has a central hole 0.10" in diameter.

The plastic base piece is of black Tenite II (see footnote 1). As indicated in the drawings presented in Ref. P-8, the plastic base piece includes a central cavity or recess to receive the square lead shield and the glass square. Also, it contains two holes for fixing the azimuth of the device when inserted in the laboratory-type reader. It is threaded to accommodate the plastic cap described below. On the back surface there is a pair of holes for the special wrench.

Footnote 1: This description applies to the DT-60(XN-3)/PD dosimeters produced in September 1951, under the present contract. Using our present knowledge, as summarized in previous sections, the design could be made slightly better.

The glass piece is cemented to the lead square by means of Miracle Type M cement, and the lead square is cemented to the plastic base piece similarly. The resulting assembly is known as the base assembly.

The plastic cap, also of black Tenite II, is threaded and contains a circular lead shield 0.034" thick and with a central hole 0.10" in diameter. The plastic cap includes a pierced ear to receive the carrying ribbon or chain. A gasket, consisting of a 0.020" thick vinylite sheeting, is included also.

When the cap is screwed onto the base assembly, the device is complete.

C. Performance.

The DT-60(XN-3)/PD device performs rather well. It has a range from 0 to 600 r and beyond; it is linear; its additivity is good, and its freedom from integration-rate-dependence likewise. If used under typical conditions and measured on a perfect reader, it provides a "two sigma" accuracy of perhaps 5 r or 20%, whichever is greater.

It is about the size of a dollar watch, and is smooth, rounded, warm to the touch, and non-allergic. It can stand elevated temperature and high humidity well, and is almost unaffected by five drops from a height of 4 ft. onto a steel deck. It is reasonably waterproof. (The slightly revised design now in mass production has better shock resistance and is entirely waterproof.) It is reasonably temperproof, and can presumably be decontaminated rather readily.

It tends to read slightly too low if raised above room temperature just before reading, or if held at low temperature just during exposure to gamma radiation. (See Ref. P-5 and P-6.) It tends to read slightly too low if dosed very rapidly and read within a half-hour thereafter. (Ref. P-17.)

Its wavelength dependence is good with respect to gamma radiation produced by an air-burst bomb and received in direction perpendicular to the UV-entrance face of the glass square (Refs. P-6 and P-19). But considerable errors must be expected if the radiation includes an appreciable soft component and if the radiation enters the glass square diagonally or through the edges. (Refs. P-18, P-19, and P-20.)

In general, and at the time when it was produced (mid-1951), it was perhaps the best existing personal dosimeter that was small, inexpensive, and stable.

Of course, it cannot be evaluated without recourse to a reader device.

D. Production.

Several hundred units were produced under the present contract and were sent to Code 854 of Buships in 1951. (As explained elsewhere, mass production of the rather similar device DT-60()/PD is underway at two industrial concerns.)

Section 3G: Other Designs of Glass Dosimeters

A. Introduction.

The previous section describes the DT-60(XN-3)/PD, or "Type H-47," design of glass dosimeter, which is excellent in most respects and is almost identical to the DT-60()/PD device now in mass production.

A better design has been worked out, however. This is the H-50 design described below.

Several other designs have been worked out, but appear superseded by the H-47 and H-50 designs.

