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FINAL REPORT

to

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on

STERILIZABLE PHOTOMULTIPLIER TUBES

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Princeton, New Jersey

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ABSTRACT

A program was carried out to develop sterilizable photomultipliers for use in space programs. Two standard EMR tube types, one with visible response and one with ultraviolet response, were modified to improve their ability to withstand the severe environment of dry heat sterilization. In this development phase the quantum efficiency of the tubes with visible response was significantly improved.

Three tubes with visible response and five tubes with ultraviolet response were subjected to three dry heat sterilization cycles of thirty-six hours at 145°C followed by gas decontamination, static acceleration, vibration, shock, and life tests.

Only moderate changes in spectral response, gain, and resolution of the Cs^{137} gamma ray were observed for the tubes with visible response following dry heat sterilization. The tubes are capable of withstanding the environmental tests. Operating at anode currents of approximately 10^{-7} amperes on life tests, the tubes showed characteristic gain stabilization at approximately 100 hours. The ultraviolet response tubes show changes of less than 10% of the initial quantum efficiency following dry heat sterilization and insignificant changes in gain.

Proposed additional improvements in sterilizable photomultipliers with visible and ultraviolet response are discussed.

Author

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1. INTRODUCTION

1.1 Objective

The objective of this program was to establish a supply of photomultipliers for use in space programs. Requirements exist for two tube types — one having a visible spectral response suitable for use with a sodium iodide crystal for scintillation counting, and one having a spectral response in the ultraviolet between 1100 Å and 3200 Å.

The photomultipliers selected for this program were required to undergo three dry heat sterilization cycles, each consisting of exposure to 145°C for a period of 36 hours.

The photomultipliers were to be obtained from either existing standard products, modification of existing standard products, or development of new tube types.

Ideally, the photomultipliers should suffer no degradation of electrical characteristics as a result of dry heat sterilization.

1.2 Description of Photomultipliers with Visible Response

The EMR Model 541D-01-14 photomultiplier is a 14-stage, end-on window tube with a semitransparent bialkali photocathode having an effective cathode diameter of one inch. The tube is sensitive to visible light and has a peak sensitivity in the blue at approximately 4100 Å.

The Model 541D was primarily designed for use in scintillation counting at high temperatures. It has a long history of successful use at high temperatures in oil well logging probes.

The unique design of venetian-blind dynodes and hard glass-kovar ring construction in an encapsulated package results in an extremely rugged tube especially suited to space applications.

The tube is potted in a fiberglass housing. The package is 4-1/4 inches long with a diameter of either 1-1/4 inches or

1-3/8 inches. Interstage resistors, welded to the kovar rings, are potted with the tube, and connection is made by means of color coded leads.

1.3 Description of Photomultipliers with Ultraviolet Response

The EMR Model 541F-08-18 is an 18-stage, end-on window tube having a spectral response extending from 1050 Å to approximately 3500 Å. The tube has a 1/8 inch diameter, semitransparent, cesium-telluride photocathode on an ultraviolet grade cleaved lithium fluoride window.

The same design of venetian-blind dynodes and hard glass-kovar ring construction is used. The tube, potted in a stainless steel shell, has a teflon seat for an O-ring which may be used to couple the tube to a vacuum monochromator. The package is 5-3/8 inches long and 1-1/4 inches in diameter.

1.4 Summary of Overall Program

The first step in the study phase of the program was the selection of the two tube types to be used. The Model 541D was selected as the visible response tube and the 541F as the ultraviolet response tube.

A number of engineering samples of the two standard products were subjected to dry heat sterilization and tested. Some modification of the standard processing techniques was indicated. For the Model 541D a new cathode processing technique was used to improve the spectral response characteristics and enable the tube to better withstand the severe dry heat sterilization environment. The Model 541F was found to be adaptable to the requirements of dry heat sterilization with only minor changes in the standard processing technique.

Four Model 541D tubes and five Model 541F tubes were prepared and potted for the final test phase.

Each tube was subjected to a program of three cycles of dry heat sterilization, gas decontamination, static acceleration, vibration, shock, thermal vacuum and life testing.

Measurements of spectral response, gain, and dark current were made initially and after each test. In addition, resolution of the Cs^{137} gamma ray was measured for the Model 541D tubes using a NaI(Tl) scintillation crystal.

2. PHOTOMULTIPLIER CHARACTERISTICS AND THEIR MEASUREMENT

2.1 Spectral Response

2.1.1 Definitions

Two terms that are particularly useful in specifying the sensitivity of a photocathode are cathode radiant sensitivity, σ_k (λ), and quantum efficiency, $Q(\lambda)$. The cathode radiant sensitivity is a measure of the sensitivity of the photocathode to monochromatic light at a particular wavelength λ expressed in units of Amperes/Watt. The quantum efficiency at a wavelength λ (in Angstroms) is the sensitivity of the photocathode expressed in units of photoelectrons per incident photon. The cathode radiant sensitivity and quantum efficiency at a given wavelength λ are related by

$$Q(\lambda) = \frac{1.24 \times 10^4 \sigma_k(\lambda)}{\lambda}$$

The spectral response characteristic of the photocathode is a plot of cathode radiant sensitivity as a function of wavelength. In practice the measurements of cathode radiant sensitivity and quantum efficiency include the effects of absorption or reflection in the window because the measurements are based on the light flux incident on the window of the photomultiplier.

2.1.2 Spectral Response Characteristics

In general the spectral response characteristics of a photomultiplier are determined by the characteristics of the photocathode itself and by the characteristics of the window. For example, the spectral response of the Model 541D photomultiplier has a maximum response in the blue at about 4100 Å which is characteristic of the bialkali photocathode and a short wavelength cut-off which is characteristic of the 7056 glass window.

The Model 541F photomultiplier has a spectral response in the ultraviolet. Its threshold at about 3500 Å and peak response between 1800 and 2537 Å is characteristic of the cesium-telluride photocathode; the short wavelength cut-off at about 1050 Å is characteristic of the lithium-fluoride window.

2.1.3 Measurement Techniques

The cathode radiant sensitivity is measured by directing a beam of monochromatic light of known intensity on the window of the tube and measuring the resulting photoelectric current. The tube is connected as a diode as shown in Figure 1. The photocathode is normally placed at a negative potential of from 150 to 300 V (as required for saturation), while the first dynode and remaining dynodes are used for collection. The first dynode is tied to the input of an electrometer such as a Keithley Picoammeter which is used to measure the photoelectric current.

For measurements of the spectral response in the visible region a Perkin-Elmer monochromator is used. The light input to the tube is measured by means of a calibrated thermocouple. The light level is adjusted for a desired output from the thermocouple, the light light beam is deflected onto the face of the tube, and the photocathode current is read.

The light source used for measurements in the visible region is a tungsten lamp. A mercury lamp is used for measurements in the ultraviolet from 2537 Å to approximately 3800 Å; this lamp has strong lines at 2537 Å, 3125 Å and 3650 Å, with several weak lines scattered between. For measurements below 1850 Å on the ultraviolet response tubes, a vacuum monochromator must be used because of absorption of the shorter wavelength radiation in air. For the vacuum monochromator measurements a comparison technique is used. A standard diode of known quantum efficiency is set up, and the light

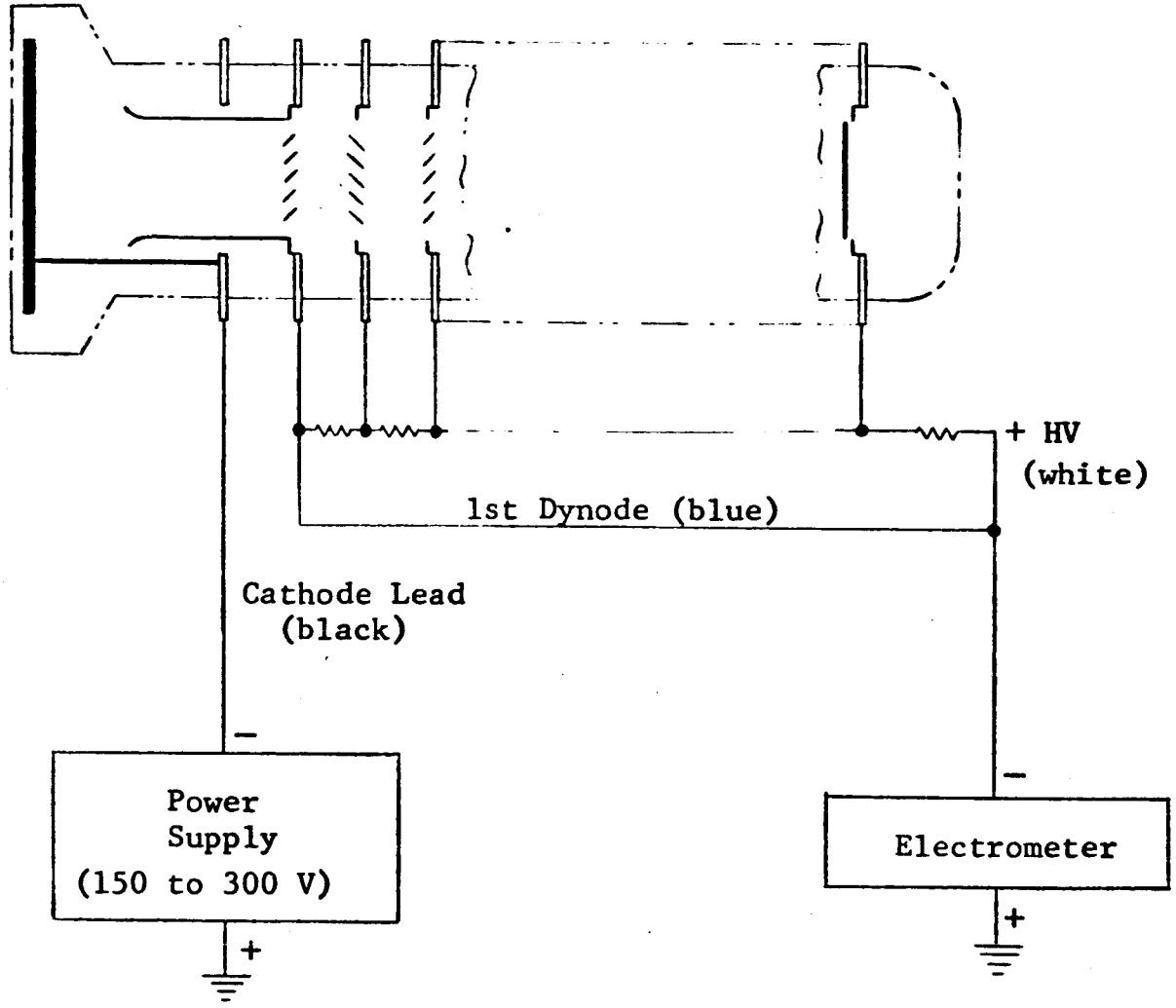


Figure 1. Schematic diagram showing the electrical connections for measuring cathode radiant sensitivity.

input is adjusted for a given response. The tube to be measured is then inserted and the resulting photoelectric current is read. The quantum efficiency is obtained from the ratio of photocurrents and the quantum efficiency of the standard tube. Measurements on the vacuum monochromator are made at wavelengths of 1236 Å, 1470 Å, 1600 Å, and 1849 Å.

2.2 Gain

The current gain of a photomultiplier is defined as the ratio of anode current to cathode current. The gain is strongly dependent on the overall voltage. Current gain is normally plotted as a function of overall voltage on a semi-log graph with gain plotted on the logarithmic scale. Useful gains range from approximately 10^4 to 10^8.

If the average gain due to secondary emission for one dynode in a photomultiplier is δ and the gain is equal for each of the n dynodes, then the total gain will be $G = \delta^n$. Since the number of stages is large, 14 for the visible response tubes and 18 for the ultraviolet response tubes, a very slight variation in the average gain per dynode can result in significantly large changes in total gain G.

The gain measurement is made in two steps. With the tube connected as a diode the light input is adjusted to produce a convenient cathode current (in the range of approximately 10^{-12} amperes). Then without changing the light input or the orientation of the tube with respect to the light spot, the tube is connected as a multiplier, and the anode current is measured as a function of the overall applied voltage.

2.3 Resolution

2.3.1 The Scintillation Detector

A scintillation detector consists of a suitable scintillation crystal optically coupled to the faceplate of a photomultiplier as shown in Figure 2. An incident

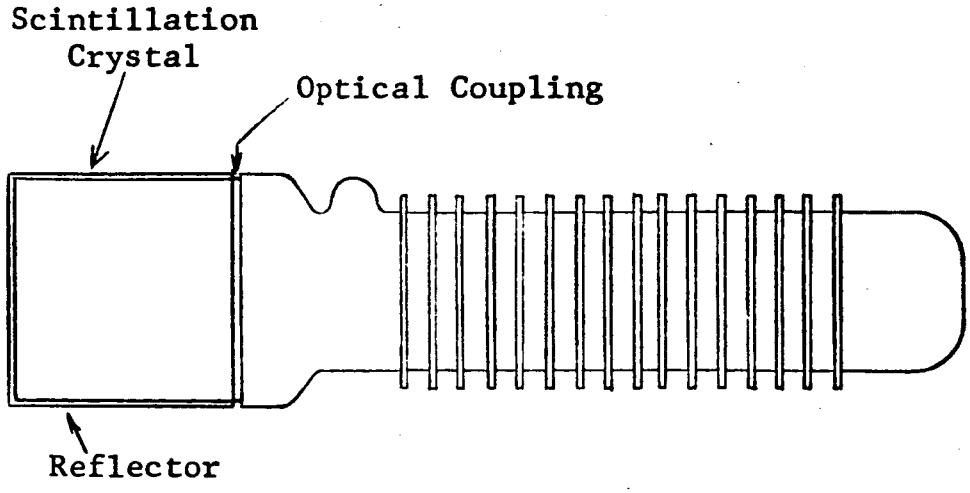


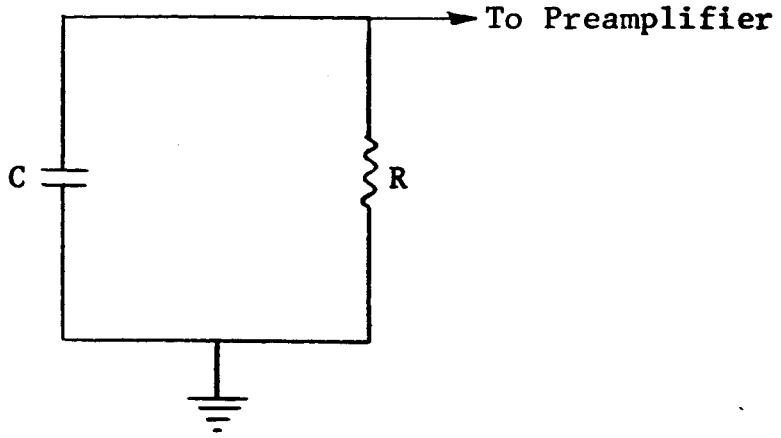
Figure 2. A scintillation detector.

gamma ray is absorbed within the scintillation crystal, and the gamma ray energy which is given up to the crystal is then re-emitted as a short burst of visible light. By means of the optical coupling, the photocathode sees the scintillation, and a number of photoelectrons are emitted. The photoelectrons collected on the first dynode of the photomultiplier are multiplied through the dynode structure resulting in a current pulse at the anode of the tube.

The equivalent circuit of the anode of the photomultiplier is shown in Figure 3. The capacitance shown is the sum of the anode capacitance, stray capacitance in the circuit, and the input capacitance of the preamplifier. The load resistor is selected to give the proper time constant.

The voltage pulse at the input of the preamplifier is shown in Figure 4. It has a rise time which is determined by the decay time τ of the crystal (in the case of thallium activated sodium iodide, $\tau = 0.25$ μsec). The decay time of the pulse is determined by the RC time constant of the anode circuit. In general the RC time constant should be very long in comparison to the decay time constant τ of the scintillation crystal. This insures that all of the charge from the current pulse is integrated at the input of the preamplifier to give the maximum pulse amplitude which is determined by $V = Q/C$ where Q is the total charge per pulse and C is the capacitance of the anode circuit.

