RADIATION DAMAGE STUDIES
ON RADIOLUMINOUS LIGHT SOURCES

by
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1980
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td></td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
</tr>
<tr>
<td>1. THEORETICAL AND EXPERIMENTAL CONSIDERATIONS</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Theory</td>
<td>2</td>
</tr>
<tr>
<td>Atomic Excitation</td>
<td>2</td>
</tr>
<tr>
<td>Fluorescence and Phosphorescence</td>
<td>3</td>
</tr>
<tr>
<td>Experimental Design</td>
<td>6</td>
</tr>
<tr>
<td>Safety Considerations</td>
<td>9</td>
</tr>
<tr>
<td>Experimental Procedure</td>
<td>10</td>
</tr>
<tr>
<td>Irradiation Geometry</td>
<td>13</td>
</tr>
<tr>
<td>Light Source Cooling</td>
<td>15</td>
</tr>
<tr>
<td>Post Irradiation Leakage Test</td>
<td>15</td>
</tr>
<tr>
<td>Annealing</td>
<td>15</td>
</tr>
<tr>
<td>Post Annealing Test</td>
<td>17</td>
</tr>
<tr>
<td>2. RESULTS AND DISCUSSION</td>
<td>18</td>
</tr>
<tr>
<td>3. CONCLUSION</td>
<td>21</td>
</tr>
<tr>
<td>APPENDIX A: SAMPLE CALCULATIONS</td>
<td>22</td>
</tr>
<tr>
<td>APPENDIX B: ABSORPTION COEFFICIENT CHARTS FOR TITANIUM, AIR AND GLASS</td>
<td>25</td>
</tr>
<tr>
<td>SELECTED BIBLIOGRAPHY</td>
<td>29</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS

Figure                                                                 Page
1. The Spectrum of Electromagnetic Radiation. ...................... 5
2. Diagram and Specifications of Radioluminous Light Sources Tested .................. 8
3. Schematic Diagram of the Farady Cup Used to Measure the Electron Beam Current to a Light Source. .................. 12
4. Schematic of Null Detection Used to Verify Energy of Electrons Irradiating the Light Sources. .................. 14
5. Sample Holder and Heat Sink for Irradiation of Radioluminous Light Sources. .................. 16
6. Percent Drop in Light Output as a Function of Irradiation Time in Half-Life Equivalents. .................. 19
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Light Output as a Function of Electron Irradiation</td>
<td>18</td>
</tr>
</tbody>
</table>

vi
ABSTRACT

To measure the damaging effects of β− emitting tritium gas on phosphors employed in radioluminous light sources, a total of six radio-luminous light sources with known luminosity levels were irradiated in an accelerated aging test with 18 keV electrons for different periods of time. The light outputs of the irradiated sources were then measured and the results were compared with those prior to irradiation. It was found that the decrease in the luminosity level of light sources, caused by radiation damage, is about 6.4 percent after an exposure period of time equivalent to one tritium half-life. Therefore, other mechanisms (e.g., phosphor aging, tritium loss, phosphor impurities) must be responsible for the large variations in half-brightness times observed for those types of light sources.
CHAPTER 1

THEORETICAL AND EXPERIMENTAL CONSIDERATIONS

Introduction

Electron interaction with the phosphors is the basis for the radioluminous characteristic of tritium light sources. The light output of these devices has made them increasingly popular in areas where a limited intensity, yet reliable, source of light is desirable.

The unique characteristic of tritium light sources is their independence from an outside source of electric power and the reliability of their operation over long periods of time. Theoretically, their brightness should not decrease more rapidly than the activity of the source. These characteristics have made tritium light sources specially suitable for lighting panel dials such as those in military and civilian equipment as well as illuminating the face plate of some liquid crystal digital watches where repeated use of battery operated light is prohibitive. Another use of tritium light sources has been in the production of "EXIT" signs where a possible power failure due to fire would not interfere with "EXIT" signs leading the way to safety.