B. The H-50 Design of Glass Dosimeter.

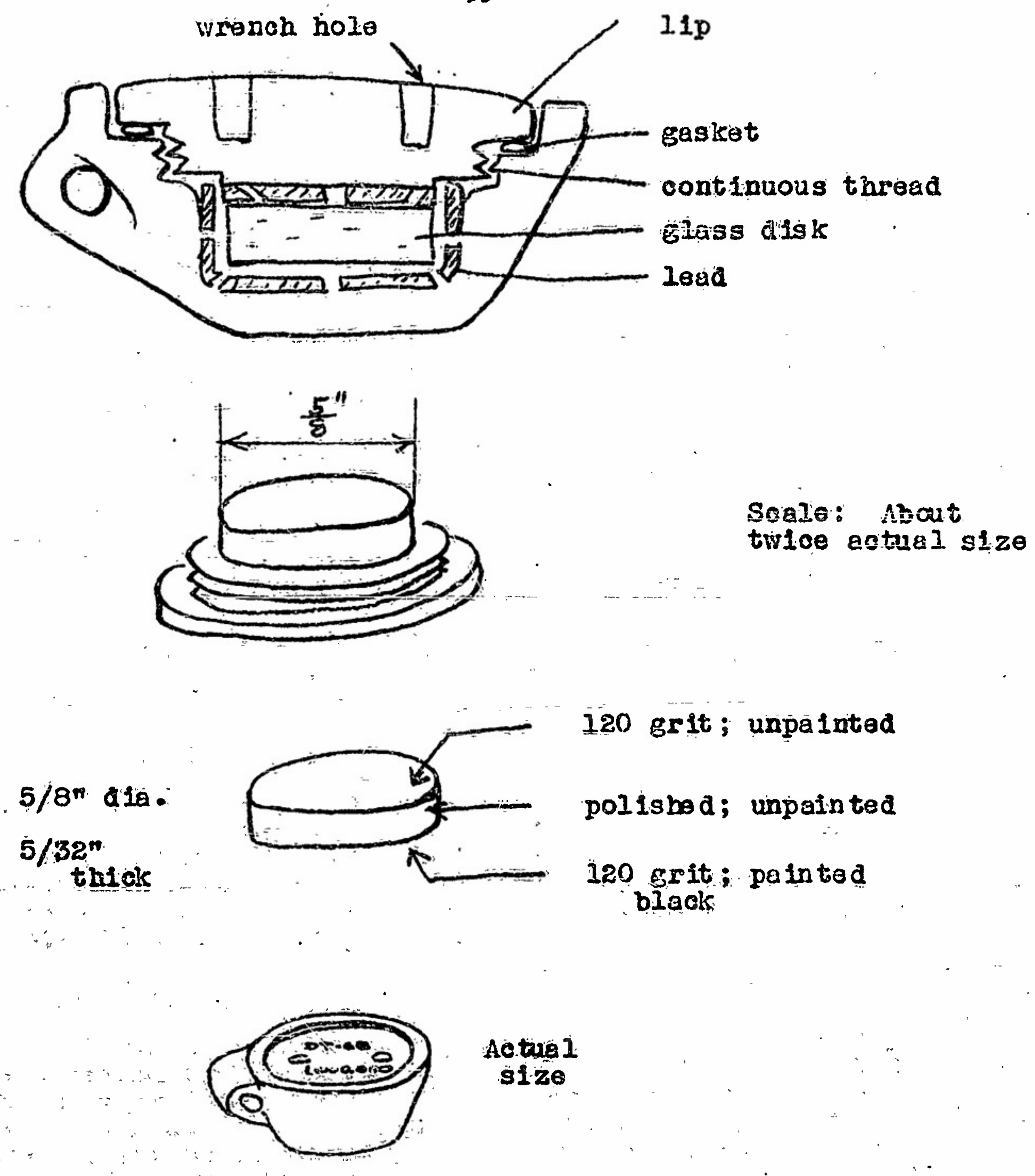
The H-50 design was intended to overcome three limitations of the DT-60(XN-3)/PD, or H-47, device described in the previous section. The limitations are as follows:

1. Energy Dependence for Oblique Rays. The lead shield system used in the H-47 design is suitable only for radiation incident perpendicularly. It performs poorly for soft radiation incident at 45 deg. from the perpendicular and very poorly for soft radiation incident at 90 deg. In certain laboratory tests, errors of 500% have been found. (Refs P-6, P-18, P-19, P-20.) Such error is to be expected since no shielding is provided for the edges of the glass pieces.

2. Large Size. It has been found that the 3/4" square glass piece used in the H-47 device is unnecessarily large. It could be made considerably smaller, and in fact the entire dosimeter could be made much smaller.

3. Interrupted Thread Closure. In the H-47 design the glass piece is recessed. This necessitates using an interrupted thread (see Plate 1), and leaves part of the lip of the base assembly unsupported, so that danger of leakage, warpage, etc. is increased and a greater burden is put on the gasket and on the plastic base piece itself.

These limitations are overcome in the H-50 design, sketched on the following page and described in detail in Ref. P-20. The heart of the H-50 design is an 8% silver phosphate glass disk 5/8" in diameter, 5/32" thick, and polished on the edge. It is mounted in non-recessed manner, so that the thread of the plastic base piece does not have to be interrupted. The lead piece included in the plastic cap is not flat, but is cup-shaped so as to shield the edges of the glass disk as well as the face.



Type H-50b Design of DT-60 Glass Dosimeter

The H-50 design is only about half the size and weight of the H-47 design, and in addition provides a more secure closure. It should be less expensive to produce. Its principal advantage, however, is that it is almost free of energy dependence for all angles of incidence of (hard or soft) gamma radiation. See Ref. P-20 for the experimental results.

Several models were made and submitted to Code 854. No attempts have been made, however, at small or large scale production.

The same reader used for the H-47 device would serve for the H-50 device, provided a minor change were made in the swinging sector, as explained in Ref. P-20.

It appears to us that the H-50 design should represent the best personal dosimeter developed to date under a military contract. It has almost every desirable feature other than a self-reading capability. Of course, like all other dosimeters which have been announced publicly, it necessarily reads incorrectly if the user's body intervenes between radiation source and dosimeter.

We recommend that serious consideration be given to mass producing the H-50 design. It should be appreciably better than the DT-60()/PD design now being mass produced.

C. "Locket" Type Dosimeter.

In October 1950 a locket-type of holder was made for holding a disk of silver phosphate glass. The holder was largely made of aluminum, and contained lead shields. It was suitable only for an earlier type of reader—the CP-95(XN-1)/PD reader. Also, it was expensive to produce and had certain other disadvantages. For further details see Ref. P-3.