The amplitude of the output pulse is determined by the number of photons emitted by the crystal for each incident gamma ray, the transfer coefficient for photons from the scintillation crystal to the cathode of the photomultiplier, the quantum efficiency of the photocathode, the collection efficiency of the photomultiplier (i.e., the fraction of photoelectrons per pulse that is collected onto the first dynode), the average gain of the photomultiplier, and the anode capacitance.



$C = C_A + C_P + C_S$

C_A = anode capacitance

C_P = input capacitance of preamplifier

C_S = stray capacitance

Figure 3. Equivalent circuit for the photomultiplier anode circuit.

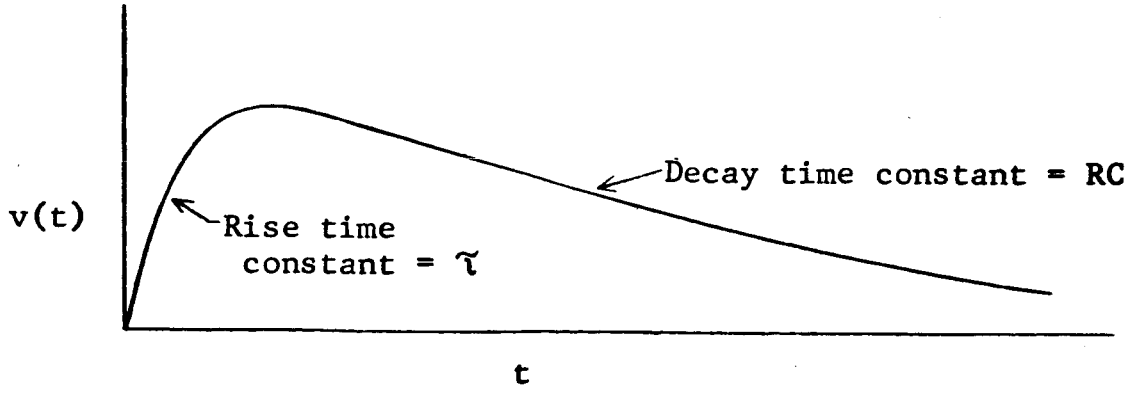


Figure 4. Voltage pulse appearing at the anode of the photomultiplier.

Since the pulse amplitude is inversely proportional to the anode capacitance, it is advantageous to have the anode capacitance as low as possible. For this reason a preamplifier is commonly placed in close proximity to the photomultiplier output. The preamplifier can drive a long cable to the pulse height analyzer without having the signal pulse degraded by the cable capacitance.

2.3.2 Pulse Height Spectra

A typical differential pulse height spectrum obtained using a sodium iodide scintillation crystal and a Cs^{137} gamma source is shown in Figure 5. The axes in this figure are labeled as they would be for data obtained from a multi-channel pulse height analyzer. The abscissa in channel number corresponds to pulse height in units of electron charge.

The shape of the pulse height spectrum may be explained by a consideration of the absorption processes in the crystal. In the photoelectric process a gamma photon interacts with an electron in the crystal giving up all of its energy to the electron. The electron energy is completely given up to the crystal, and a fraction of this energy is emitted in the form of light. In the case of the photoelectric interaction the total energy of the gamma photon is given up to the crystal, and the number of photons per scintillation is directly proportional to the gamma ray energy. The result is a photo-peak as shown in Figure 5 with the pulse amplitude proportional to the energy of the incident gamma ray.

A competing absorption process is that of Compton scattering. In this case an incident gamma photon gives up only a fraction of its energy to an electron within the crystal, and the lower energy scattered photon may escape from the crystal volume. In this case only the fraction of the incident gamma energy which was given up to the electron

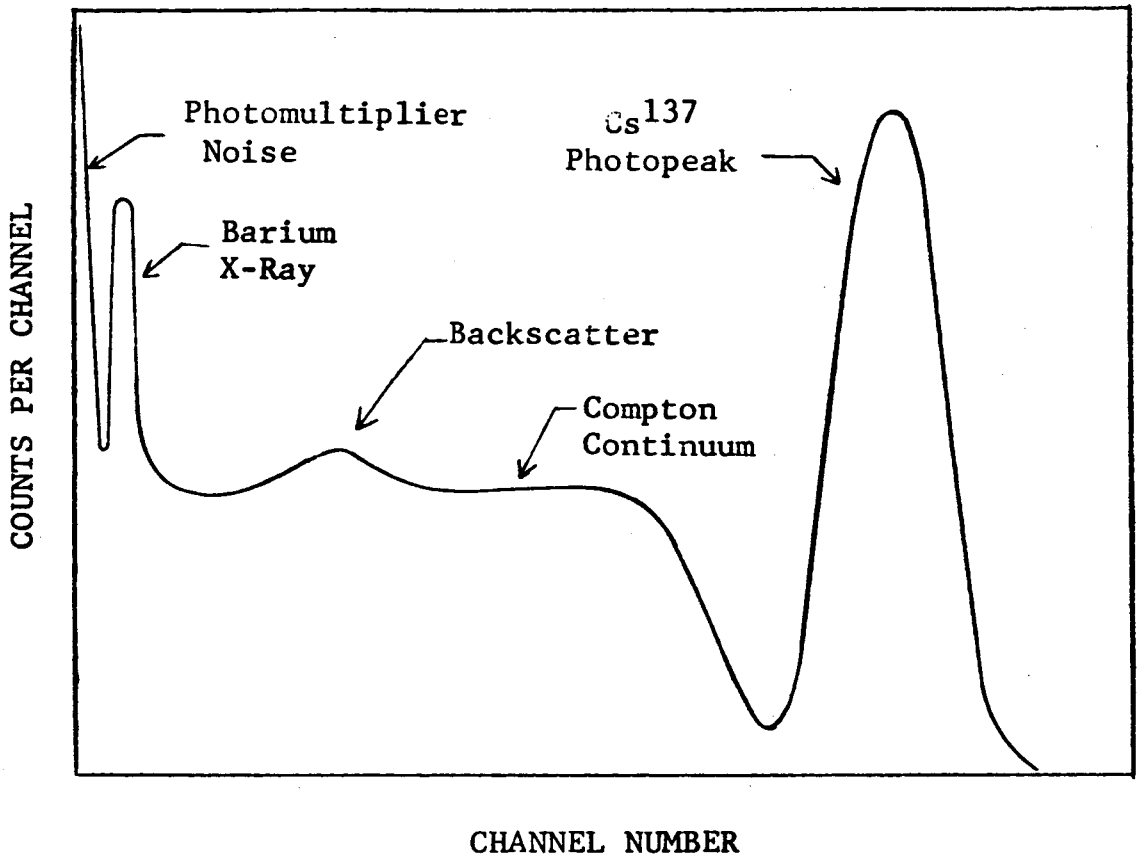


Figure 5. A typical differential pulse height spectrum using a NaI(Tl) scintillation crystal and a Cs^{137} source.

is seen by the photomultiplier as visible light. This results in a lower amplitude pulse than was seen with the photoelectric effect. Since the energy of the scattered gamma is a function of the energy of the primary gamma and the scattering angle, a pulse height continuum is seen due to the Compton scattering process.

Two other peaks are seen in the spectrum. Superimposed on the Compton continuum is a small peak due to back-scattered photons. The photo-peak corresponding to 32 kev is due to the barium k x-ray. Photomultiplier noise pulses are seen at pulse amplitudes below that of the barium x-ray.

2.3.3 Resolution

The width of the photo-peak is a measure of the statistical variation in pulse height for a given monoenergetic gamma and an indication of the ability of the system to resolve two different gamma rays closely spaced in energy. The resolution W_T is defined as

$$W_T = \frac{\triangle E}{E} \times 100\%$$

where E is the position of the photo-peak and $\triangle E$ is the width of the photo-peak at half-maximum. The shape of the photo-peak is closely approximated by a Gaussian distribution.

The statistical variation in pulse heights for monoenergetic gamma rays is a result of statistical variations in the number of photons emitted by the scintillator per absorbed gamma and statistical variations due to the photomultiplier. The total line width W_T consists of two components, W_P due to statistical variations in the photomultiplier and W_C due to an intrinsic resolution of the scintillation crystal. The total resolution W_T is related to the

photomultiplier resolution and the resolution of the crystal by

$$W_T^2 = W_P^2 + W_C^2$$

The resolution of the photomultiplier W_P can be measured directly using a light pulser. A cathode ray tube with the proper phosphor can be pulsed in such a way as to simulate the light pulses from a scintillation crystal. Knowing the resolution of the photomultiplier W_P, the resolution of the crystal can be determined from the total resolution using the above equation.

An alternative technique for separating the photomultiplier resolution from the total resolution is described by Onno and Bell. This technique involves measuring the total resolution for different values of anode time constant RC. An analysis of this data then allows one to separate the resolution of the crystal and the resolution of the photomultiplier.

The contribution to the total resolution which is intrinsic to the crystal is determined by such factors as the crystal size, geometry, quality and packaging of the cyrstal, and the type reflector material used. The optical coupling between the scintillation crystal and the photomultiplier must be maximized for the best total resolution.

The total resolution is inversely proportional to the square root of the number of photoelectrons per pulse arriving at the first dynode of the photomultiplier. For this reason the best resolution is obtained when the quantum efficiency is high and the collection efficiency for electrons to the first dynode is close to one.

2.3.4 Measurement

For all the resolution measurements made during this study, the scintillation crystal was optically coupled to

the photomultiplier using Dow Corning C-20057 compound. Care was taken to insure that there were no bubbles between the crystal and the faceplate.

In resolution measurements, factors which contribute to total resolution must be considered. The counting geometry must be optimized for best resolution. In our resolution measurements placing the Cs^{137} source in contact with the end of the crystal can and in line with the axis of the crystal was found to be the most suitable geometry. The counting rate with the source in this position was approximately 2000 counts/second.

Several precautions must be observed to insure proper operation of the electronics. When excessive photomultiplier gains are used, especially with high quantum efficiency tubes, the preamplifier may be overdriven introducing distortion in the pulse height spectrum. A gain of 1×10^5 is commonly used. The output of the linear amplifier in the multichannel analyzer should be observed with an oscilloscope to insure that the amplifier is not being overdriven. The zero of the multichannel analyzer should be checked using a mercury pulser to insure that zero channel corresponds to zero pulse height.

2.4 Dark Current

2.4.1 Definition

The dark current of a photomultiplier is the anode current that is measured when the tube is operated in total darkness.

2.4.2 Sources of Dark Current

Sources of dark current are electrical leakage, thermionic emission, field emission, residual gas ionization, and tube fluorescence. The two major components are

thermionic emission and electrical leakage. The component of dark current which is due to electrical leakage can be reduced effectively by thorough cleaning and dessication of the tube followed by potting in a high resistivity potting compound which hermetically seals the tube. The thermionic component of dark current is readily identified by plotting dark current as a function of temperature.

2.4.3 Measurement

In practice the measurement of photomultiplier dark current requires considerable care in order to achieve reproducible results. In the case of low work-function cathodes such as the bialkali, the major component of dark current is that due to thermionic emission. For this reason it is important that the temperature be recorded along with the dark current data.

In the measurement of dark current the tube is placed in a completely light tight box and connected as a multiplier. The most convenient arrangement is to operate the tube with negative high voltage; that is, the cathode is at a negative high voltage, and the anode, being at ground potential, can be tied directly to the input of an electrometer. One precaution that should be observed when this arrangement is used is that the cathode should not be placed in the vicinity of an external ground potential. When a tube is operated at negative high voltage and the ground potential is brought in contact with or in close proximity to the faceplate of the tube, an increased dark current will be observed.

The dark current is a function of the time which a tube is aged in the dark. For accurate and reproducible measurements the tube should be aged until the dark current settles to a constant value.

3. PRELIMINARY STUDY OF STANDARD PRODUCTS

A number of engineering samples of standard products were studied to determine their ability to withstand dry heat sterilization. Because of its long history of successful application for scintillation counting at high temperatures in oil-well logging operations, the Model 541D was selected as the tube with visible response which was most suitable for the sterilization program. The Model 541F-08 with a lithium fluoride window was selected as the tube with an ultraviolet response which was most suitable to the requirements of the sterilization program. The tubes selected for this study underwent three dry heat sterilization cycles at 145°C for a period of 36 hours. Measurements of spectral response, gain and dark current were made on each tube.

3.1 Photomultipliers with Visible Response

Twelve engineering samples of standard Model 541D tubes were obtained for this Preliminary Study. The data obtained from these tubes represent the performance of tubes before the development program for sterilizable tubes was accomplished.

The average cumulative changes in quantum efficiency at 4200 Å for the twelve tubes (expressed in percentage change from the initial value) were 39, 52, and 57% decreases after 1, 2, and 3 dry heat sterilization cycles respectively. The large changes in cathode sensitivity after dry heat sterilization were not completely unexpected considering the severity of the sterilization environment when compared to the temperatures at which the photocathode is normally processed.

A further problem was the wide scatter in results. For example, after the first cycle although an average decrease of 39% was observed, the data was spread between a minimum value of 20% and a maximum value of 55%. After two cycles the data showed an average decrease of 52% with scatter between a minimum of 20% and a maximum of 78%. After 3 cycles an average decrease was observed with the data scattered between the minimum of 29% and a maximum of 71%. Because of the scatter it was not feasible to predict the changes due to any particular cycle to within a reasonable accuracy.

The current gain at 2600 V was found to decrease by an average of 18% after the first sterilization cycle and the average net change in gain remained constant for the remaining two cycles. The dark current was found to undergo a very slight increase on the average, but the observed change was not significant when compared to the accuracy of measurement.

3.2 Photomultiplier with Ultraviolet Response

Four engineering samples of Model 541F-08 photomultipliers were subjected to three dry heat sterilization cycles. Measurements of spectral response, gain, and dark current were made initially and after each of the dry heat cycles.

The cesium telluride cathode was found to be more stable under conditions of dry heat sterilization than the bialkali cathode. After three cycles the quantum efficiency at 2537 Å was found to have an average decrease of 14% and the resulting quantum efficiency was found to be predictable within an accuracy of 12%. The average cumulative decreases in gain were 27, 23, and 18% after 1, 2, and 3 cycles respectively.

A net decrease in the average dark current was observed after each of the three cycles. The dark current data, since the tubes were unpotted, have no significance other than to show that no appreciable degradation in the tube dark current characteristics were to be expected as a result of dry heat sterilization.

3.3 Summary

The results of the Preliminary Study on the standard Model 541D photomultipliers indicated that changes in the cathode processing techniques should be made in order to improve the predictability of cathode sensitivity after dry heat sterilization. It was felt that some experimentation in the cathode processing technique could result in a reduction of residual alkali materials remaining in the tube after seal-off.

Although changes in cathode sensitivity for the Model 541F photomultiplier were not severe, it was felt that a reduction in the amount of cesium remaining in the tube after processing would improve the stability of the cathode sensitivity and gain, and would improve the predictability of these parameters.

As part of the sterilization program a development phase was undertaken to improve the stability and predictability of electrical characteristics of both the 541D tube with visible response and the 541F tube with ultraviolet response.

4. DEVELOPMENT PHASE

4.1 Photomultipliers with Visible Response

The first experiment on the visible response cathode was to process a Model 542D (same cathodes as the 541D but in a 1-3/4 inch diameter) using the standard production processing technique followed by a 150°C bake while the tube was still on the vacuum system. The tube was baked for a period of one hour in order to remove any excess alkali materials. The quantum efficiency of this tube at 4200 Å was 5.9% and the gain at 2600 V was 1.4×10^6. Following three dry heat sterilization cycles, the quantum efficiency had dropped by 62% and the gain had increased by 21%.

The second experiment with visible response photomultipliers was to process a Model 542 using the standard processing technique. This tube was used as a control to compare the processing experiments to the standard tube. The quantum efficiency of this tube was 6.8% at 4200 Å, and the gain 1.2×10^6. Following three dry heat sterilization cycles, the quantum efficiency decreased by 68%, and the gain increased by 76%. It was therefore concluded that the standard processing technique did not provide the processing control deemed desirable for the sterilization program.