The life expectancy of radioluminous light sources is a function of a number of factors among which is the radiation damage produced by the $\beta^-$ particles bombarding the phosphor. In an effort to understand and predict the importance of radiation damage to the phosphor on the life expectancy of these light sources, the present study was undertaken.
Theory

Atomic Excitation

An atom can be brought into an excited state when one of its electrons absorbs energy in some way. A free electron accelerated by an electric field can transmit enough energy to a bound electron to put it into a higher energy state. After the bombarding electron has transferred energy to the atom and excited it, the electron will carry away any excess energy as kinetic energy. After the excitation, the atomic electron tends to return to its ground state. If it was excited to \( n = 4 \) from the \( n = 1 \) level, it may jump from 4 to 1 in one step. It may also go 4, 2, 1 or 4, 3, 1 or 4, 3, 2, 1. In each step of the de-excitation, the electron must lose an amount of energy equal to the difference of the energy levels. The only mechanism available for this energy loss is through the emission of electromagnetic radiation which occurs when an electron goes from a higher energy state to a lower one, the energy of the quantum of radiation, \( h\nu \), being equal to the energy difference of the states. If we let the quantum number \( n = n_2 \) represent a higher energy state and \( n = n_1 \) represent a lower energy state \( (n_1 < n_2) \), then:

\[
h\nu = E_{n_2} - E_{n_1} \tag{1}
\]

Considering the energy states that are possible for electrons with \( n = 1, 2, 3, \ldots \), we have:
\[ E_n = -\frac{m_e e^4 z^2}{8\varepsilon_0^2 h^2 n^2} \]  

where \( m_e \) and \( e \) are the electron mass and charge respectively and \( z \) is the atomic number. \( \varepsilon_0 \) is the permittivity of free space, \( h \) is the Plank constant and \( n \) is the quantum number. Substituting for the energies from Eq. (1), we have for the frequency of the emitted radiation:

\[ \nu = \frac{m_e e^4 z^2}{8\varepsilon_0^2 h^3} \left[ \frac{1}{n_2^2} - \frac{1}{n_1^2} \right] \]  

Or in terms of wave numbers:

\[ \nu = \frac{1}{\lambda} = \frac{\nu}{c} = \frac{m_e e^4 z^2}{8\varepsilon_0^2 h^3 c} \left[ \frac{1}{n_2^2} - \frac{1}{n_1^2} \right] \]  

Atomic electron can absorb discrete amounts of energy from bombarding electrons; however, it should be mentioned that atoms may also absorb energy from photons, but there is an important difference. Absorbed photons disappear entirely. A photon with more energy than the ionization energy of an atom can always be absorbed, because the excess energy will appear as kinetic energy of the photoelectrons. A photon with less than the ionization energy cannot be absorbed unless its energy is equal to one of the vibrational or rotational excitation energies of the absorbing molecules.

Fluorescence and Phosphorescence

Another application of the energy level concept discussed above is in the explanation of fluorescence and phosphorescence. In
fluorescence, excitation can be produced by photons of invisible ultraviolet light, e.g., produced by an electric discharge through mercury vapor. Once these photons strike fluorescent material, they excite the atomic electrons of the fluorescent material. If the excited electrons fell back to their normal state in one step, they would re-emit the ultraviolet light which would still be invisible. But the excited electrons return to their normal state usually in more than one step. Each step produces radiation of less energy than the original excitation so that the energy of the ultraviolet light is converted into visible light. Figure 1 shows the energy spectrum of electromagnetic radiation. Photons of visible light have energies between 6 to 10 eV, and those of ultraviolet light have energies in the range 10 to $6 \times 10^3$ eV. The various tints that different lamps have are controlled by the nature of the fluorescent material used.