D. Other Types of Dosimeter.

Various other types of glass dosimeters were tried. Some of these consisted of little more than an aluminum "pill-box" in which the glass piece was housed—unpainted, uncemented, and unlabeled; thin lead shields were included, however. Others consisted simply of a rubber pouch containing a loose glass disk. A photograph of some of these devices is included in Ref. P-6.

Perhaps the greatest disadvantage of these very simple schemes is that the glass piece could not be identified readily, so that different persons' pieces might become interchanged accidentally.

Section 3H. The CP-95(XN-3)/PD Laboratory-Type Reader

A. Introduction.

The CP-95(XN-3)/PD Radiac Computer Indicator, or laboratory-type reader, was intended mainly for laboratory use, as in making control tests on dosimeters or unmounted glass squares. But, as explained in Section 3-D, it was intended also to serve as the basis of design of a field reader (to be designed in detail by Admiral Corporation).

B. Design.

A photograph of the laboratory-type reader is shown in Plate I.

A detailed description of the design is presented in Ref. P-24 as a 22-page appendix. Ref. P-11 contains Drawing C-75773, which shows the principal features of the mechanical design. Ref. P-24 presents the electrical wiring diagram (Drawing C-82506 issued August 14, 1952.)

In summary, the device is a "black box" slightly larger and heavier than a standard typewriter. Samples are loaded and unloaded at the front end; the meter and control knobs are located here also.

The samples are mounted—one at a time, and face down—on a swinging sector. To read a sample, the operator swings the sector to the left as far as it will go. The light-excluding door closes automatically and the sample is positioned automatically in the path of the beam of UV radiation. A 2"-focal length concave mirror collects the fluorescent light and delivers it to the Group 1 931-A photomultiplier, whose output is amplified, rectified, and fed to a microammeter calibrated directly in roentgens.

The UV lamp, an RP-12 type F-5000 cockpit lamp, is covered by a specially-selected 5 mm. Corning 5860 UV-pass filter. Between the concave mirror and the photomultiplier there is a specially-selected 3 mm. Corning 3482 orange-pass filter. (Reasons for choosing these components, and their exact specifications, are indicated in Section 3-D.)

The photomultiplier-and-amplifier system provides for a very wide range of sensitivity adjustment; coarse adjustment and fine adjustment knobs are provided. Also, a zero adjustment is provided, to permit cancelling out any specified amount of pre-dose fluorescence. Electrical linearity is assured by appropriate application of negative feedback.

The output signal is indicated on the microammeter's three-inch scale, calibrated directly in roentgens in two ranges: 0 to 200 r and 0 to 600 r.

The device accommodates dosimeters of DT-60(XN-3)/PD type or equivalent type. It operates off 60 cycle, 110-125 volt supply, and includes considerable voltage stabilization.

The device includes two fixed standards: an M-Std. and an L-Std. The former includes a square of manganese-containing glass (from melt 9530, say) which has a fluorescence corresponding to about 150 r; the exact value is clearly marked directly on the standard itself. The L-Std. includes a square of Pyrex 7740 glass, and has a fluorescence corresponding to about 5 r; the exact value is indicated on the standard itself.

The device is provided also with a sturdy carrying case, a supply cord, a key for opening the dosimeter, and an instruction manual.

C. Operation.

Detailed operating instructions are presented in Ref. P-24. The instructions may be summarized as follows:

To find what a sample reads in roentgens, (a) turn the instrument on and allow it to warm up for five minutes; (b) insert the L-Std. and M-Std. in the swinging sector's stations A and B; (c) swing the sector until each of these standards is in the measurement position, and at the same time adjust the "Zero" and "Calibrate" knobs until each of the standards produces the reading inscribed on it; (c) now insert the "unknown" sample in the sector's third station, swing the sample into the measurement position, and note the meter reading. This is the roentgen reading of the unknown sample.

D. Operation in the "N.U. System."

Readings may be made in the usual "roentgen" system or in an arbitrarily-defined "New Units" or "N.U." system. The roentgen system is, of course, the system to be used in the field, and is the only system which shows directly the nominal dose received by the dosimeter.

In quality control testing, the NU system has been found to have some advantages, notably the advantage that negative values are avoided. Using the roentgen system, an undosed dosimeter which has abnormally little background or "pre-dose" fluorescence might read less than 0 r; but in the NU system, which corresponds essentially to roentgen value plus 37, negative values cannot exist. For example, an undosed sample having abnormally little fluorescence might read -7 r; but the NU reading would be +30. A sample having no fluorescence whatsoever (e.g. a completely opaque sample, such as a block of metal) would be read as -37 r, or as 0 NU.