During the course of a cathode development program carried out by the Research Department at EMR, a technique of cathode formation had been developed in which the cathode is formed in successive layers until maximum sensitivity is achieved. This technique permitted much finer control over the rate of evolution of alkali materials into the tube. Because it was readily adaptable to the formation of the bialkali cathode it was decided to use the layer technique for the processing of sterilizable bialkali photocathodes.

The layer technique resulted in a 541D having a quantum efficiency of 20% at 4100 Å, a gain of 6.4×10^6 at 2600 V, and a total resolution (with crystal) for the Cs^{137} gamma of 7.2%. During the course of the developmental program, a total of seven tubes with bialkali cathodes were processed using the layer technique.

A disadvantage of the new type cathode was observed as the dry heat sterilization was carried out. The layer type bialkali cathodes became highly resistive after one or more sterilization cycles. In the case of a resistive photocathode, the tube does not exhibit the same saturation characteristics, and at high light levels the quantum efficiency for a highly resistive cathode appears to be lower than the true quantum efficiency. Some degradation in the gamma-ray resolution could also be attributed to the high resistivity of the photocathode.

At this point an attempt was made to solve the problem of high resistivity in the photocathode. Two tubes made in which the photocathodes were deposited on tin oxide conductive substrates were unsuccessful because of a chemical reaction between the tin oxide and the hot sodium introduced during the processing.

An attempt was made to increase the photocathode conductivity by modifying the photocathode formation. This was done by processing the bialkali cathode using a normal layer technique, but instead of stopping when the maximum sensitivity was achieved, additional layers were deposited until a slight decrease in photocathode sensitivity was observed. This was followed by the addition of a layer of antimony which decreased the photocathode sensitivity by about 10%. The photocathodes processed in this way showed no high resistivity effects following sterilization. This concluded the development phase on photomultipliers having visible response.

4.2 Photomultipliers with Ultraviolet Response

The preliminary study of engineering samples of Model 541F-08 photomultipliers having ultraviolet response showed that some improvement in stability and predictability of electrical characteristics would be desirable, and it was felt that these improvements could be brought about by reducing the amount of excess cesium in the tube.

The first experiment undertaken was to reduce the amount of free cesium in the tube prior to completion of the photocathode. Although the tube showed better stability (having a moderate decrease in quantum efficiency of 15% and a very minor decrease in gain of 4% after three sterilization cycles), the initial quantum efficiency was only 1%, and the initial gain was only 1.2×10^5. The reduced quantum efficiency and gain was due to the deficiency of cesium in the tube.

The next experiment was to process a tube in the normal manner and remove excess cesium following cathode formation by baking at 150°C for one hour while the tube was still on the vacuum system. This technique was much more successful. The initial quantum efficiency was 4%, and the gain was 5.3×10^5. The change in quantum efficiency was only 5% and the change in gain was 11% after three dry heat sterilization cycles.

The next experiment was to process in the normal manner with the addition of a post-processing bake at 100°C for one hour. Here the quantum efficiency and gain were higher, but the stability was lost. The initial quantum efficiency was 9.1%, and after three cycles it dropped by 36%. The initial gain was 1.6×10^6, and this showed an increase of 50% after three dry heat cycles. It was concluded that the bake at 100°C was not sufficient to remove the excess cesium from the tube and was not sufficient to give the desired stability.

The final experiment was undertaken to prove the value of the 150°C post-processing bake. This tube, processed in the normal manner but with tight control, and given a 150°C bake on the pumps for a period of one hour, had an initial quantum efficiency of 6.3% which dropped to 5.5% after three cycles and a gain of 2.8×10^6 which increased by 16% after three cycles.

It was felt that the value of the post-processing bake was well established, and the development program on photomultipliers with ultraviolet response was concluded.

4.3 Preparation of Tubes for the Final Test Phase

Four Model 541D-01 photomultipliers with visible response were prepared for the final testing phase of the program using the modified layer bialkali processing technique. The tubes were wired as shown in Figure 6. The standard tubes are normally wired with only three leads; however, on these tubes a wire was brought out from the first dynode in order to facilitate measurements of quantum efficiency and gain. The tubes were potted in fiberglass housings with a mixture of Sylgard 183 and Eccospheres.

Five Model 541F-08 photomultipliers with ultraviolet response were processed using the modified cesium-telluride cathode. They were resistorized and wired in the same manner as the 541D tubes and potted in the standard stainless steel shells.

Notes:

1- Resistor values equal throughout unit, 3.9 meg.

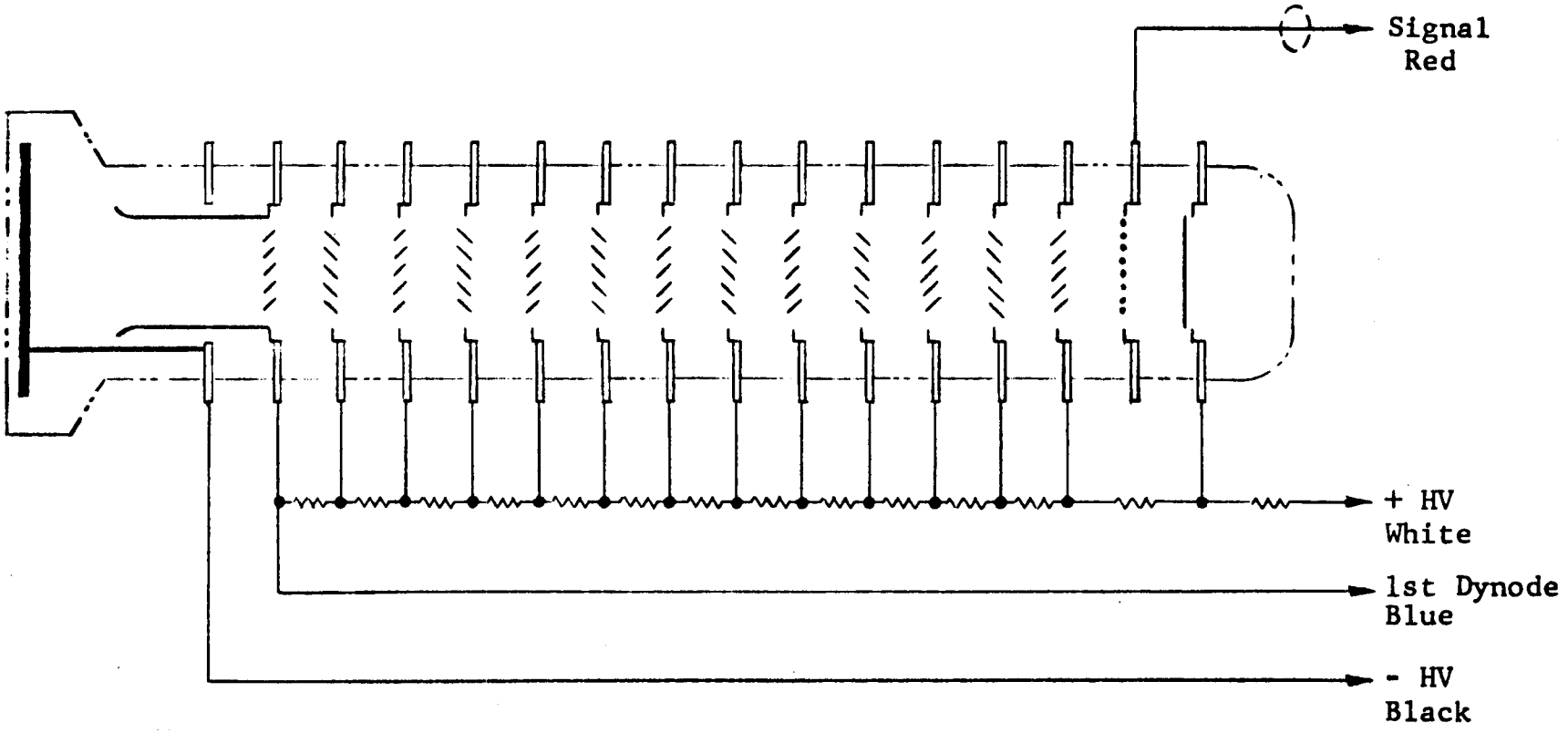


Figure 6. Schematic diagram for the sterilizable photomultipliers.

5. DRY HEAT STERILIZATION

5.1 Procedure

The dry heat sterilization was carried out in an electric oven equipped with a high sensitivity temperature control and a set of interval timers. In the dry heat sterilization cycle the temperature was increased from ambient to 145°C in a period of 36 hours.

A maximum heating and cooling rate of approximately 5°C per minute must be observed for the 541F-08 tubes because of the silver chloride window seal.

5.2 Definitions for Reporting of Data

At this point a note on the handling of the data is in order. For any given parameter x, data has been obtained initially and after each of three cycles on n tubes where n = 3 for the visible response tubes and n = 5 for the ultraviolet response tubes. A particular value of x is represented as x_{ij} where i = 1···n is the tube number and j = 0, 1, 2, 3 is the number of dry heat sterilization cycles to which the tube has been subjected.

The average value of x after the j-th cycle is defined by

$$\bar{x}_j = \frac{1}{n} \sum_{i=1}^{n} x_{ij}$$

The net change in x_i after j cycles is

$$\triangle x_{ij} = x_{ij} - x_{io}$$

From this definition a positive value for $\triangle x_{ij}$ indicates an increase in x_i.

The net fractional change in x_i after j cycles is

$$\frac{\Delta x_{ij}}{x_{io}} = \frac{x_{ij} - x_{io}}{x_{io}}$$

The net fractional change expressed in per cent will be called the net per cent change.

The average fractional change after j cycles will be used in discussing predictability of electrical characteristics and is defined by

$$\left(\overline{\frac{\Delta x_j}{x_o}}\right) = \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta x_{ij}}{x_{io}}$$

5.3 Results for Photomultipliers with Visible Response

In discussing results the quantum efficiency at 4100 Å, corresponding to the peak in the emission spectrum for NaI(Tl), is used as the best indicator of the spectral behavior. Gain at 2600 volts, dark current, and the resolution of the Cs^{137} gamma ray are reported.

Four tubes were completely tested through three dry heat sterilization cycles. Tube 541D-01 (D839) showed abnormal gain and resolution characteristics following the first dry heat cycle, and later failed mechanically during shock tests. The results for this tube were eliminated from the computation of average characteristics because of the abnormal characteristics and subsequent mechanical failure. Data are averaged only for the three Model 541D tubes which were carried through the complete testing program of dry heat sterilization, gas decontamination, environmental tests, and life tests.

A compilation of complete data for each tube is given in Appendix A. Average values for each of the electrical characteristics are given in Table A.

TABLE A

EFFECT OF DRY HEAT STERILIZATION ON THE AVERAGE ELECTRICAL CHARACTERISTICS OF THE TUBES WITH VISIBLE RESPONSE

Number of Cycles	QE (%) at 4100 Å	Gain at 2600 V	Voltage for 10^6 Gain	Resolution (%) of Cs^{137} gamma
0	13.1	1.1×10^6	2570	10.1
1	9.8	1.2×10^6	2600	10.8
2	8.2	1.3×10^6	2520	11.7
3	8.1	1.2×10^6	2540	11.5

5.3.1 Spectral Response

The three tubes, D833, D873, and D877, had an average initial quantum efficiency of 13.5% at 4100 Å. The average cumulative percentage decreases were 25, 37, and 38% for the three dry heat cycles, respectively. Figure 7 shows the average spectral response initially and after each of three cycles of dry heat sterilization for the three tubes. Figure 8 shows the effect of dry heat sterilization on the average quantum efficiency at 4100 Å for the tubes having visible response.

5.3.2 Gain

The effect of dry heat sterilization on the average gain at 2600 volts for the sterilizable photomultipliers with visible response is shown in Figure 9. The gain undergoes net increases of 12, 21, and 12% after one, two, and three cycles respectively.

A composite gain curve showing the average gain characteristics to be expected initially and after each of three cycles is given in Figure 10. These curves represent an average of the gain data for the three tubes.

A useful and most significant measure of the current gain characteristics of photomultipliers is the overall voltage required for a specified gain. The normal gain specified for EMR tubes is 1×10^6. The average initial voltage for a gain of 1×10^6 is 2570 volts, and following dry heat sterilization this value changes by +30, -50, and -30 volts. The net percentage changes in voltage are +1.2, -1.9, and -1.2% for one, two, and three cycles respectively.

The accuracy of the regulated high voltage power is 2% with a long term stability of 0.1% per day. An overall accuracy in measurement of gain changes is estimated at ± 10%.

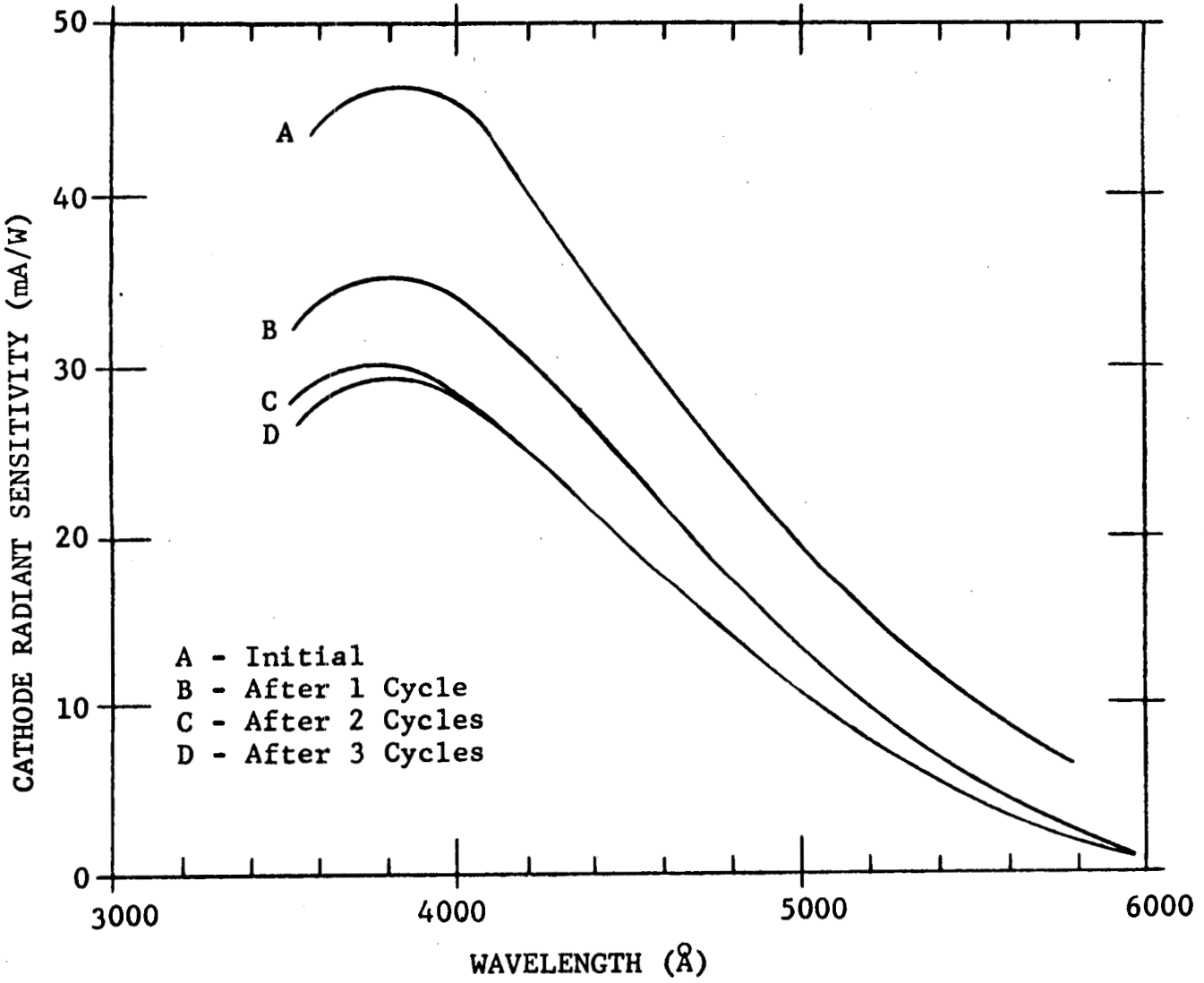


Figure 7. Average spectral response characteristics of Model 541D-01 photomultipliers subjected to dry heat sterilization.