Some materials on the other hand have excited metastable states, when an electron is excited into one of these states, it does not return to its normal state at once, but may remain excited for an appreciable time. Some materials emit a persistent light, called phosphorescence, which may last several hours after all external excitation is removed. These materials are sometimes used on the screen of cathode-ray tubes, and they are sometimes used to make light switches glow, so that they may be visible in the dark. Most fluorescent tubes exhibit some phosphorescence. It may be observed in a dark room a few minutes after the light is turned off.
<table>
<thead>
<tr>
<th>Frequency, hertz</th>
<th>Name of radiation</th>
<th>Photon energy, eV</th>
<th>Wavelength, angstroms</th>
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</thead>
<tbody>
<tr>
<td>$10^{22}$</td>
<td>Gamma rays</td>
<td>$10^7$</td>
<td>$10^{-3}$ -- 1 X-unit, XU</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>Hard X-rays</td>
<td>$10^6$</td>
<td>$10^{-2}$</td>
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<td>$10^{19}$</td>
<td>Soft X-rays</td>
<td>$10^5$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>Ultraviolet</td>
<td>$10^4$</td>
<td>$10$ -- 1 angstrom, Å</td>
</tr>
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<td>$10^{17}$</td>
<td>Infrared</td>
<td>$10^3$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>Visible light</td>
<td>$10^2$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>(UHF)</td>
<td>$10^1$</td>
<td>$10^4$ -- 1 micron, μ</td>
</tr>
<tr>
<td>$10^{14}$</td>
<td>Shortwave</td>
<td>$10^{-1}$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^{13}$</td>
<td>(LF)</td>
<td>$10^{-2}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>(VLF)</td>
<td>$10^{-3}$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$10^{11}$</td>
<td>Standard broadcast</td>
<td>$10^{-4}$</td>
<td>$10^8$ -- 1 centimeter, cm</td>
</tr>
<tr>
<td>$10^9 - 10^6$</td>
<td>TV, FM</td>
<td>$10^{-5}$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>$10^8$</td>
<td>Standard Broadcast</td>
<td>$10^{-6}$</td>
<td>$10^{10}$ -- 1 meter, m</td>
</tr>
<tr>
<td>$10^7$</td>
<td>(LF)</td>
<td>$10^{-7}$</td>
<td>$10^{11}$</td>
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<td>$10^5$</td>
<td>Long wave</td>
<td>$10^{-8}$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>(VLF)</td>
<td>$10^{-9}$</td>
<td>$10^{13}$ -- 1 kilometer, km</td>
</tr>
<tr>
<td>$10^3$</td>
<td></td>
<td>$10^{-10}$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 The Spectrum of Electromagnetic Radiation. — Wehr and Richards, 1967.
Experimental Design

The intensity and the lifetime of a tritium light source is a function of a number of factors such as the radioactive decay of the tritium, chemical degradation of phosphor due to aging, tritium escape from the light source, and possible radiation damage on the phosphor coating used inside each light source.

The latter mechanism of failure which might contribute to a decrease in the luminosity level of a tritium light source is the result of a prolonged electron interaction with phosphor atoms. Emerging β-particles from decaying tritium can affect phosphor molecules in such a way that a decrease in the light output of the radioluminous source might result.

A direct approach toward a quantitative study of radiation damage on phosphors would include periodic light intensity measurements from several samples of radioluminous light sources over an exposure period equivalent to that of several half-lives of tritium gas. Knowing the decay rate of tritium, one can verify the predicted exponential decrease in the light output of tritium sources with the actual light intensity measurement taken. Of course, any inconsistency in the results, assuming no other mechanism of failure, should point to a phosphor inefficiency caused by electrons bombarding the phosphor. This method, however, was not employed in our study, because of the long time period required and the inherent problem of duplicating the precise experimental geometry for each measurement.
To reduce the period of study to a shorter time scale, it was decided that an external, high intensity source of electrons be utilized. This approach had the advantage that the period of study could be reduced from several years to only a few hours.