To find what a sample reads in the NU system, (a) turn the instrument on and allow it to warm up for five minutes; (b) insert an M-Std. in the sector's central station; (c) swing the sector until the M-Std. is in the measurement position; (d) turn the zero adjustment entirely off (all the way to the right); (e) adjust the "Calibrate" knob until the meter reading agrees with the NU value (or r values plus 37) assigned to the M-Std; (f) now insert the "unknown" sample in the sector, swing the sample into the measurement position, and note the reading. This is the NU reading of the unknown sample. For a more detailed account, see Ref. P-18.

(Note: The origins, definitions, and applications of the NU system and certain other systems are described in detail in Ref. P-18. The earlier, non-linear readers used the roentgen system and also an "arbitrary fluorescent units" (AFU) system. The earliest linear readers—operated prior to the Buships January 16, 1952 meeting standardizing the target values for pre-dose reading and sensitivity, used the roentgen system and also a "linear units" (LU) system. During the last year, however, all principal readers have been linear in character and have been operated with respect to the target pre-dose and sensitivity values adopted at the January 16, 1952 meeting. The present "roentgen" and "NU" systems refer to dosimeters complying with the conventions adopted at that meeting.)

E. Performance.

Ref. P-10 summarizes the principal performance characteristics of the laboratory-type reader. Ref. P-17 discusses the electrical linearity, and Refs. P-22 and P-27 discuss errors relating to photomultiplier fatigue and mirror adjustment.

Ref. P-22 lists all principal sources of error, explains how these errors may be minimized, and provides a check list which may assist in making weekly checks of the overall performance.

Generally speaking, the laboratory-type reader performs well and requires little maintenance. If maintained properly and used with correctly-calibrated standards, it affords a precision of approximately 2 r or 2%, whichever is greater, and a "two sigma" accuracy of approximately 5 r or 5%, whichever is greater.

The accuracy may be less than this if the standards used have not been calibrated recently, or if they have been calibrated incorrectly. Ref. P-26 explains why calibration difficulties are unavoidable—and will continually increase—unless a suitable "absolute fluorimeter" is made available.

Accuracy may decrease also if the mirror adjustment deteriorates, if the CK-1022 regulator tube begins to fail, if the photomultiplier tube fails and is replaced by one having incorrect spectral response, or if certain other troubles appear. Refs. P-22 and P-24 list the factors of greatest importance.

F. Production.

Six of the laboratory-type readers CP-95(XN-3)/PD were produced under the present contract. They were completed prior to November 1, 1951. Five were shipped to Buships Code 854. Most of these were later returned to Polaroid so that the improved, linear electrical circuit could be installed.

An additional quantity of laboratory-type readers was made by Polaroid for Buships and Air Forces between November 1951, and January 1952, under NObsr 57040. Another lot was made in November and December 1952, for Buships and Air Forces, under NObsr 57500.

G. "High-Precision" Laboratory-Type Reader.

Institutions engaged in routine, large-scale quality-control testing or acceptance testing of dosimeters need extremely accurate readers. Ref. P-24 explains how readers may be adjusted with especially great care--and provided with parts selected according to especially close tolerances--so that unusually high accuracy results. Accuracy is improved also by using a substitution method of employing M-Stds., as explained in Ref. P-24.

It cannot be stressed too often, however, that the accuracy achieved still leaves much to be desired as regards control laboratory purposes. Errors of 2 r or 2%, whichever is larger, are common. Constant vigilance is needed to prevent the errors from amounting to 3 r or 3%, or even more. Such errors are, of course, far larger than are encountered in most other branches of technology. The difficulty stems from the fact that fluorescence measurements are difficult, involving two sets of wide-cone, broad-band, radiation distributions, one set involving the UV input and the other involving the orange-light output. No standard routines are available--even at the National Bureau of Standards--for evaluating absolutely the fluorescence from translucent parallelepipeds. The present program required trail-blazing in a difficult field that has been consistently shunned previously.

Section 31. Other Specific Designs of Readers

Before the CP-95(XN-3)/PD design of reader was conceived, several other types of readers had been tried out.

Ref. P-8 describes an "XN-0" reader completed on October 17, 1950. This reader was suited only to measuring glass disks mounted in locket-type holders, and had various mechanical and optical limitations.

As explained in Ref. P-8, an "XN-1" reader, generally similar to the XN-0 except for having a sloping panel and certain other minor improvements, was completed on October 31, 1950. Details of the design are presented in Ref. P-3. (A small quantity of readers resembling the XN-1 reader was produced by Admiral Corp. in January 1951.)

The CP-95(XN-3)/PD reader, described in the previous section, is considerably better than the XN-0 and XN-1 readers in all principal respects, and the latter readers are now entirely obsolete.

Section 3J. Designs of Fixed Standards

A. Introduction.

Section 3E explained the need for fixed standards, and the various problems encountered in designing and producing them. The present section describes the standards actually produced.