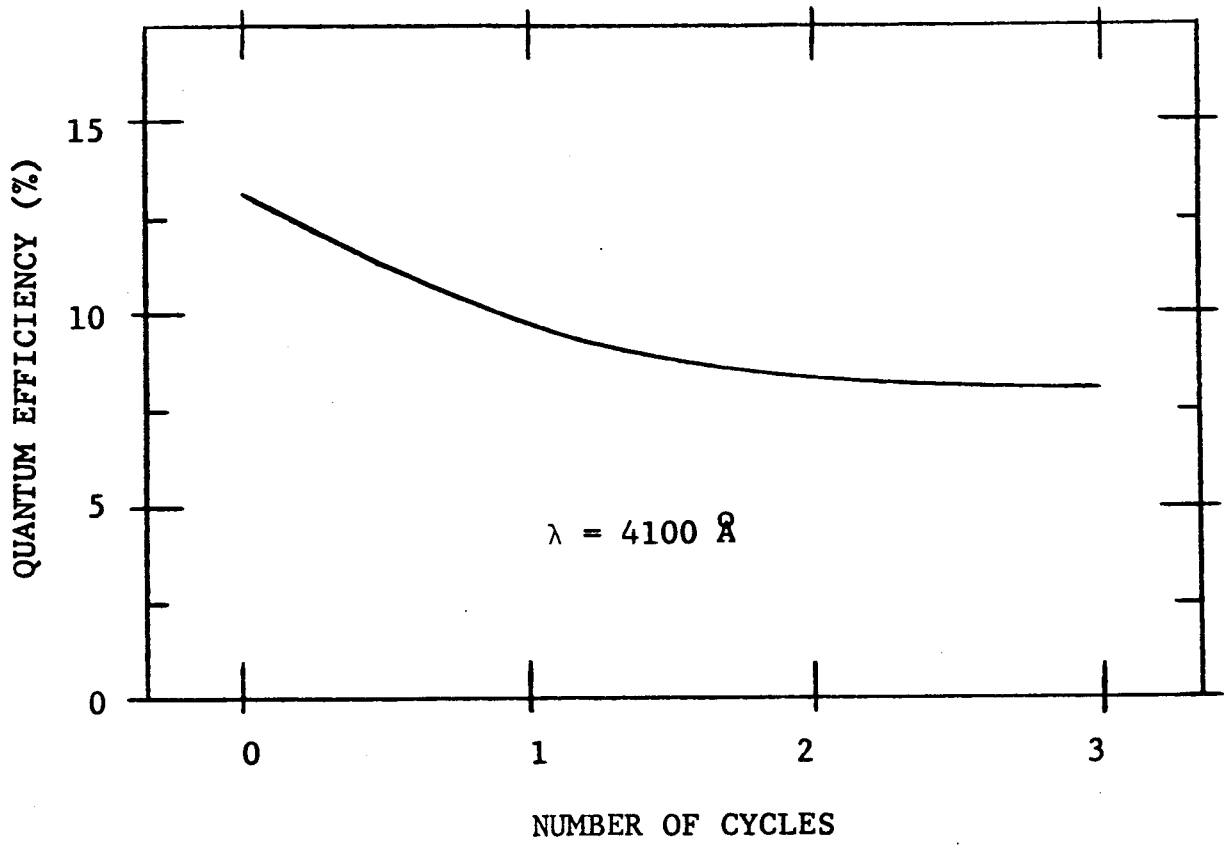


Figure 8. Effect of dry heat sterilization on the average quantum efficiency of the Model 541D-01 photomultipliers with visible response.

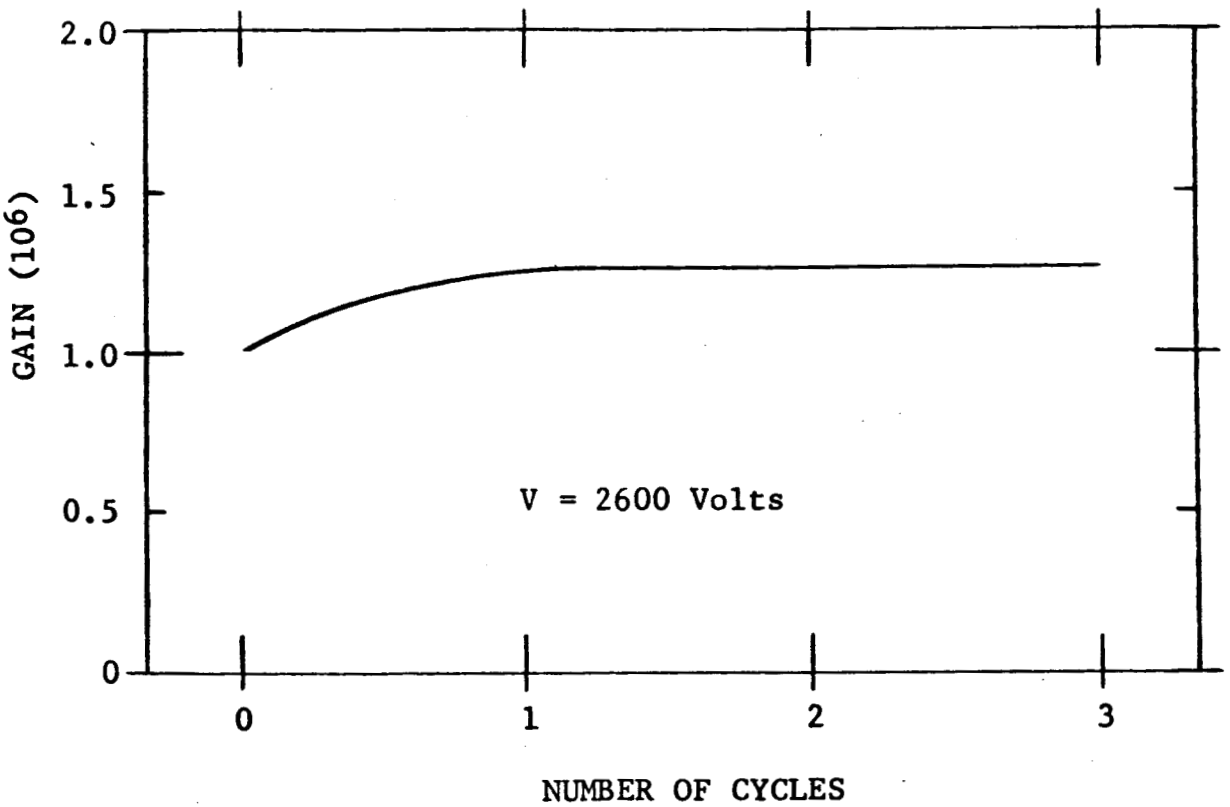


Figure 9. Effect of dry heat sterilization on the average gain for the Model 541D-01 photomultipliers with visible response.

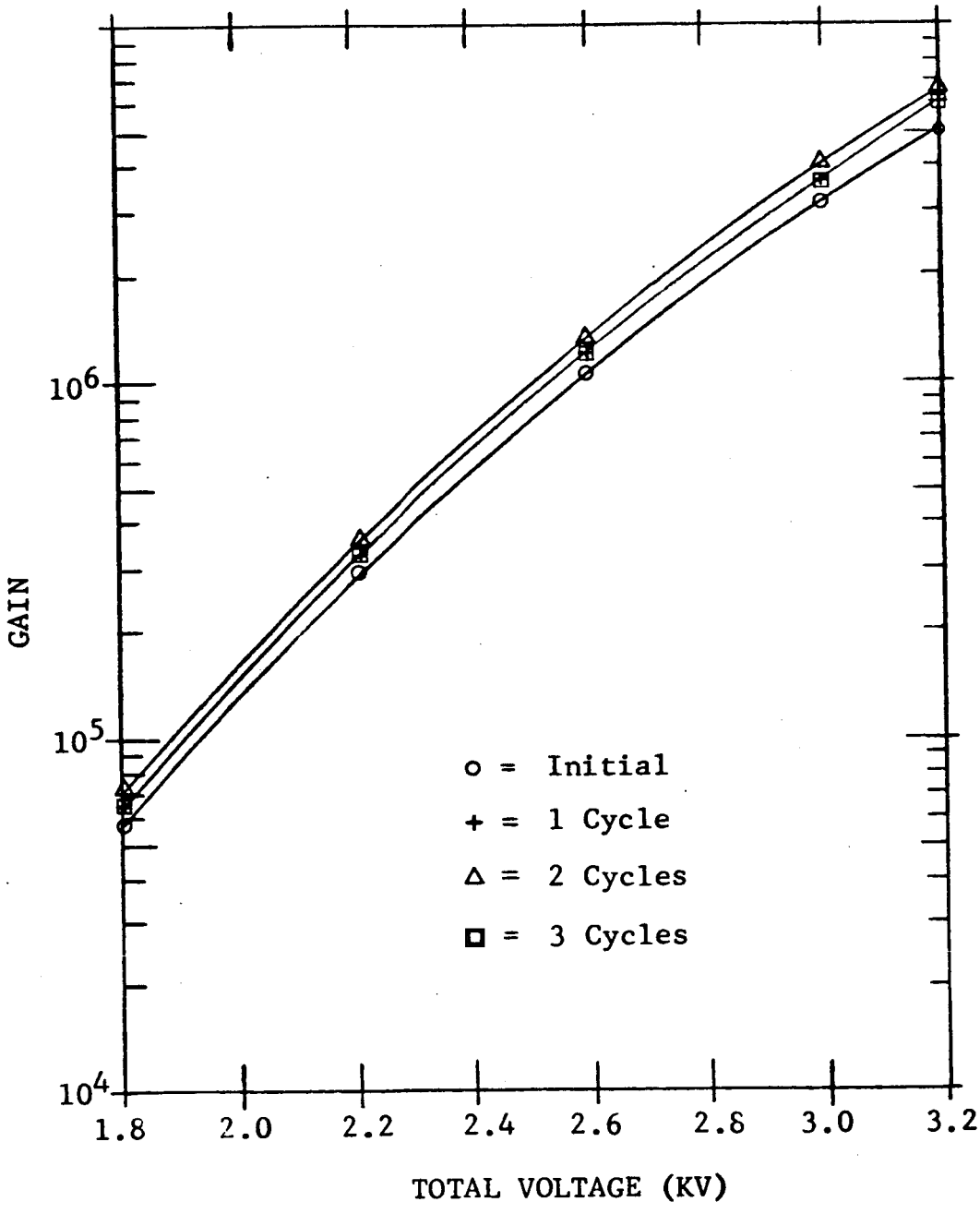


Figure 10. Average gain curves for the Model 541D-01 photomultipliers during dry heat sterilization.

5.3.3 Resolution

The average initial resolution of the Cs^{137} gamma ray using the Model 541D photomultipliers was 10.1%. Following dry heat sterilization the average resolution was 10.8, 11.7, and 11.5% after one, two, and three cycles respectively.

The effect of dry heat sterilization on the average resolution is shown in Figure 11. Absolute net changes in resolution were + 0.7, + 1.6, and + 1.4% after one, two, and three cycles respectively.

5.3.4 Dark Current

The dark current data are of importance only from the point of view that no significant increase in dark current results from dry heat sterilization. Dark current data show an average dark current of 1.0×10^{-10} Amperes corresponding to an average gain of 1.2×10^{6}.

5.3.5 Predictability

The quantum efficiency Q_j at 4100 Å after j cycles can be predicted from the initial quantum efficiency using the average net fractional change obtained from measurements on the study sample of identical tubes.

In this case a new sample is not available on which to test the accuracy of prediction, so the accuracy must be inferred from the spread in data from the study sample. Assuming the new sample has approximately the same spread in characteristics as the study sample, the absolute error in predicted values of Q_j is estimated at less than 2.5%.

The assumption that the new sample will have approximately the same spread in percent change in electrical characteristics is reasonable, because the tube processing

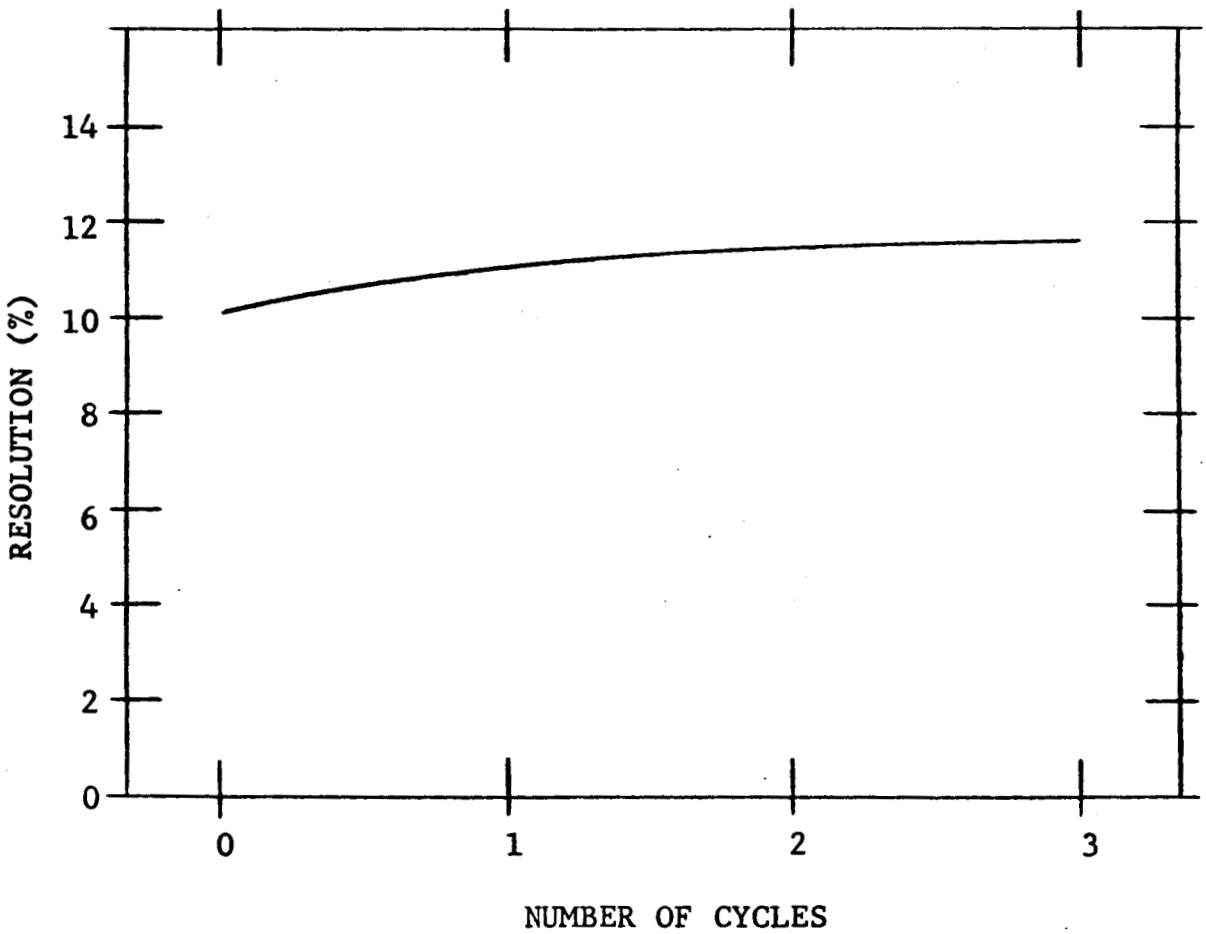


Figure 11. Effect of dry heat sterilization on the average resolution of the Cs^{137} gamma ray using the Model 541D-01 photomultipliers.

technique allows adequate control to reproduce characteristics from run to run as well as from tube to tube within a given run.

Gain data indicate that the average error in predicted gains at 2600 volts will be less than 20%.