The electron accelerator employed was a 1.25 MeV Radiation Dynamics "Dynamitron" capable of supplying electron currents of up to 10 ma. The high energy range of emerging electrons was sufficient to ensure 18 keV electrons reaching the phosphor coating inside the radioluminous light sources. This 18 keV electron energy was sufficient and necessary in order for the electrons from the accelerator to be energetically compatible with the maximum energy β particle from the decaying tritium gas. The high voltage on the electron accelerator was, however, set for an electron energy above 18 keV to offset for energy losses that the electron beam would experience as it passes through the accelerator's titanium window, air, and finally the glass casing used for encapsulating the radioluminous light sources. For this reason, use was made of electron absorption coefficient charts for titanium, air and glass. These charts appear in Figs. B.1, B.2 and B.3 of Appendix B.

The radioluminous sources used in this experiment were six green colored light sources (Part #11739179-1, Fig. 2) each containing five curies of tritium gas. Before irradiating the samples, the light output of each sample was accurately measured in a fixed, reproducible geometry. The light sources were then divided into three groups of two. The first group received an electron radiation dose equivalent to one-half of one tritium half-life (6.16 years' exposure to 5 Ci). The
Lacquer, acrylic, color white

\[ \frac{1}{4} \pm \frac{1}{32} \text{ Dia (window free from Phosphor)} \]

\[ .59 \pm .02 \text{ (spherical)} \]

Glass capsule .04 ± .02 thick

Phosphor color

\[ \frac{7}{32} \text{ Dia (Max)} \]

<table>
<thead>
<tr>
<th>Part Number</th>
<th>11739179-1 (see note 1)</th>
<th>11739179-2 (see note 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness Microlamberts (min)</td>
<td>600</td>
<td>1660</td>
</tr>
<tr>
<td>Color of phosphor</td>
<td>Green</td>
<td>Orange</td>
</tr>
<tr>
<td>spectral peak</td>
<td>5250Å±50Å°</td>
<td>5950Å°±100Å°±50Å°</td>
</tr>
<tr>
<td>½ peak width</td>
<td>100Å°±50Å°</td>
<td>900Å°±100Å°</td>
</tr>
</tbody>
</table>

Notes:

1. Capsule filled with 99% pure (less than 1% tritium oxide) tritium \(^{3}\text{H}\) 5.0 curie (MAX) as measured at time of manufacture.

   Internal pressure .66 (MAX) atmospheres (nominal) at 70°F.

2. Capsule filled with 99% pure (less than 1% tritium oxide) tritium \(^{3}\text{H}\) 9.0 curie (MAX) as measured at time of manufacture internal pressure 2.5 (MAX) atmospheres (nominal) at 70°F.

Fig. 2 Diagram and Specifications of Radioluminous Light Sources

Tested. -- all dimensions in inches.
second group was exposed to an irradiation dose equivalent to one tritium half-life for 5 Ci of H-3, and the third group received irradiation dose equivalent to two tritium half-lives exposure for an activity of 5 Ci. After irradiation the light output of each light source was again carefully measured (in the same geometry) after first annealing out the color centers produced by the radiation. The decrease in light output was assumed to be caused by phosphor damage equivalent to that produced by the tritium decay mechanism.

Safety Considerations

Experimenting with radioluminous light sources requires certain safety precautions if exposure to tritium gas is to be avoided. Tritium is a radioactive gas which emits low energy ($E_m = 18$ keV) $\beta^-$ particles. Though these particles are not too penetrating when outside the body, H-3 can easily be diluted in air and enter the body, thus extreme care is required in handling and experimenting with tritium light sources in the event of breakage of the sources.