B. M-Stds.

The Type M-104 Standard. In 1951 much use was made of some medium-fluorescent standards (M-Stds.) of Type M-104. This type, which is described in detail in Ref. P-14, is of hybrid design, employing two pieces of glass. One piece, of Bausch and Lomb manganese glass type S-41, produced intense fluorescence, but was rather opaque to its own fluorescent light. The other piece, of Corning #7740 pyrex glass, was transparent and essentially non-fluorescent; it was used merely as a light-conduit for the fluorescent light issuing from the S-41 piece. The glass pieces were clamped in place, instead of being cemented, so that they could be removed and cleaned. The standard performed reasonably well, but was expensive to make and was reliable only if the incident beam of UV radiation was uniformly intense over the entire cross section. The standard carrying the serial number M-104 served as the basis of the AFU calibration scheme mentioned on a previous page; see Ref. P-17, P-18.

The Type M-121 Standard. The Type M-121 M-Std. was very similar to the M-104 type, except that the piece of pyrex glass was omitted, an air-space being left in its place. This type was less expensive than the M-104 type, but perhaps performed less reliably.

The Type M-201 Standard. The Type M-201 standard resembled a typical dosimeter, but included a glass square made from Bausch and Lomb manganese glass of type E-9530. The standard performed well, although some slight aging effects were observed.

The Type M-311 Standard. The Type M-311 standard was very similar to the M-201 standard, except that (a) the manganese glass used was from a different batch, namely E-9586, and (b) the glass square was clamped in place, rather than being cemented in place, in order to reduce the danger of drift due to contamination by the cement and to permit taking the standard apart for cleaning.

The Type M-400 Standard. The Type M-400 standard, of semi-fixed type, consisted essentially of a regular dosimeter which had been exposed to a gamma radiation dose of 100 to 150 r.

The Type M-1001 Standard. The Type M-1001 standard was of "masked" type. It is described fully in Ref. P-26. The glass square used is from Bausch and Lomb glass G-1109, which is excellent except for having an overly-intense fluorescence. A mask containing nine small holes is placed immediately in front of the glass square's UV entrance face, to reduce the amount of fluorescent light produced.

Calibrating the M-Std. The standards produced since April 1952, have been calibrated on the Serial #12 master reader and using the M-Std. Pool described in a later section (Section 3K). See Section 3E for further details.

Production of M-Stds. In all, perhaps 500 individual standards have been produced. Of these, about half are of Type M-400—"dosed dosimeter" type. Standards have been supplied by us with all readers produced by us. Also, freshly-calibrated standards have been sent periodically to most of the institutions participating in the glass dosimeter program.

Performance of the M-Stds. The M-Stds. have performed reasonably well, although not well enough to satisfy all the demands of quality control laboratories. Even when freshly calibrated by us, the standards may be in error by perhaps 2 or 3%. In routine use the standards often change slightly with time; the causes of the changes are not fully understood but are probably related to surface "curing," surface contamination, and changes produced by prolonged exposure to daylight, UV, etc. There is a great need for producing more and better standards, for establishing a central laboratory for re-calibrating standards periodically, frequently, and authoritatively; also, an absolute fluorimeter is needed, as explained elsewhere, to find to what extent, if any, the entire basis of calibrating the standards is drifting.

C. L-Stds.

Design. Nearly all low-fluorescent standards (L-Stds.) have been made using Corning #7740 pyrex glass, the glass square being cemented to a plastic holder in the usual way. If the standards tend to fluoresce slightly less than desired (i.e., slightly less than 37 NU or 0 r), the fluorescence is increased by exposing the standards for a few hours to the UV radiation from a quartz mercury arc.

Some (semi-fixed) L-Stds. have been provided merely by using undosed dosimeter.

Calibration. L-Stds. produced since April 1952 have been calibrated using the Serial #12 master reader and the M-Std. Pool.

Production. In all, perhaps 200 L-Stds. have been produced. An L-Std. has been included with each reader shipped.

Performance. The L-Stds. have performed reasonably well. However, since these standards exhibit such very weak fluorescence, the effects of surface changes, fingermarks, etc. are relatively serious, so that the standards must be handled with care and re-calibrated frequently if highest accuracy is desired. (As explained elsewhere, there is little occasion to use L-Stds. if the readers in question are linear.)

D. Other Types of Standards.

Perhaps 50 standards of other types have been made. Some of these have been intended to use in evaluating the spectral response of photomultiplier tubes. Others have been used in testing linearity of readers, or in demonstrating how well the readers perform on dosimeters having extremely weak or extremely strong fluorescence.

Section 3K. The M-Std. Pool

A. Introduction.

Since April 1952 the basis of all calibration work has been the "M-Std. Pool" established and maintained at Polaroid Corporation under the present contract. All quality control tests and acceptance tests performed at Polaroid Corporation or at the various other institutions concerned have depended on the existence of the M-Pool, and on its constancy.

Section 3E explains in detail why an M-Pool is needed; the present section tells what the M-Pool consists of and how it performs.