Resolution of the Cs^{137} gamma ray, which is the most significant parameter for tubes used in scintillation counting, has the least observed spread. From the available data, the expected absolute error in resolution is less than 1% corresponding to a percent error of less than 10%.

5.4 Results for Photomultipliers with Ultraviolet Response

Five Model 541F-08 photomultipliers were subjected to three dry heat sterilization cycles. Electrical characteristics reported here are spectral response, gain and dark current.

A compilation of complete data on each tube is given in Appendix B, and average characteristics are given in Table B.

5.4.1 Spectral Response

The quantum efficiency at 2537 Å is taken as the best indicator of spectral response characteristics of the photomultipliers with ultraviolet response.

The average initial quantum efficiency for the five tubes was 11%. Following dry heat sterilization, there was no significant change in the average quantum efficiency after the first and second cycles. After the third cycle the average quantum efficiency was 10%, representing a net percentage decrease of 7% of the initial value.

The effect of dry heat sterilization on the average quantum efficiency at 2537 Å is shown in Figure 12. The

TABLE B

EFFECT OF DRY HEAT STERILIZATION ON THE AVERAGE ELECTRICAL CHARACTERISTICS OF THE TUBES WITH ULTRAVIOLET RESPONSE

Number of cycles	QE (%) at 2537 Å	Gain at 2600 V	Voltage for 10^6 gain
0	11	2.6×10^6	2520
1	11	2.4×10^6	2500
2	11	2.3×10^6	2520
3	10	2.6×10^6	2470

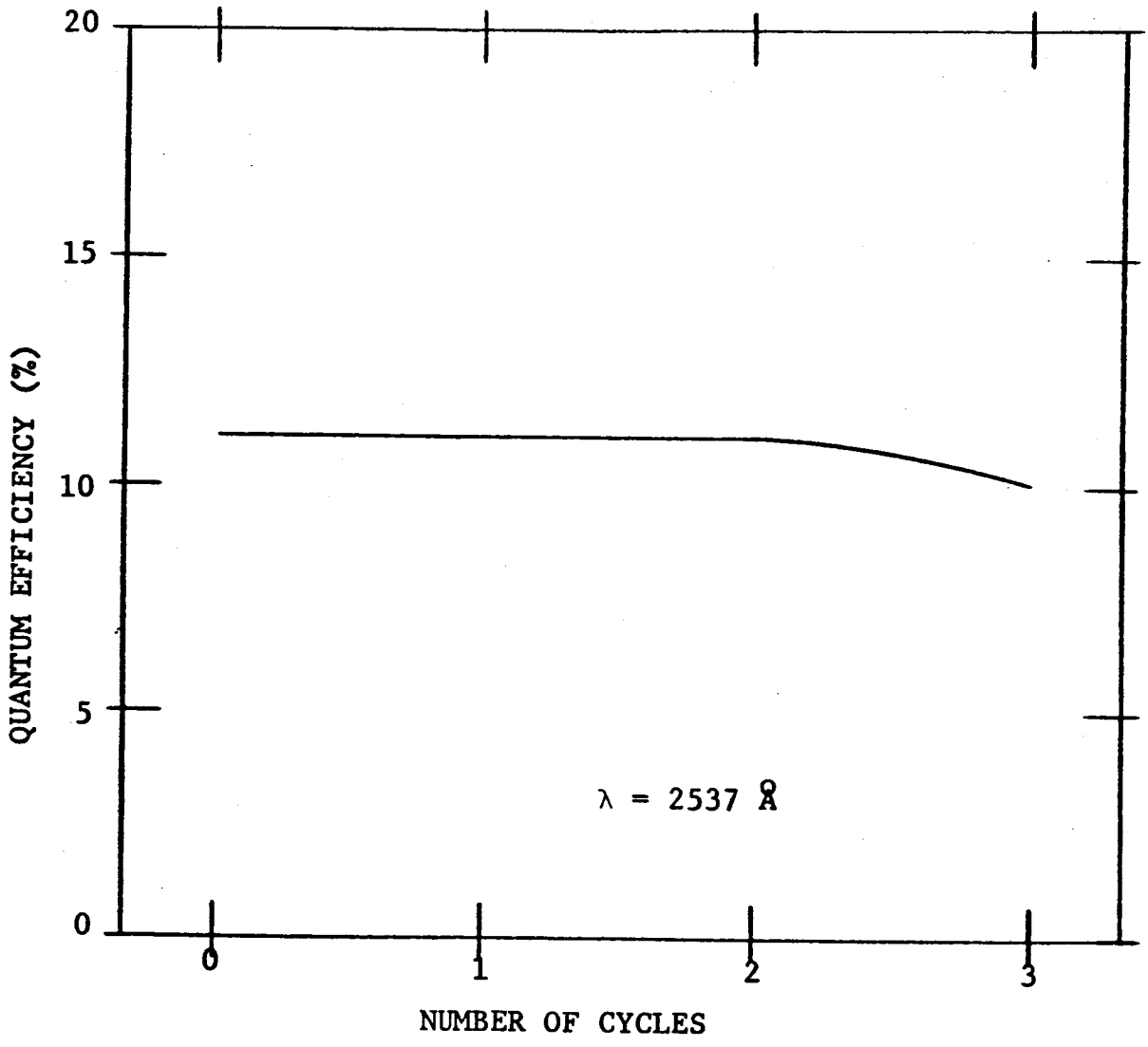


Figure 12. Effect of dry heat sterilization on the average quantum efficiency for the Model 541-08 photomultipliers with ultraviolet response.

typical spectral response characteristics to be expected initially and after each of three cycles obtained by averaging data for the five tubes are given in Figure 13.

5.4.2 Gain

The gain G at 2600 volts for the ultraviolet response tubes is taken as the indicator of the gain characteristics. The average gain curves given in Figure 14 show the expected gain characteristics of sterilizable Model 541F-08 photomultipliers prior to and following each cycle of dry heat sterilization. The effect of the dry heat sterilization on the average gain at 2600 volts is given in Figure 15.

The average initial gain at 2600 volts is 2.6×10^6. Average net percent changes in gain are insignificant following the first two cycles and following the third cycle an increase of 14% was observed.

The average voltage required for a gain of 10^6 before dry heat sterilization was 2520 volts. The average change in voltage following the third cycle was -30 volts. This is a net percent change of 1% which is within the estimated error of measurement.

5.4.3 Dark Current

The dark current measurements on the five ultraviolet response tubes show no significant changes in dark current due to dry heat sterilization.

5.4.4 Predictability

The average error in predicted quantum efficiencies for 541F tubes is estimated at 10% of the initial value on the basis of the spread in data from the sample of five tubes.

The gain data shows a larger spread with maximum average expected errors of 10, 10, and 16% after 1, 2, and 3 cycles, respectively.

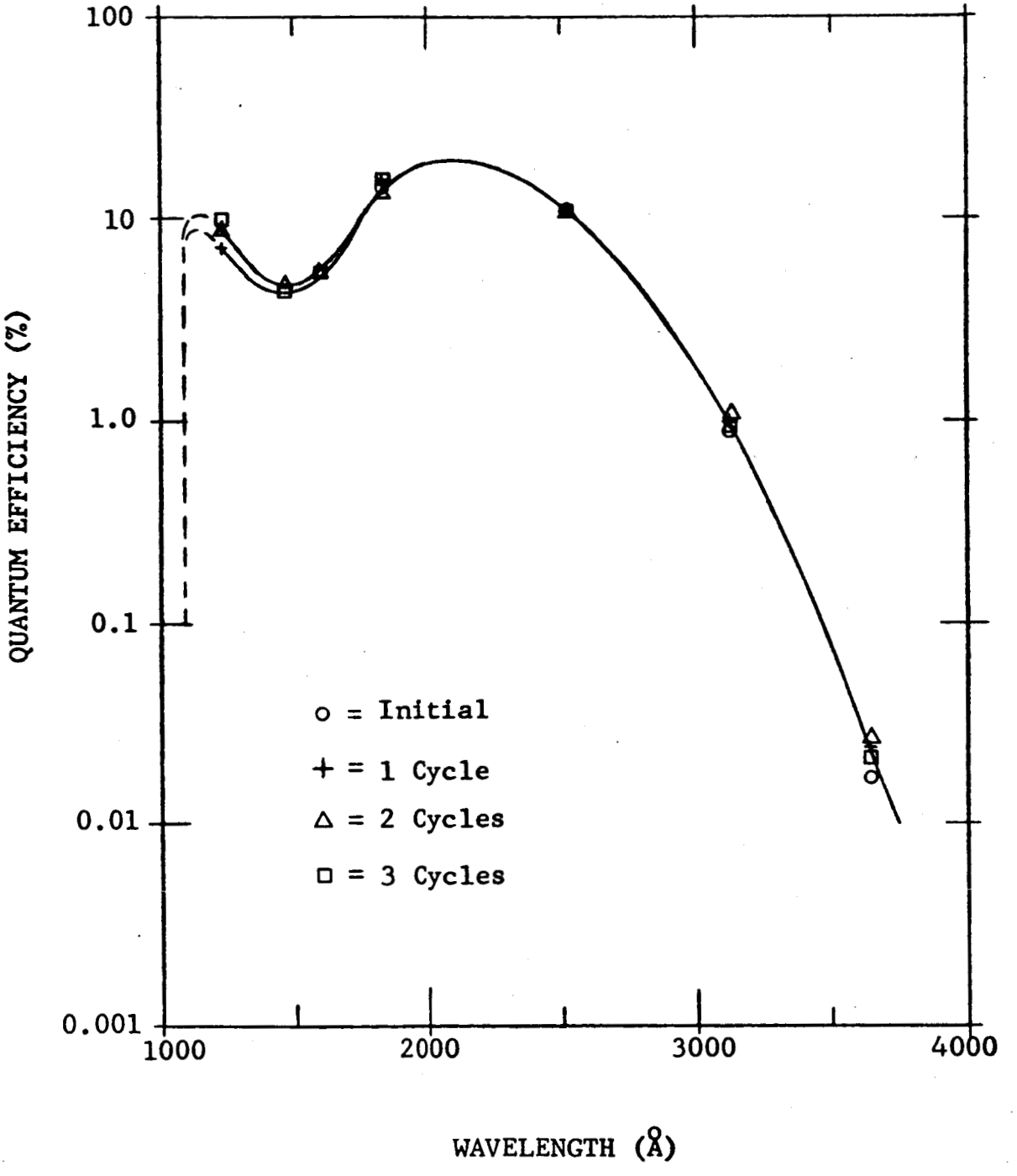


Figure 13. Effect of dry heat sterilization on the average spectral response for Model 541F-08 photomultipliers.

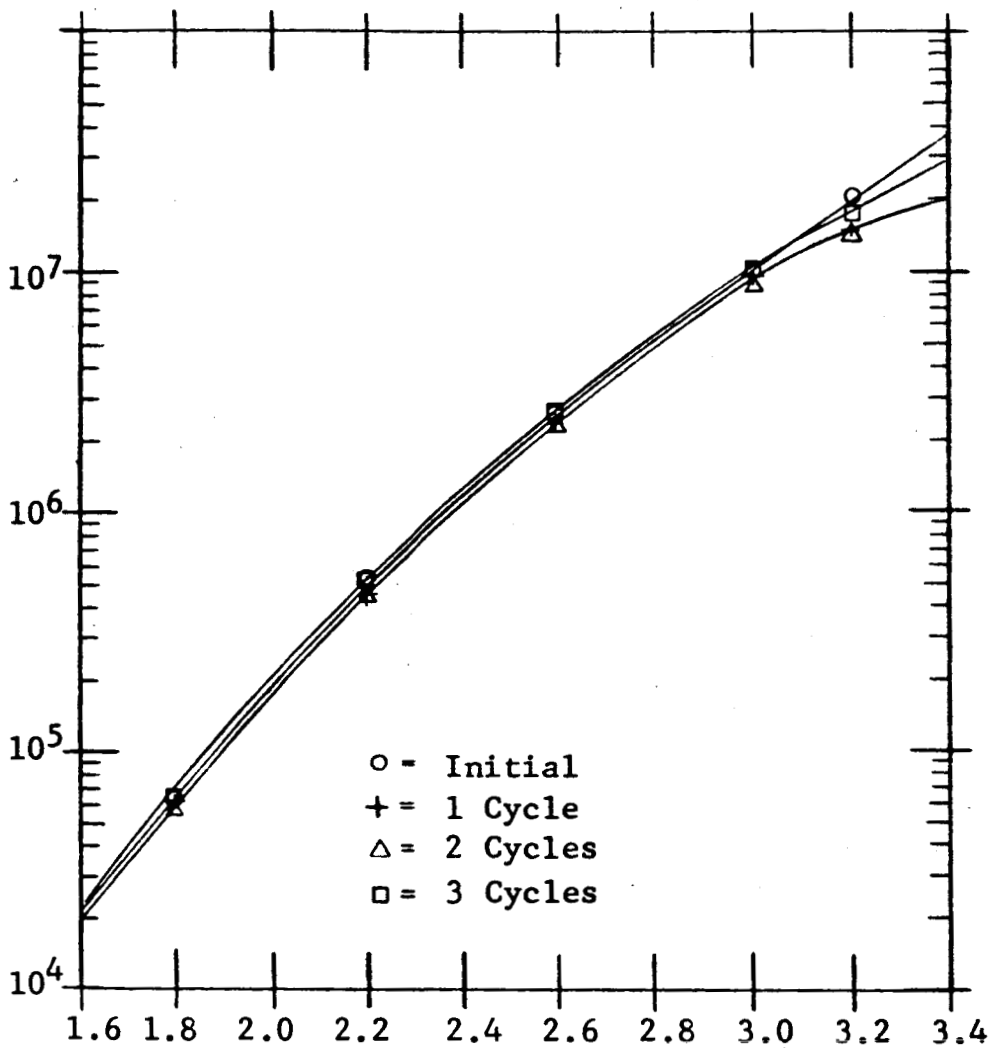


Figure 14. Effects of dry heat sterilization on the average gain characteristics of Model 541F-08 photomultipliers.

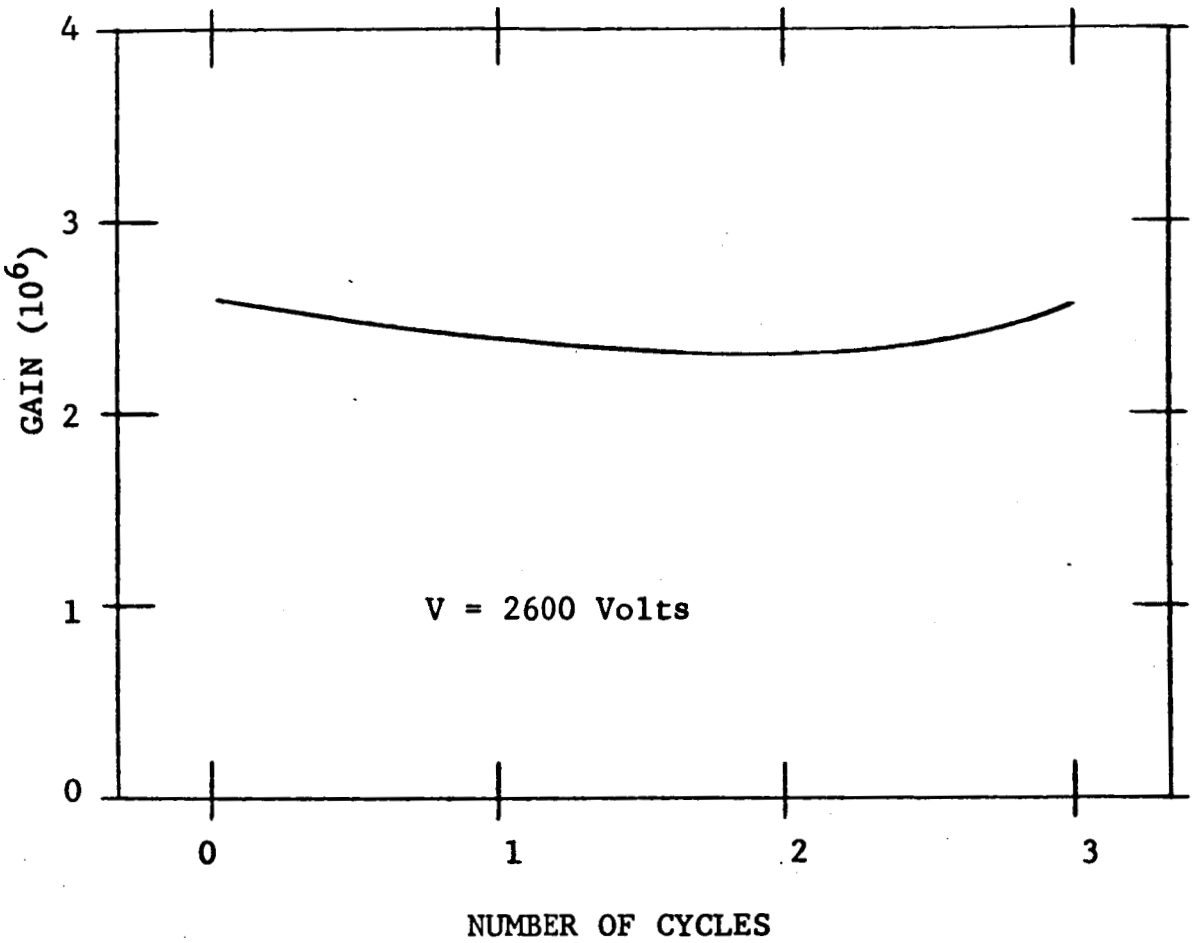


Figure 15. Effect of dry heat sterilization on the average gain for the Model 541F-08 photomultipliers with ultraviolet response.