It is necessary during the course of this experiment to irra-
diate glass capsules containing tritium with high energy electrons, a process which could lead to an abrupt temperature rise in the glass capsules containing tritium gas. If this temperature rise exceeds the safe limit, 160$^\circ$F, as set forth by the manufacturer, the glass might crack and result in the release of tritium to the environment. In addition, thermal shock may lead to cracking or fracturing of the glass capsules.
To draw a set of safety guidelines, in case of an accident leading to the release of tritium gas, it was first necessary to determine the dilution factor of tritium in the laboratory in the event of a release. Knowing the laboratory volume and the amount of tritium in curies used in the experiment it is possible to calculate that the dilution factor was insufficient and the safe limits for tritium in a restricted area could be exceeded. This necessitated the use of an exhaust fan. By measuring the exhaust rate of the fan and considering the laboratory volume, the necessary calculations were performed and the following guidelines were drawn and approved by the University Radio-isotope Safety Committee:

1. The exhaust fan should be switched on at least 10 minutes before entering the accelerator room to clear the room in the event that a light source ruptured.

2. The exhaust fan should be kept on at all times when the room is occupied and during irradiation.

3. No one shall enter the accelerator room until the fan has been running for at least 10 minutes after each irradiation.

Experimental Procedure

Prior to irradiating light sources with an electron beam, it was necessary to make an accurate measurement of electron current density reaching each light source. This current measurement was essential for calculating the total number of electrons striking the phosphor coating within each light source. To measure electron currents, use was made of
a Farady Cup. The schematic diagram of the Farady Cup which was designed and assembled for this experiment is shown in Fig. 3.

The opening in front of the Farady Cup has an area equal to the cross section of a light source thus allowing the measurement of the current equivalent to that striking radioluminous light sources being irradiated in the experiment. The positive side of a 200 V dc power supply was connected to the cup and the negative side to the front plate. This potential difference was sufficient to prevent the secondary electrons produced by the primary electrons striking the cup, from being collected by the front shield and reduce the actual current flowing through the Keithley Electrometer as shown in Fig. 3. By utilizing this arrangement, one could easily adjust the accelerator current reaching each source to the desired level which in this experiment was selected at .8 ma. Calculation of exposure time equivalent to 5 Ci tritium is given in Appendix A.

The next step in preparing for the experiment was to ensure that electron energies reaching the phosphor coating are equal to the maximum energy of the $\beta^-$ from decaying tritium, i.e., at the $E_m$ of 18 keV. To measure electron energies reaching radioluminous light sources, and thus permit adjustment of the accelerator high voltage to the desired level, use was made of electron absorption coefficients for electron energy losses as the beam passes through the accelerator titanium window, air and glass capsules containing the tritium and phosphor coating. This enabled the accelerator high voltage to be set roughly for the experimental geometry employed, yielding an effective electron energy at the
Fig. 3 Schematic Diagram of the Faraday Cup Used to Measure the Electron Beam Current to a Light Source
phosphor of 18 keV. For fine tuning of the high voltage setting, a target detector was placed at the exact location, in front of the electron beam, as the radioluminous light sources under the experiment. The schematic diagram of the null detector employed appears in Fig. 4.

The variable high voltage dc supply was first set at 18 keV, throwing the null detector off center. The accelerator high voltage was then gradually increased until the electrons reaching the target developed a voltage drop across $R$ equal to 18 keV, thus forcing the null detector to the center position reaching 0 current. This assured 18 keV electrons reaching the target area; however, the accelerator high voltage had to be increased slightly using the Absorption Coefficient Chart, to offset for electrons slowed down in the glass material before striking the phosphor coating.

Irradiation Geometry

A total of six green color phosphor light sources was selected. The light output of each light source was then measured in units of micro-lamberts ($\mu$L) using the facilities at the American Atomic plant. After dividing the light sources into three groups of two, each group was placed at a distance of 30 cm from the electron source and were irradiated for periods of 86.5, 173 and 346 minutes respectively. Detailed calculations relating to irradiation geometry and time intervals appear in Appendix A.
Fig. 4  Schematic of Null Detection Used to Verify Energy of Electrons Irradiating the Light Sources
Light Source Cooling

Irradiating the light sources with high energy electrons could lead to an increase in the temperature of glass capsules containing the tritium gas. This temperature rise, which was determined in a destructive test using blank capsules, can at first crack the glass casing and, in case of prolonged exposure to the electron beam, lead to a total glass melting. To avoid this difficulty, liquid coolant along with forced air flow were employed to remove excessive heat from the samples while being irradiated. Figure 5 depicts the aluminum sample holder and the direction of air flow for cooling the outer surface of samples. Each sample was placed on the outer surface of the sample holder with the aid of silicon grease to improve the heat transfer from glass to aluminum.