B. Composition of the M-Pool.

The M-Pool, established by Polaroid Corporation on April 8, 1952, consists of a collection of approximately fifty M-Stds., dosed dosimeters, and unmounted glass squares. More exactly, the pool consists of six categories of items: dosed dosimeters, unmounted squares of dosed silver phosphate glass, Type M-104 standards (containing manganese and pyrex glass pieces), Type M-201 and M-211 standards (containing cemented-in pieces of manganese glass), Type M-301 standards (containing clamped pieces of manganese glass), and a miscellaneous collection of glass pieces of widely differing composition, finish, color of fluorescent light, etc.

A more detailed description of the pool may be found in Ref. P-21.

Obviously the pool is intended to include such a great variety of sample types that its validity will not be wiped out if some one type of glass proved to be unstable, or if some one type of mounting tended to introduce spurious fluorescence.

All items of the pool are kept in a special felt-lined box.

C. Performance of the M-Pool.

During the eight-month period in which it has been in existence, the M-Pool has performed moderately well. No one member of the pool appears to have changed drastically (in intensity of fluorescence) relative to another member.

But the performance has by no means been perfect. For example, the average fluorescence of the dosed dosimeter members appears to have decreased slightly but definitely (roughly 5%) relative to the average fluorescence of the dosed, unmounted squares of silver phosphate glass.

If no such change had occurred, we might have assumed with some confidence that the average reading of the pool members had remained constant. But when we find that one member has changed relative to another, or that one entire group has changed relative to another, we are embarrassed: we do not know which group, if either, has remained constant. We see that some general uncertainty, or drift, has entered; and we have no means of determining the sign of the drift or its magnitude.

It is perhaps reasonable to suppose that the present M-Pool may have drifted up or down by 5%, possibly more, since it was set up. See Ref. P-26.

Drift can be eliminated only by providing a suitably-designed absolute fluorimeter, such as has been proposed in Ref. P-26. No M-Pool, no matter how large, can suffice; there would always be the possibility that the entire pool had drifted.

Section 3L. Future Possibilities

A. Introduction.

Sections 3A through 3F inclusive have discussed the design considerations, components, etc., which affect the design of dosimeters, readers, and standards; Sections 3F through 3K have described the actual designs used in the principal dosimeters, readers, and standards produced under the present contract.

It appears appropriate to summarize the various improvements that might be made by exploiting our present accumulated knowledge and perspective.

B. Improvements in Dosimeters.

Edge Shielding. A large improvement could be made in dosimeter performance (relative to the DT-60(XN-3)/PD design) by providing lead shielding for the edges of the lead piece, as well as for the faces. The Type H-50 design, described in Section 3G, would accomplish this.

Thinner Shielding. Additional improvements could be made by using a shield thickness appropriate to radiation incident at typical angle (about 57 deg. from the perpendicular), rather than special angle (perpendicular direction). See Section 3B.

Smaller Overall Size. The entire dosimeter could be made smaller, lighter, and more positively watertight by using an uninterrupted thread. The H-50 design described in Section 3G accomplishes this.

Better Glass. It is likely that a slightly revised formulation of the glass would give a better performance. As explained in Section 3A, the present "8%" glass has various undesirable characteristics, such as temperature coefficient, build-up, latent fluorescence, appreciable pre-dose reading. It is entirely possible that a glass of slightly lower concentration (6 or 7%, say), or of slightly higher concentration (9 or 10%, say) would be found to be appreciably superior.

The experimental basis for choosing the present 8% formulation is not overly substantial. Also, recent experience has proven conclusively that the glass suppliers could readily supply glass having considerably greater sensitivity than is currently specified. A sensitivity increase of 50% to 100% should perhaps be feasible, and without any increase in pre-dose reading.

Clearer Statements of Tolerances. Some uncertainty exists as to the tolerances which are permissible in the size, shape, and finish of the glass squares. Some of the tolerances (such as those on the thickness of the glass square) should be left very wide, to permit the manufacturer to make adjustments which will permit obtaining good results even with glass batches of slightly off-target sensitivity. Other tolerances should perhaps be tightened, to ease the requirements on reader adjustment.

Better Understanding of Dosimeter Performance. There is a need to learn a lot more about dosimeter performance. For example, it would be well to learn more about:

Response to gamma rays (of various wavelengths) incident obliquely.

Variability of temperature effects from one batch of glass to another.

Rate of build-up for doses of different magnitude and for different post-dose storage temperatures.

Constancy of sensitivity of an undosed dosimeter when newly made, 1 month later, 1 year later, etc.

Constancy of fluorescence in a dosed dosimeter one hour after completing the exposure; also one month later; also one year later. Several different storage temperatures should be used.

Effect of storing undosed and dosed dosimeters at 120 deg. F. for several months.

Mechanical properties (shock-resistance, water-tightness, etc.) after several months' storage under various conditions of temperature and humidity.

Performance in actual use in the field, in naval vessels, in airplanes, etc.

C. Improvements in Readers.

Small improvements should be made (in the interest of quality control laboratories) in the laboratory-type reader. Specifically:

Better means for adjusting the azimuth and focal setting of the concave mirror should be worked out; also a standarized procedure for determining when these settings are correct.