6. GAS DECONTAMINATION

6.1 Procedure

The nine tubes (four Model 541D-01's and five Model 541F-08's) were subjected to gas decontamination in one group. The tubes were placed in a sealed chamber which was maintained at a temperature of 110 ± 9 °F in an atmosphere of 12% ethylene oxide and 88% freon 12 at a concentration of slightly greater than 450 mg/liter for a period of 32 hours.

The relative humidity was maintained at approximately 50% by means of maintaining the proper temperature differential between the test chamber and a water vessel. At the end of the 32 hour test period the chamber was purged with dry nitrogen.

The tubes were inspected visually and given complete electrical tests following the gas decontamination.

6.2 Results for Photomultipliers with Visible Response

The visual inspection of the Model 541D-01 tubes revealed no observable physical changes or deterioration as a result of gas decontamination, and no significant changes in the average electrical characteristics were observed. Tube D873 showed a decrease in quantum efficiency of 12% at 4100 Å which is just outside the estimated in the quantum efficiency measurement.

6.3 Results for Tubes with Ultraviolet Response

A visual inspection of the Model 541F tubes revealed no observable changes in the physical appearance of the tubes and no degradation of potting materials, wire, or lithium fluoride window were observed.

The average quantum efficiency at 2537 Å decreased by 12%. This was somewhat unexpected considering the exceptional stability of the 541F tubes under the much more severe environ-

ment of dry heat sterilization. It is unlikely that this change in quantum efficiency is due to actual changes in the sensitivity of the photocathode but is most likely caused by a slight clouding of the lithium fluoride window due to absorption of water vapor during the gas sterilization.

Lithium fluoride crystals are normally stored in dry boxes and when exposed to high humidity conditions exhibit a decrease in transmission due to absorption of water vapor. In extreme cases the lithium fluoride takes on a clouded appearance. The windows of the 541F photomultipliers showed no evidence of fogging; however, the amount of fogging required to produce a decrease in transmission of 12% would be readily visible to the eye.

No significant changes in gain or dark current were observed.

7. ENVIRONMENTAL

Environmental tests were performed on four Model 541D-01 tubes having visible response and five Model 541F tubes having ultraviolet response. Each of the tubes was tested under conditions of static acceleration, vibration, shock, and thermal vacuum. The environmental tests with the exception of the 1000 g shock, were performed by the Reliability and Quality Assurance Department of EMR at Princeton. A report on these tests is included as Attachment C.

The 1000 g shock test was performed at the Environmental Dynamics Division of the Turbo Machine Company, Inc., at Monrovia, California.

Since most of the environmental tests were done outside of the laboratory, a small portable test set was constructed and used to check for operation or non-operation of the tubes following each test. In addition to the operation check, the tubes were given a visual inspection and a rattle check.

7.1 Static Acceleration

Each tube was subjected to a static acceleration of ± 190 g for 20 minutes along each of three orthogonal axes which are defined in Figure 1 of Appendix C. The sequence of testing was in the +z, -z, +y, -y, +x and -x directions.

During the course of the static acceleration after six minutes at 190 g in the + x direction, tube 541F-D817 slipped from its initial mounting position in the test fixture and the front end of the tube struck the accelerator wall. On the 541F tube the stainless steel shell extends beyond the face of the tube so the only damage was a flattening of the front end of the stainless steel shell.

Following static acceleration tests, all of the 541F tubes showed some denting and out-of-round distortion of the stainless

steel shells as a result of applied acceleration and clamping forces. The 541D tubes showed no such mechanical damage.

All tubes passed the electrical operational check and rattle check following static acceleration. Tube D-817 was given a complete electrical test following the mechanical damage when it slipped from the test fixture and found to have suffered no degradation in electrical characteristics.

7.2 Vibration

The following tests were performed along each axis of each of the tubes:

A. A sinusoidal vibration swept at one half-octave per minute

(a) ± 0.5 inch constant displacement, 5-17 cps
(b) 5 g rms, 17-50 cps
(c) 15 g rms, 50-100 cps
(d) 35 g rms, 100-2000 cps

B. Wide band-noise, 25 g rms, 9 minutes duration, 15-2000 cps.

There was no apparent mechanical damage to the photomultipliers as a result of these tests. All tubes passed the visual inspection, rattle check, and operation test.

7.3 Shock

7.3.1 Tests at EMR

Each of the photomultipliers was subjected to the following shock tests, with each test performed five times in each direction along each of the three axes:

A. ± 150 g terminal peak sawtooth, 5.0 millisecond rise time

B. ± 200 g terminal peak sawtooth,
0.5 millisecond rise time

Eight of the nine photomultipliers tested passed the visual inspection and operational check.

Tube 541D-D839 underwent the 150 g shock test with no apparent mechanical or operational defects. On the 200 g shock test the tube underwent five shocks in each of the following directions, +x, -x, +y. Following the fifth shock in the +y direction the focusing electrode was tilted toward the -x direction. At this point the tube was removed for complete electrical tests and found to have a reduced gain and QE as a result of the reduced collection efficiency.

The tube was then returned to the shock test machine, and the shocks in the remaining directions were finished. During the remaining shocks in the -y and +z direction no change was observed; however, following the first shock in the -z direction, the direction of tilt of the focusing electrode was reduced, and the focusing electrode was pointed more toward the center or normal position. During the remaining four shocks in the -z direction the direction of tilt rotated by 90° from the -x direction to the +y direction. At the completion of the shock tests, the angle of tilt had increased to the point that only several thousandths of an inch separation between the edge of the focusing electrode and the aluminum coating in the head of the tube.

All of the tubes were given complete electrical tests following the 200 g shock test.

Excluding the results for the tube which failed, the remaining tubes with visible response showed an average net decrease in quantum efficiency of 9% and an average net

decrease in gain of 30% as a result of the series of environmental tests. No significant degradation in resolution of the Cs^{137} gamma ray was observed. The maximum net change in resolution was only 0.2% which is within the error of measurement.

The tubes with ultraviolet response showed no significant changes in the average quantum efficiency, gain, or dark current as a result of the environmental tests through the 200 g shock test.

7.3.2 Tests at Environmental Dynamics

The 1000 g shock tests were performed at the Environmental Dynamics Division of the Turbo Machine Company in Monrovia, California. These could not be done at Princeton because of equipment limitations.

The ED-50 pre-accelerated shock machine was used to produce a sawtooth shock pulse having a peak acceleration of 1000 g and a rise time of three milliseconds. The test fixtures were designed and fabricated at EMR.

All tubes with the exception of 541D-D839 which failed on the 200 g test were given five shocks each in each of the +x, -x, +z, and -z directions. The tubes were not shocked in the y directions because of the symmetry of the tube.

An electrical check for operation was made after the first and fifth shocks in each direction. The operational check, visual inspection, and rattle check showed no electrical or mechanical failure following the 1000 g shock tests for each of the tubes with the exception of D839 which was damaged during the 200 g tests.

Tube 541D-D839 was subjected to the 1000 g shock tests. It was still operational following the 200 g tests

although the focusing electrode had been mechanically displaced. Operational checks were made after each shock to determine the point at which the focusing electrode-first dynode assembly would detach completely and the tube would be rendered non-operational.

Following shocks in the +x and -x directions the focusing electrode had changed position but was still attached, and the tube remained operational.

The focusing electrode separated during the first drop in the +z direction. The focusing electrode with the first dynode and field shaping screen separated as a single unit. The focusing electrode was flattened slightly on the edge that struck the faceplate, and a partial crack occurred in the faceplate seal, but the envelope remained under vacuum. Tests were discontinued at this point. The tube was non-operational following the separation.

The damaged tube was subsequently opened and inspected under the microscope. All spot welds holding the focusing electrode-first dynode assembly into the second kovar ring were faulty. The welds broke loose with no tearing of material which would be seen as a result of material failure around good welds. The focusing electrode assembly is mechanically the weakest point in the tube structure because of the cantilever mounting.

Complete electrical tests were made at EMR on the eight remaining tubes. The tubes with ultraviolet response showed no significant changes in quantum efficiency, gain, or dark current as a result of the 1000 g shock tests.

The tubes with visible response showed a recovery in quantum efficiency to the same average value observed prior to environmental testing. The small drop in average QE following the 200 g shock test was either due to error in measurement or was of a transient nature.

The average gain of the visible response tubes underwent a drop of 49%. The gain recovered later following the thermal vacuum test indicating that the drop in gain was not permanent.

Within the error of measurement the average resolution of the Cs^{137} gamma ray was unchanged as a result of the 1000 g shock tests.

7.4 Thermal Vacuum

The eight remaining photomultipliers (three Model 541Ds and five Model 541Fs) were subjected to two thermal vacuum tests. In the first test the tubes were subjected to a temperature of +75°C under vacuum for twelve days. The second test was carried out at a temperature of -10°C under vacuum for a period of four days.

The eight tubes were tested in two groups of four tubes each. Each group of four tubes was sealed into a glass envelope, evacuated on the tube processing station, and sealed off under vacuum. The sealed-off units were then cycled in a temperature chamber.

Following the thermal vacuum test at + 75°C the envelope was opened up and complete electrical tests were made on all tubes. After testing the tubes were resealed into the glass envelopes, evacuated, and subjected to the -10°C vacuum environment.

For the photomultipliers with visible response, no significant change in quantum efficiency was observed as a result of the + 75°C thermal vacuum environment. The gain increased by 49% following the first thermal vacuum test at + 75°C returning to the same value observed prior to the shock test. This average change in gain of 49% corresponded to a change of 4% in voltage required for a gain of 10^6.

Following the thermal vacuum test at -10°C, the tubes with visible response show an average increase in quantum efficiency of 10%. No significant change in gain was observed following the -10°C thermal vacuum environment.

The most significant electrical parameter of the tubes with visible response is the resolution of the Cs^{137} gamma ray. The average resolution showed no change due to the + 75°C thermal vacuum environment, and following the -10°C thermal vacuum environment an improvement in resolution of approximately .3% was observed.

No significant changes in quantum efficiency were observed for the tubes with ultraviolet response as a result of the + 75°C thermal vacuum environment or the -10°C thermal vacuum environment. An average net decrease in gain of 15% was observed following the + 75°C thermal vacuum test, and no significant change in gain occurred as a result of the -10°C thermal vacuum environment.

8. LIFE TESTS

As part of the reliability study on sterilizable photomultipliers the eight photomultipliers were subjected to operational life tests for a period of 1000 hours.

8.1 Procedure

The tubes were operated in a life test rack having a common high voltage power supply. A voltage of 2200 volts was used. The tubes with visible response were energized by means of tungsten lamps, and the tubes with ultraviolet response were energized by means of an ultraviolet germicidal lamp. The anode current of each tube was monitored separately during the course of the life tests. The light input to each tube was adjusted to provide an anode current of approximately 1×10^{-7} amperes.

All tubes were removed from the life test rack and given complete electrical tests at intervals of 50, 100, 500, 750 and 1000 hours.

8.2 Results for Tubes with Visible Response

The behavoir of the electrical characteristics during life tests are best illustrated by a plot of the average characteristics as a function of time on life tests. Figure 16 shows the variation in QE at 4100 Å during life tests. The average quantum efficiency undergoes an increase of approximately 15% within the first 100 hours of operation and remains relatively constant throughout the remainder of the 1000 hours. Figure 17 shows the variation in gain with time on life tests. The gain is found to decrease rapidly within the first 100 hours and then remains relatively constant throughout the remainder of the 1000 hours. The decrease in gain coincides with the increase in quantum efficiency indicating that possibly a migration of alkali materials from the dynode produced the decrease in gain

TABLE C

AVERAGE ELECTRICAL CHARACTERISTICS OF THE TUBE WITH VISIBLE RESPONSE DURING LIFE TESTS

Operating time (hours)	QE (%) at 4100 Å	Gain at 2600 V	Voltage for 10^6 gain	Resolution (%) of Cs^{137} gamma
0	8.5	9.8×10^5	2630	11.4
50	9.0	5.8×10^5	2840	11.4
100	9.6	5.2×10^5	2890	11.3
500	9.9	4.3×10^5	2990	11.6
750	9.8	3.9×10^5	3040	11.3
1000	9.2	3.9×10^5	3060	11.5

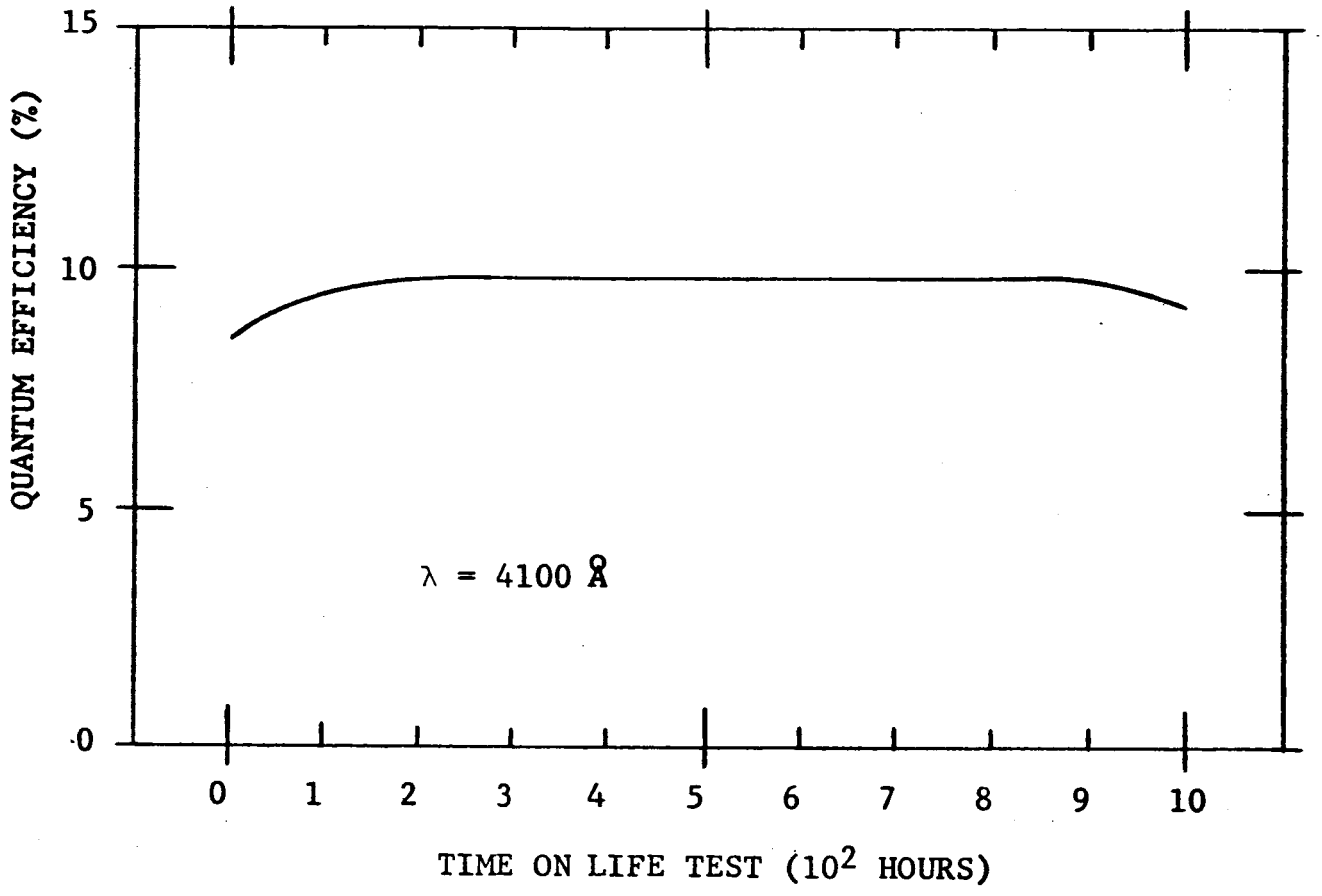


Figure 16. Variation in the average quantum efficiency for the Model 541D-01 photomultipliers on life test.