Post Irradiation Leakage Test

After irradiating all samples, it was necessary to test the integrity of each light source to determine if any leakage of tritium from glass capsules had occurred. For this purpose each light source was soaked in 5 ml of distilled water for a period of 24 hours. The water samples were checked on a liquid scintillation counter; no leakage of tritium was detected.

Annealing

High energy electrons striking a glass can often alter its structure and cause partial loss of transparency. This effect was observed in the glass casing of the light sources after irradiation was
Forced air flow

Coolant in

Coolant out

Fig. 5 Sample Holder and Heat Sink for Irradiation of Radioluminous Light Sources
performed. To remove the color centers and make possible, accurate light intensity measurement possible, each source was annealed after irradiation at a temperature of 80°C for a period of two hours to anneal out the color centers.

Post Annealing Test

Although the temperature required for annealing was within the safe limits according to factory standards, a second leakage test was performed by soaking the light sources again in 5 ml of distilled water and checking water samples after 24 hours as before. This test cleared the way for the final light intensity measurements and their comparison with corresponding values prior to irradiation.
CHAPTER 2

RESULTS AND DISCUSSION

Table I presents the light output for each sample before and after irradiation. A graphical presentation of the same data expressed in percent drop in the intensity of light output for each group appears in Fig. 6. It should further be emphasized that group one is composed of samples 1 and 2, group two composed of samples 3 and 4 and group three is composed of samples 5 and 6.

Table I  Light Output as a Function of Electron Irradiation

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Dose equi. (half-life)</th>
<th>Irra. time (min)</th>
<th>Light out. (before)μL</th>
<th>Light out. (after)μL</th>
<th>% Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2</td>
<td>86.3</td>
<td>774</td>
<td>753</td>
<td>2.7%</td>
</tr>
<tr>
<td>2</td>
<td>1/2</td>
<td>86.5</td>
<td>610</td>
<td>595</td>
<td>2.4%</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>173</td>
<td>603</td>
<td>565</td>
<td>6.3%</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>173</td>
<td>500</td>
<td>468</td>
<td>6.4%</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>346</td>
<td>596</td>
<td>541</td>
<td>9.2%</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>346</td>
<td>665</td>
<td>609</td>
<td>8.4%</td>
</tr>
</tbody>
</table>
Fig. 6 Percent Drop in Light Output as a Function of Irradiation Time in Half-Life Equivalents
A first glance at the data presented in Table I indicates that the percentage drop in the light output of radioluminous light sources increases with increasing irradiation time intervals. Though these increases are not exactly linear, they have some resemblance to an exponentially decreasing quantity indicating that for the longest irradiation time interval, as in group three, the increase in radiation damage to phosphor atoms proceeds at rate smaller than that for group one and group two.

It can also be noticed that the degree of uncertainty over the accuracy of the results is fairly low when considering groups one and two, but this uncertainty increases when a much longer irradiation time interval is involved. Indeed, the overall accuracy of the experiment could have been increased if a larger number of samples were included in each group; unfortunately we had a limited number of light sources to work with.
CHAPTER 3

CONCLUSION

As can be verified from the results of the experiment, an average of 8.8 percent decrease in the light output of a radioluminous light source could occur over a period of time equivalent to two tritium half-lives, assuming radiation damage to phosphor atoms as the only mechanism affecting the light output of a tritium light source. However, there are more important mechanisms of failure such as natural decay of tritium gas, physical integrity of glass casings holding this gas, and chemical degradation of phosphor elements due to aging that can affect the usefulness of a radioluminous light source and that should also be considered in any long range plan utilizing radioluminous light sources. Therefore, it appears that an accelerated test of phosphor damage cannot be used to indicate expected half-brightness times for those sources, as this mechanism for loss of phosphor efficiency seems to be minor compared to other mechanisms.
APPENDIX A