A more permanent scheme for selecting Group I photomultiplier tubes should be worked out. The present scheme depends on use of certain arbitrarily-selected samples, which might become lost or broken.

The tolerances observed in selecting Group I photomultipliers should be re-examined. Some relaxing of tolerances may be appropriate. Perhaps a test should be arranged for the uniformity of response across the surface of the photocathode.

As experience is gained, improvement should be made in the procedures and schedules for checking the performance of reader components.

A study should be made of the variability of readings obtained on supposedly-identical readers.

There is a very great need for developing an absolute fluorimeter as stressed in Ref. P-26.

Now that dosimeters are in routine mass-production, the need for field readers has increased. Presumably two or more types might be needed, including: standard field reader; very light-weight, battery-operated reader.

D. Improvements in Standards.

There is considerable need for finding how stable the present N-standards are. More aging tests should be made, and an effort should be made to find just why the samples tend to change slightly with time.

Additional quantities of standards will be required every few weeks by the quality control laboratories concerned. Some appropriate group must design and build these standards. Moreover, some competent, authoritative group must calibrate them.

An absolute fluorimeter is badly needed; and until such exists, the present N-pool should be maintained and improved.

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Section 4. Conclusions

The present work has brought the "glass dosimeter" from the stage of being an interesting possibility to the stage of being a proven reality. The device has a performance unmatched by any competing product, and yet should cost only about $1. in mass production.

The silver phosphate glass itself is excellently suited to use as the detecting element. The so-called "8%" formulation is a very good one; perhaps a slightly different formulation would be even better.

A "Type H-47" design was worked out for the complete dosimeter, or DT-60(XN-3)/PD radiac detector. This design is small, rugged, watertight, and economical. It provides lead shielding for the faces, but not the edges, of the glass piece. Several hundred units were produced and delivered to Buships.

Later, an improved design known as H-50 was worked out. Besides being smaller, the improved design shields the glass piece on all sides, so that good performance is achieved even if the radiation approaches from the side.

A laboratory-type reader, or CP-95(XN-3)/PD radiac computer indicator, was designed, tested, and found to perform well. Six units were produced.

Several types of fixed standards, required in adjusting the sensitivity of the laboratory-type reader, were designed. Several hundred units were made and supplied to the various institutions using the laboratory-type readers.

Part III

Appendices

Part II

Recommendations

1. The glass dosimeter should be put to widespread use. It performs excellently, lasts for years, yet should cost only about $1.

2. The H-50 design of dosimeter should be used instead of the H-47 design. It should provide greater accuracy and at the same time should be smaller, more watertight, and less expensive. See Section 3G.

3. An absolute fluorimeter should be made. Until it is made, there can be no assurance that our basis for calibrating standards is constant. See Sections 3E and 3K.

4. Some competent laboratory should be designated to carry on the function of calibrating standards, maintaining the master reader, and generally serving as a central standards laboratory. Unlike other branches of technology, fluorescence dosimetry is without any ready-made foundation or standardizing agency. See Section 3E.

5. Many minor improvements should be made in dosimeters, readers, and standards. See Section 3L for a list of improvements which appear within reach.

6. More should be learned about the performance of the glass dosimeter now in mass production. See Section 3L for a list of performance characteristics about which more information is needed.