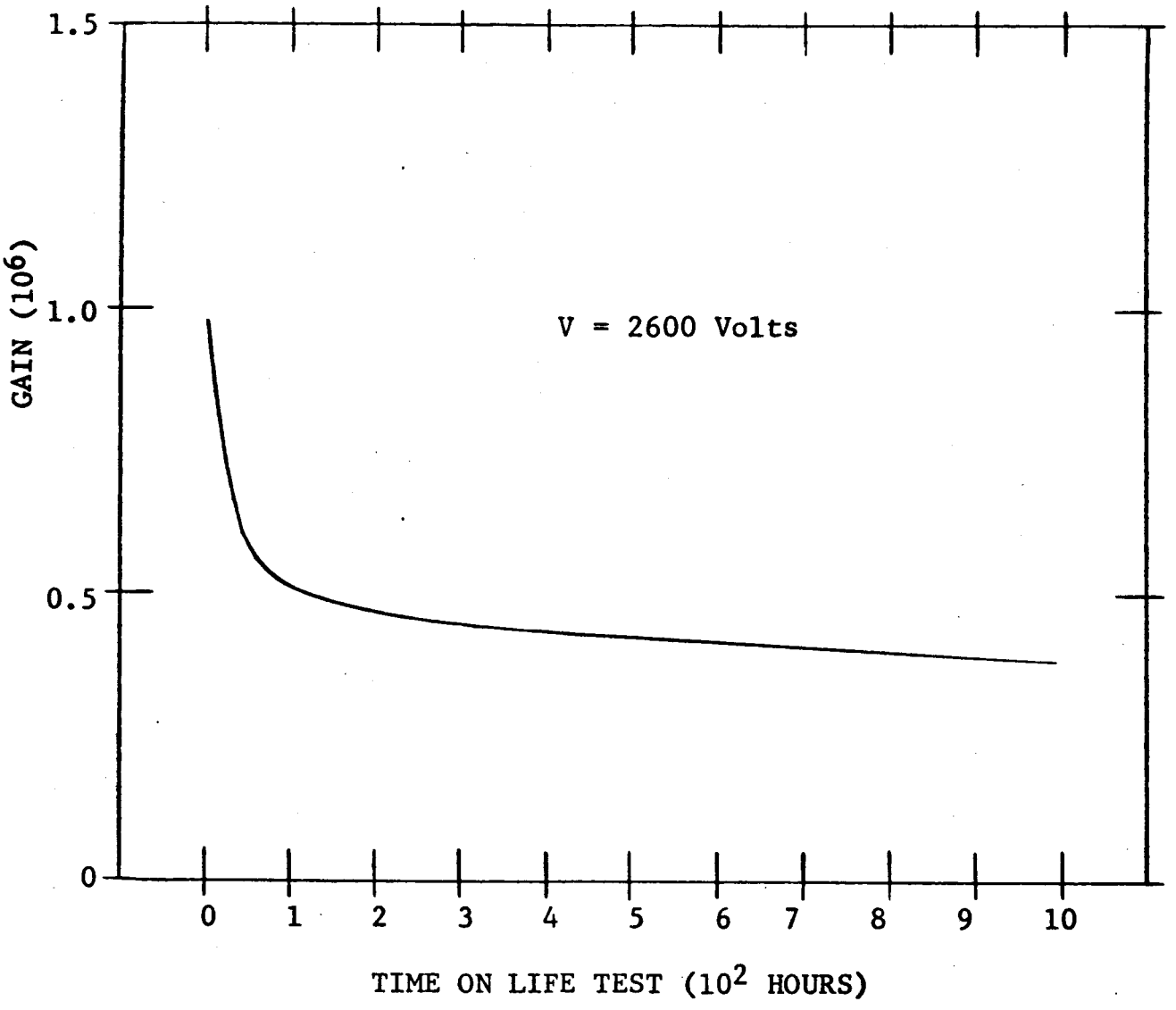


Figure 17. Variation in the average gain of the Model 541D-01 photomultipliers on life test.

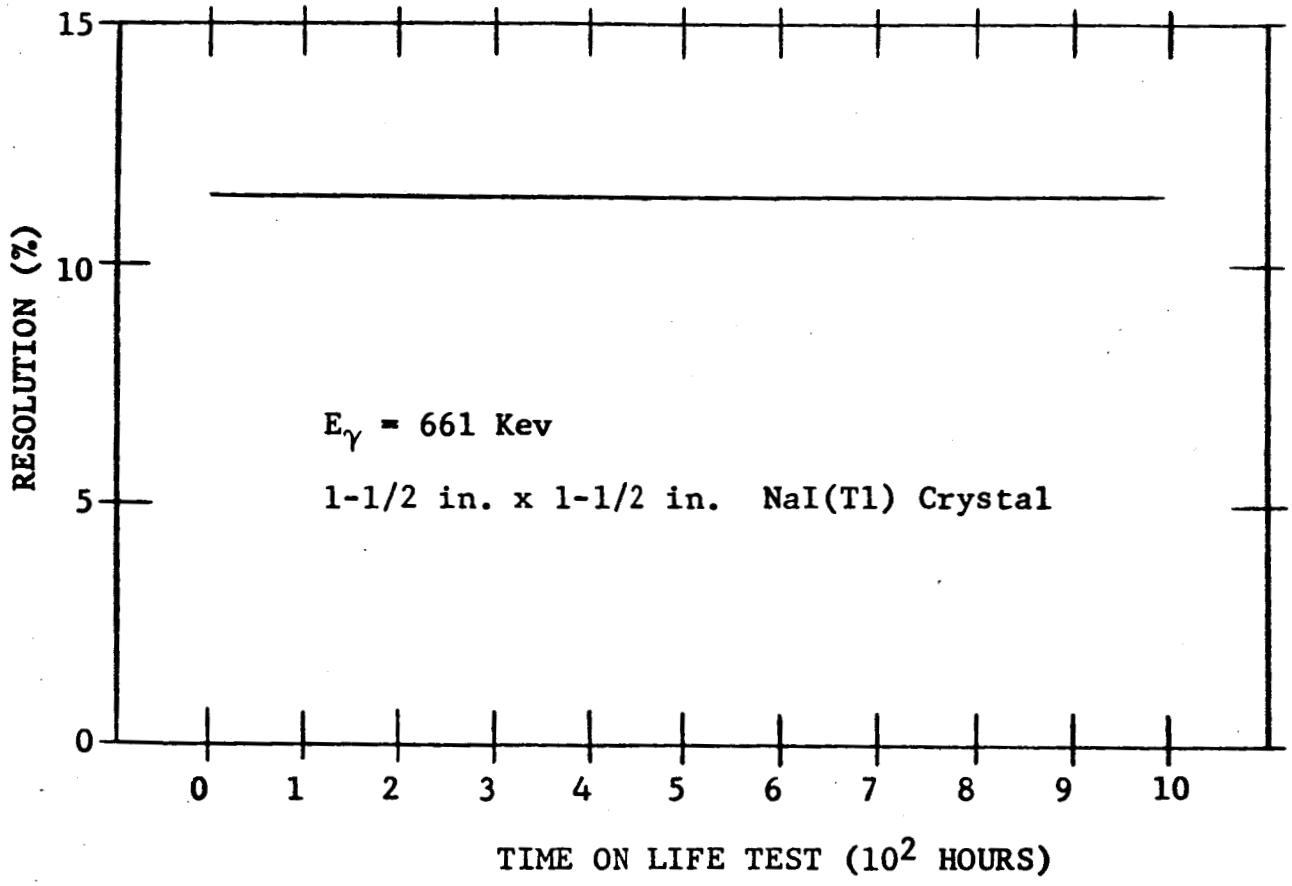


Figure 18. Average resolution during life test for the Model 541D-01 photomultipliers.

and enhanced the quantum efficiency. This process apparently reaches an equilibrium after approximately 100 hours.

The energy resolution, which again is the most significant parameter for tubes to be used for scintillation counting, shows no significant changes throughout the 1000 hours of life tests.

8.3 Results for Tubes with Ultraviolet Response

The variation in the average quantum efficiency at 2537 Å for the tubes with ultraviolet response is shown in Figure 19. It is seen that the quantum efficiency undergoes a gradual increase with time on life tests. The net percent increase in quantum efficiency after 1000 hours is approximately 15%.

The average gain undergoes a rapid decrease during approximately the first 100 to 150 hours on life tests, and this is followed by a gradual decrease throughout the remainder of the 1000 hours. The variation in average gain at 2600 volts for the tubes on life test is given in Figure 20.

8.4 Reliability

The eight photomultipliers were operated on life tests for a period of 1000 hours. An analysis of the reliability data was based on the Quality Control and Reliability Handbook H108. Considering the total of eight tubes as comprising one sample batch the calculations based on tables of sequential testing show that the sample has a 90% probability of mean-life-to-failure in excess of 3140 hours. It should be noted that this figure is solely contingent on the number units in the sample batch and the period of testing in that no failures occurred during life test. Because of the limited number of tubes no segregation by tube type has been considered for the reliability calculations.

TABLE D

AVERAGE ELECTRICAL CHARACTERISTICS OF THE TUBES WITH ULTRAVIOLET RESPONSE DURING LIFE TESTS

Operating Time (hours)	QE (%) at 2537 Å	Gain at 2600 V	Voltage for 10^6 gain
0	8.4	1.9×10^6	2540
50	8.2	1.6×10^6	2590
100	8.1	1.4×10^6	2640
500	8.9	1.2×10^6	2740
750	9.6	1.1×10^6	2780
1000	9.7	1.0×10^6	2830

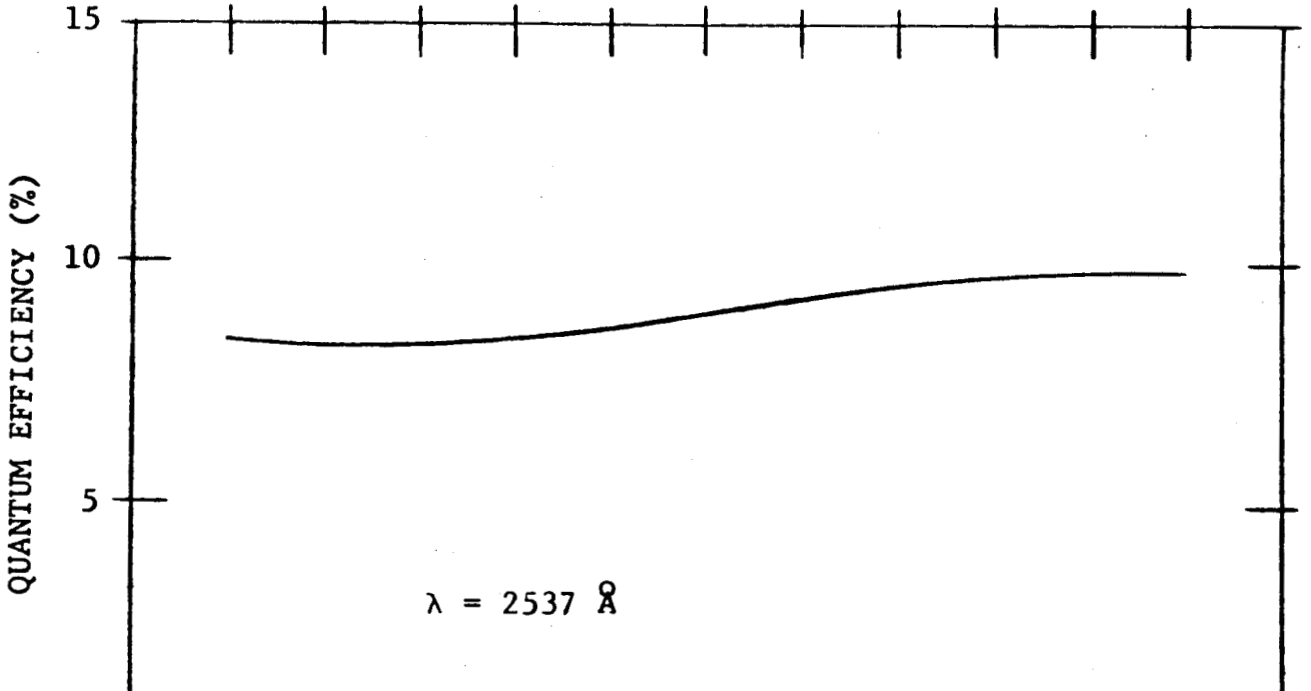


Figure 19. The average quantum efficiency of Model 541F-08 photomultipliers during life tests.

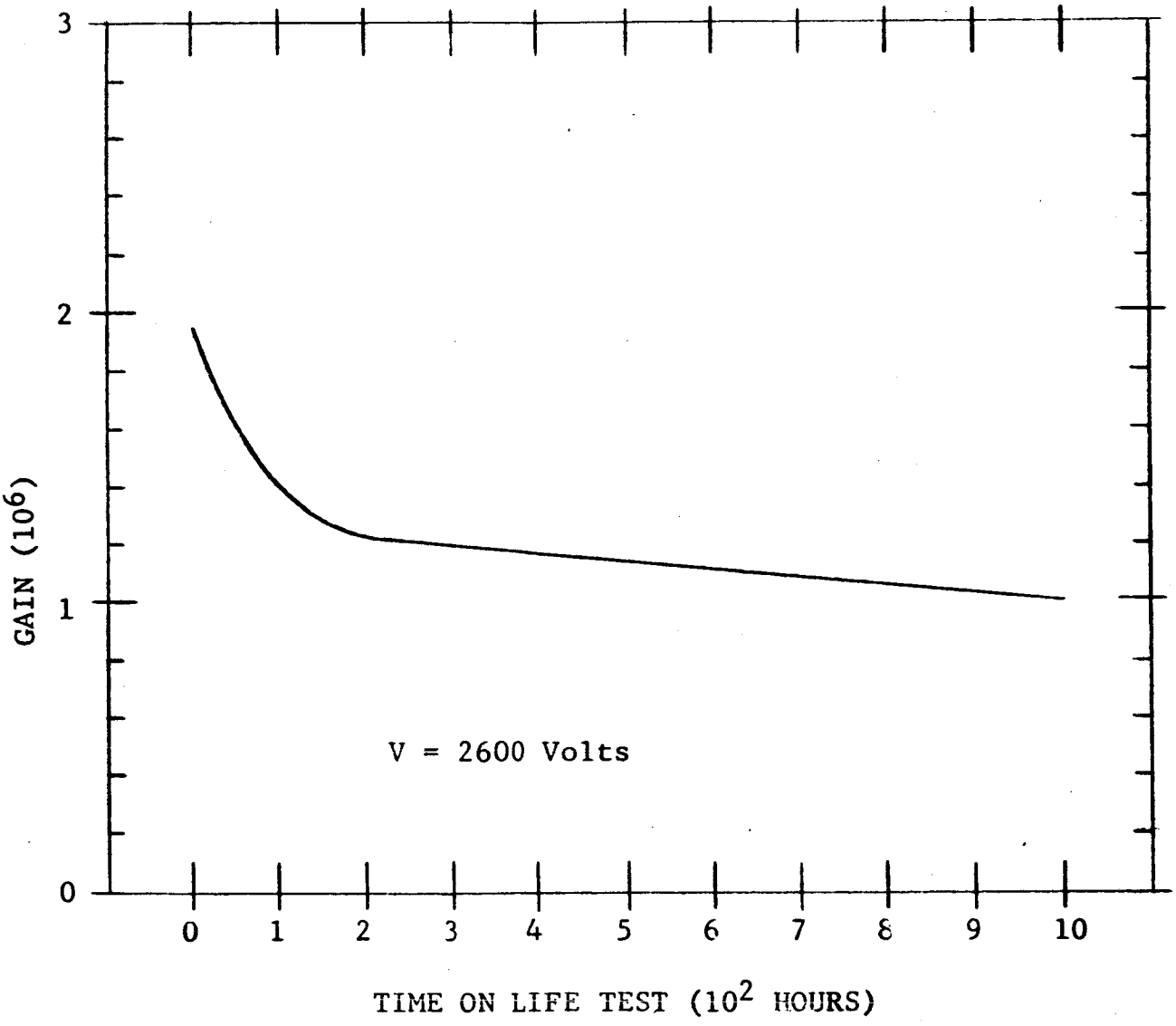


Figure 20. The average gain of Model 541F-08 photomultipliers on life test.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

9.1.1 Photomultipliers with Visible Response

The EMR Model 541D-01 photomultiplier processed especially for sterilization survives the severe environments of a 145°C bake for a period of 36 hours with only moderate changes in spectral response, gain, dark current and resolution of the Cs^{137} gamma ray.