SAMPLE CALCULATIONS

Dose Equivalent Calculations

In order to determine the period of time required for exposing light sources and also adjusting the electron beam current from the accelerator, it was necessary to calculate the total number of electrons striking phosphor atoms in a sample containing five curies of radioactive tritium during one-half life of $^3$H. Having this information and the accelerator current, the irradiation period could easily be found. The number of $\beta^-$ particles produced in one-half life can be found by using:

$$ A = N \lambda = N \frac{\ln 2}{T_{1/2}} = \text{activity} \quad (A.1) $$

for 5 curies of tritium,

$$ A = 5 \times 3.7 \times 10^{10} = 18.5 \times 10^{10} \text{ dis/sec}. $$

The total number of disintegrations in one-half life or 12.33 years is given by $N/2$; from Eq. A.1 we obtain

$$ \frac{N}{2} = \frac{A \times T_{1/2}}{2 \times 0.693} = \frac{18.5 \times 10^{10} \times 12.33 \times 3.15 \times 10^7 \text{ sec/yr}}{2 \times 0.693} \quad (A.2) $$

$$ \frac{N}{2} = 5.2 \times 10^{19} = \text{number of } \beta^- \text{ produced in one-half life in 5 Ci } ^3\text{H} $$

Target current = 0.8 ma = $0.8 \times 10^{-3} \text{ amp} \times \frac{6.28 \times 10^{18} \text{ electrons/sec}}{\text{amp}} \quad (A.3)$
Target current = $5 \times 10^{15}$ elec/sec.

Total irradiation time equivalent to total number of $\beta^-$ emitted from five curies of tritium gas in 12.33 years (from A.2 and A.3) is:

$$\text{irr. time} = \frac{5.2 \times 10^{19} \beta^-}{5 \times 10^{15} \text{ elec/sec}} = 1.04 \times 10^4 \text{ sec.}$$

$1.04 \times 10^4 \text{ sec} \times \frac{1 \text{ min}}{60 \text{ sec}} = 173 \text{ min.}$

In other words, the total number of electrons striking phosphor atoms from an electron current of 0.8 ma for 173 minuted is equivalent to the total number of electrons striking the phosphor from five curies of tritium gas for 12.33 years.

**Irradiation Geometry Calculations**

These calculations pertain to physical distance between the accelerator and samples under irradiation and the high voltage setting on the accelerator to ensure 18 keV electrons reaching the phosphor coating inside the radioluminous light source.

Table A.I below presents physical constants relating to the titanium window and glass capsules along with the air gap used between the accelerator and the light sources. Thus, the total electron energies required to reach the phosphor inside the light source is:

$$E_m = (0.17 + 0.18 + 0.6) \text{ MeV} = 0.95 \text{ MeV.}$$

The high voltage setting of the accelerator dial was, however, increased to 0.97 MeV to make electrons reaching the phosphor coating energetically compatible with the $\beta^-$ maximum energy from the decaying tritium.
Table A.1 Properties of Materials the Electron Beam Traverses

<table>
<thead>
<tr>
<th>Element</th>
<th>Thickness (cm)</th>
<th>Min. Electron Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>$7.62 \times 10^{-3}$</td>
<td>0.17</td>
</tr>
<tr>
<td>Air</td>
<td>30</td>
<td>0.18</td>
</tr>
<tr>
<td>Glass</td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>
APPENDIX B

ABSORPTION COEFFICIENT CHARTS
FOR TITANIUM, AIR AND GLASS
Fig. B.1 Electron Range in Titanium as a Function of Energy
Fig. B.2 Electron Range in Air as a Function of Energy
Fig. B.3 Electron Range in Glass as a Function of Energy
SELECTED BIBLIOGRAPHY