Part III

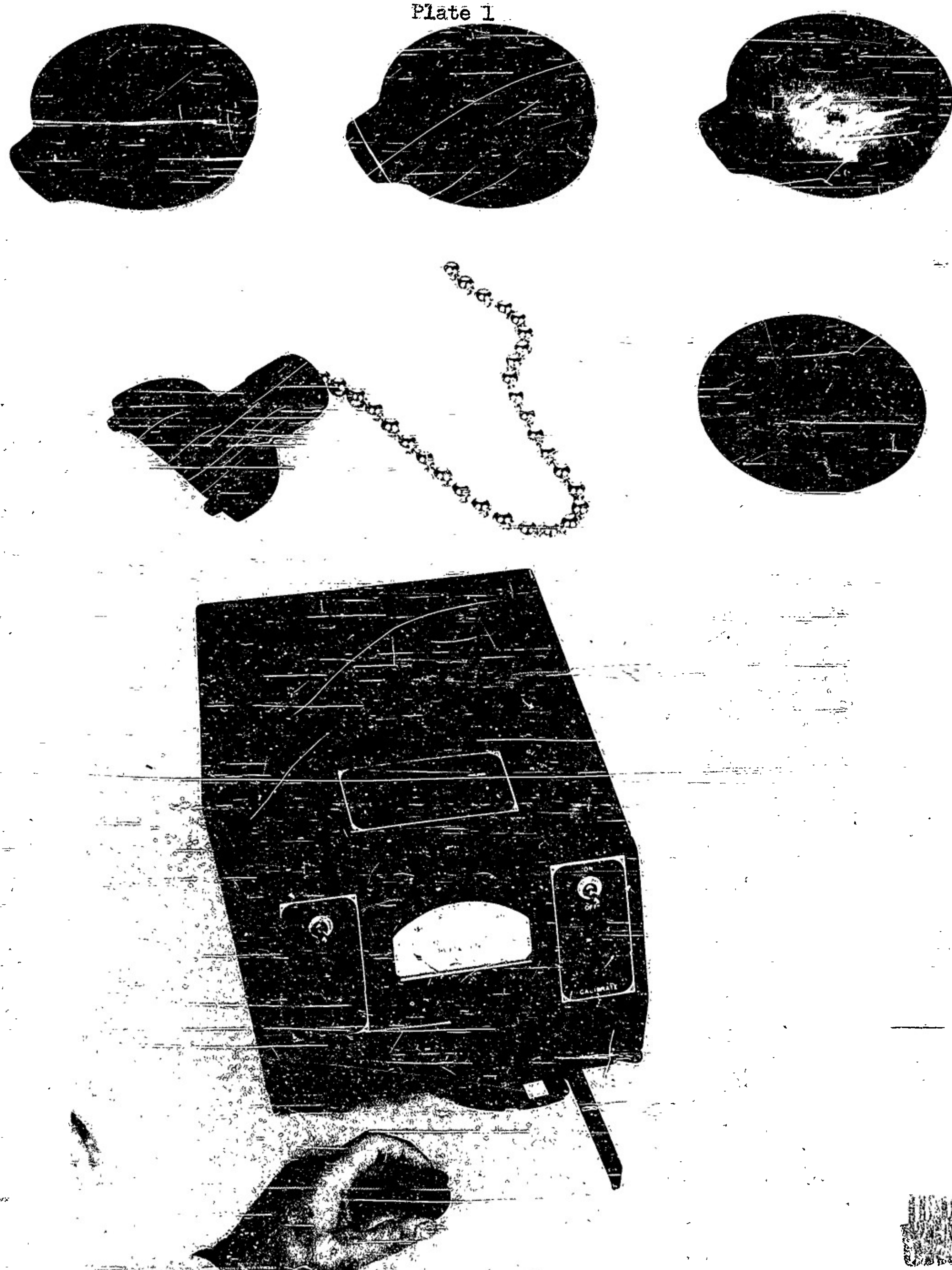
Appendices

Appendix 1. Plate 1. Upper Photograph: The Type H-47 design of DT-60(XN-3)/PD radiac detector, or glass dosimeter.

Lower Photograph: The CP-95(XN-3)/PD radiac computer indicator, or laboratory-type reader.

Appendix 2. Bibliography.

Plate 1



Appendix 2.

Bibliography

Various pertinent references are listed below, arranged according to the institution concerned. N stands for Naval Research Laboratory. P stands for Polaroid Corporation.

N-1 W.A.Weyl, J.H.Schulman, R.J.Ginther, L.W.Evans, "Fluorescence of Silver in Glasses." J. Electrochem. Soc., 95, 70, (1949).

N-2 J.H.Schulman, "Dosimetry of X-Rays and Gamma-Rays," NRL Report 3736, Sept. 26, 1950.

N-3 J.H.Schulman, R.J.Ginther, C.C.Klick, R.S.Alger, and R.A.Levy, "Dosimetry of X-Rays and Gamma Rays by Radiophotoluminescence." NRL Reprint No. 7-52. (Also: J.Applied Physics, 22, p. 1479, (1951).

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P-1 Monthly Report by the Polaroid Corporation's Research Department on work performed under contract NObsr-59257. Covers work done during August 1950. Written by W.A.Shurcliff.

P-2 As above, but covering the month of September 1950.

P-3 " " " " " " " October 1950.

P-4 " " " " " " " November 1950.

P-5 " " " " " " " December 1950.

P-6 " " " " " " " January 1951.

P-7 " " " " " " " February 1951.

P-8 " " " " " " " March 1951.

P-9 " " " " " " " April 1951.

P-10 " " " " " " " May 1951.

P-11 " " " " " " " June 1951.

P-12 " " " " " " " July 1951.

P-13	As	above,	but	covering	the	month	of	August 1951.
P-14	"	"	"	"	"	"	"	September 1951.
P-15	"	"	"	"	"	"	"	October 1951.
P-16	"	"	"	"	"	"	"	November 1951.
P-17	"	"	"	"	"	"	"	December 1951.
P-18	"	"	"	"	"	"	"	January 1952.
P-19	"	"	"	"	"	"	"	February 1952.
P-20	"	"	"	"	"	"	"	March 1952.
P-21	"	"	"	"	"	"	"	April 1952.
P-22	"	"	"	"	"	"	"	May 1952.
P-23	"	"	"	"	"	"	"	June 1952.
P-24	"	"	"	"	"	"	"	July 1952.
P-25	"	"	"	"	"	"	"	August 1952.
P-26	"	"	"	"	"	"	"	September 1952.
P-27	"	"	"	"	"	"	"	October 1952.

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