A substantial improvement in quantum efficiency and high temperature stability has been attained by using new cathode processing techniques.

The tubes are capable of undergoing gas decontamination with no significant changes in electrical or physical characteristics and surviving severe environmental conditions of static acceleration, vibration, shock and thermal vacuum.

When operating at anode currents of approximately 1×10^{-7} Amperes, the tubes on life test undergo slight changes in quantum efficiency and substantial changes in gain which appear to be characteristic for the tubes, but stabilize after approximately 100 hours when, presumably, equilibrium conditions within the tube are reached. The single most important parameter for tubes used in scintillation counting applications, energy resolution, remains constant within the experimental error throughout the duration of the life test.

9.1.2 Photomultipliers with Ultraviolet Response

The EMR Model 541F-08 photomultipliers modified for the sterilization program have remarkably good stability during dry heat sterilization. The average

quantum efficiency showed no change following two cycles and less than 10% change following the third cycle. Changes in gain were insignificant.

These extremely rugged tubes are capable of withstanding the environmental tests with no physical damage or degradation of electrical characteristics.

Life test performance data shows that these tubes undergo slight increases in quantum efficiency over the duration of 1000 hours. The average gain decreases substantially but stabilizes after approximately 100 hours with only a slight decrease over the remainder of the life tests.

9.2 Recommendations

9.2.1 Improvements in Tubes with Visible Response

The average quantum efficiency of the 541D-01 tube was increased to approximately three times the typical quantum efficiency for the standard product by using the layer cathode processing technique. Because the gain in cathode sensitivity was accompanied by a problem of high resistivity in the cathode following sterilization, a modification in the processing was necessary which reduced the sensitivity from its peak value.

A more desirable solution to the problem of high resistivity would be to process the cathode on a suitable conductive substrate having high transmission for the spectral range of interest. The attempt along this line using a tin oxide substrate was unsuccessful because of its reactivity with the photocathode materials. Further experimentation on the use of conductive substrates using more chemically inert materials would result in the

maximum cathode sensitivity without the high resistivity effects following sterilization.

Also, on the basis of the sterilization and life test data, an improvement in stability can be attained by including in the preparation of each tube one dry heat sterilization cycle and at least several hundred hours operating time. The improvement in stability of electrical characteristics would compensate for the reduction in initial quantum efficiency and gain.

9.2.2 Improvements in Tubes with Ultraviolet Response

Although the 541F-08 photomultipliers are well adapted to sterilization, further improvements could be obtained by maintaining very close control over the cathode processing and subjecting each tube to several hundred hours operation as part of the tube's initial preparation.

In a research program running concurrently with the sterilization program, a new, more solar-blind ultraviolet cathode, rubidium telluride, has been developed. The new cathode appears to have better stability and lower dark current than the cesium telluride. It is extremely promising as a photomultiplier with ultraviolet response suitable for sterilization. Of particular interest is a side-window version of Rb_2Te with peak quantum efficiencies in the ultraviolet of nearly 20%.

E. J. Dumas
Project Engineer

M. Rome, Director
Research & Development

EJD/pas

APPENDIX A

SPECTRAL RESPONSE - MODEL 541D - SERIAL NO. 833

CRS (μA/W)

Test	3600 Å	3800 Å	4000 Å	4100 Å	4200 Å	4400 Å	4800 Å	5600 Å	6000 Å
Initial	--	45.8	46.0	45.1	43.4	38.9	29.1	15.2	--
Dry Heat #1	--	34.2	32.8	31.5	28.4	26.1	18.5	7.3	--
Dry Heat #2	--	27.9	25.6	24.3	22.5	18.9	11.8	4.6	--
Dry Heat #3	32.0	30.4	27.1	25.7	24.1	20.3	12.8	5.0	3.3
Gas Dec.	31.5	29.3	26.1	25.2	22.9	19.3	12.0	4.6	3.0
200 g	28.8	26.1	22.9	21.2	19.8	16.2	9.7	3.4	2.1
1000 g	28.8	30.4	27.4	26.1	23.8	19.9	12.1	4.6	2.7
+75 Therm.Vac.	32.4	31.5	27.9	26.1	25.2	21.1	12.9	4.9	3.1
-10 Therm.Vac.	34.2	32.4	27.9	27.0	23.4	21.2	12.6	4.5	2.9
50 hr. Life	45.0	37.8	31.9	28.8	25.6	21.6	13.0	4.7	3.0
100 hr. Life	40.5	38.2	35.1	31.9	29.2	25.2	15.7	5.8	3.6
500 hr. Life	35.1	36.0	32.4	30.6	28.8	24.3	14.8	5.4	3.3
750 hr. Life	33.7	34.2	31.5	29.7	27.9	23.4	14.9	5.3	3.3
1000 hr. Life	36.9	36.0	33.3	31.5	28.8	24.3	15.8	5.8	3.7

SPECTRAL RESPONSE - MODEL 541D - SERIAL NO. D873

CRS (μA/W)

Test	3600 Å	3800 Å	4000 Å	4100 Å	4200 Å	4400 Å	4800 Å	5600 Å	6000 Å
Initial	--	44.8	42.3	39.8	37.1	30.1	18.8	6.3	--
Dry Heat #1	37.3	40.5	39.1	36.9	34.9	29.7	18.4	4.0	0.9
Dry Heat #2	29.5	32.4	31.5	30.1	29.1	24.8	14.6	2.9	0.7
Dry Heat #3	29.2	32.8	31.5	29.7	27.9	24.7	14.8	3.2	0.9
Gas Dec.	27.0	28.8	27.4	26.1	24.7	20.7	12.0	1.8	0.3
200 g	25.2	28.3	27.0	24.7	23.8	19.9	11.4	1.9	0.3
1000 g	22.9	27.4	26.1	25.2	23.6	19.7	11.7	2.0	0.3
+75 Therm.Vac.	25.2	27.0	26.1	26.1	25.6	22.1	14.4	4.2	1.8
-10 Therm.Vac.	32.0	32.5	30.5	30.5	28.5	25.0	16.8	3.1	0.4
50 hr. Life	40.5	37.8	34.2	30.5	27.8	23.4	13.5	2.2	0.4
100 hr. Life	36.0	37.8	35.5	33.7	31.5	27.5	15.7	2.6	0.6
500 hr. Life	30.6	36.0	35.1	33.3	31.5	26.5	15.7	2.6	0.5
750 hr. Life	31.5	36.9	36.0	35.1	33.3	27.9	17.0	2.8	0.6
1000 hr. Life	30.6	32.8	33.3	31.5	29.7	23.8	14.8	2.4	0.4

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SPECTRAL RESPONSE - MODEL 541D - SERIAL NO. D877

CRS (μA/W)

Test	3600 Å	3800 Å	4000 Å	4100 Å	4200 Å	4400 Å	4800 Å	5600 Å	6000 Å
Initial	--	48.6	47.4	45.0	42.3	36.0	24.0	5.7	--
Dry Heat #1	28.8	30.8	29.9	28.4	26.7	23.6	14.8	4.3	1.7
Dry Heat #2	26.3	27.9	27.0	26.4	24.7	20.9	13.1	3.7	1.6
Dry Heat #3	25.2	26.4	25.4	24.3	22.5	19.3	12.0	3.3	1.4
Gas Dec.	25.2	26.1	25.7	24.3	22.7	19.6	12.5	3.7	1.6
200 g	25.0	25.5	23.8	22.8	21.2	18.0	11.3	3.4	1.4
1000 g	24.3	27.4	27.0	25.2	23.8	19.8	13.3	3.8	1.7
+75 Therm.Vac.	22.5	28.8	27.0	26.5	24.7	20.7	12.1	3.5	1.5
-10 Therm.Vac.	32.4	29.7	27.9	27.0	25.2	22.0	13.9	4.0	1.7
50 hr. Life	36.8	35.0	31.9	29.7	27.9	22.5	13.9	3.8	1.6
100 hr. Life	32.4	32.4	30.6	29.7	27.9	23.4	15.3	4.3	1.8
500 hr. Life	28.3	31.5	32.4	31.5	30.1	26.1	16.4	5.0	2.2
750 hr. Life	29.7	34.2	34.2	32.4	31.5	26.1	17.1	4.8	2.1
1000 hr. Life	27.9	30.6	30.6	28.8	27.4	24.5	15.7	4.5	2.0

GAIN - MODEL 541D - SERIAL NO. D833

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	6.8×10^4	3.5×10^5	1.3×10^6	3.7×10^6	6.1×10^6
Dry Heat #1	7.8×10^4	4.0×10^5	1.5×10^6	4.7×10^6	8.0×10^6
Dry Heat #2	8.8×10^4	4.7×10^5	1.8×10^6	5.4×10^6	9.2×10^6
Dry Heat #3	8.8×10^4	4.4×10^5	1.6×10^6	5.0×10^6	8.5×10^6
Gas Dec.	8.2×10^4	4.1×10^5	1.5×10^6	4.4×10^6	7.4×10^6
200 g	7.0×10^4	3.4×10^5	1.2×10^6	3.5×10^6	5.6×10^6
1000 g	5.2×10^4	2.5×10^5	9.4×10^5	2.8×10^6	4.6×10^6
+75 Therm.Vac.	7.8×10^4	3.9×10^5	1.5×10^6	4.2×10^6	7.0×10^6
-10 Therm.Vac.	6.5×10^4	3.4×10^5	1.3×10^6	3.6×10^6	5.5×10^6
50 hr. Life	4.7×10^4	2.2×10^5	7.8×10^5	1.7×10^6	2.7×10^6
100 hr. Life	4.1×10^4	2.0×10^5	7.1×10^5	1.9×10^6	2.9×10^6
500 hr. Life	3.4×10^4	1.7×10^5	5.9×10^5	1.6×10^6	2.5×10^6
750 hr. Life	3.3×10^4	1.5×10^5	5.6×10^5	1.5×10^6	2.5×10^6
1000 hr. Life	3.1×10^4	1.4×10^5	5.0×10^5	1.4×10^6	2.2×10^6

GAIN - MODEL 541D - SERIAL NO. D873

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	5.5×10^4	2.7×10^5	9.9×10^5	2.7×10^6	4.3×10^6
Dry Heat #1	5.5×10^4	2.8×10^5	1.0×10^6	3.0×10^6	4.8×10^6
Dry Heat #2	5.3×10^4	2.7×10^5	9.9×10^5	2.9×10^6	4.8×10^6
Dry Heat #3	5.5×10^4	2.7×10^5	1.0×10^6	2.9×10^6	4.8×10^6
Gas Dec.	5.3×10^4	2.6×10^5	9.8×10^5	2.9×10^6	4.6×10^6
200 g	4.3×10^4	2.0×10^5	7.1×10^5	2.0×10^6	3.3×10^6
1000 g	3.9×10^4	1.9×10^5	6.8×10^5	2.0×10^6	3.2×10^6
+75 Therm.Vac.	4.4×10^4	2.3×10^5	8.9×10^5	2.7×10^6	4.3×10^6
-10 Therm.Vac.	4.0×10^4	1.8×10^5	6.8×10^5	1.9×10^6	3.0×10^6
50 hr. Life	2.2×10^4	1.0×10^5	3.4×10^5	9.4×10^5	1.3×10^6
100 hr. Life	1.8×10^4	8.5×10^4	2.9×10^5	7.6×10^5	1.2×10^6
500 hr. Life	1.1×10^4	4.9×10^4	1.6×10^5	4.4×10^5	6.7×10^5
750 hr. Life	1.0×10^4	4.4×10^4	1.5×10^5	3.9×10^5	6.0×10^5
1000 hr. Life	8.7×10^3	3.8×10^4	1.3×10^5	3.4×10^5	5.2×10^5

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GAIN - MODEL 541D - SERIAL NO. D877

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	4.9×10^4	2.6×10^5	9.3×10^5	2.8×10^6	4.4×10^6
Dry Heat #1	5.7×10^4	3.0×10^5	1.1×10^6	3.3×10^6	5.5×10^6
Dry Heat #2	5.9×10^4	3.1×10^5	1.1×10^6	3.5×10^6	5.5×10^6
Dry Heat #3	5.0×10^4	2.6×10^5	1.0×10^6	2.9×10^6	4.7×10^6
Gas Dec.	5.6×10^4	2.9×10^5	1.1×10^6	3.5×10^6	5.6×10^6
200 g	3.3×10^4	1.6×10^5	5.8×10^5	1.7×10^6	2.8×10^6
1000 g	3.2×10^4	1.5×10^5	5.8×10^5	1.7×10^6	2.7×10^6
-175 Therm.Vac.	4.7×10^4	2.3×10^5	8.9×10^5	2.7×10^6	4.3×10^6
-10 Therm.Vac.	5.0×10^4	2.5×10^5	9.6×10^5	2.8×10^6	4.2×10^6
50 hr. Life	3.6×10^4	1.7×10^5	6.1×10^5	1.8×10^6	2.7×10^6
100 hr. Life	3.3×10^4	1.6×10^5	5.7×10^5	1.6×10^6	2.6×10^6
500 hr. Life	3.1×10^4	1.5×10^5	5.5×10^5	1.6×10^6	2.6×10^6
750 hr. Life	2.8×10^4	1.3×10^5	4.7×10^5	1.3×10^6	2.1×10^6
1000 hr. Life	2.9×10^4	1.4×10^5	5.4×10^5	1.6×10^6	2.6×10^6

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APPENDIX B

QUANTUM EFFICIENCY (%) - MODEL 541F - SERIAL NO. D799

Test	1236	1470	1600	1849	2537	3125	3650
Initial	--	--	--	--	16	--	--
Dry Heat #1	--	--	--	--	14	0.8	0.03
Dry Heat #2	8.4	4.6	6.3	18	13	1.1	0.04
Dry Heat #3	9.5	5.0	6.2	14	12	0.9	0.04
Gas Dec.	6.7	5.8	5.2	15	9.9	0.8	0.02
200 g	11	4.7	5.2	14	9.9	0.8	0.03
1000 g	13	2.0	6.7	15	9.5	0.7	0.02
+75 Therm.Vac.	6.5	5.9	8.6	14	10	0.7	0.02
-10 Therm.Vac	9.1	6.8	6.3	16	9.5	0.7	0.02
50 hr. Life	--	--	--	--	9.3	0.7	0.02
100 hr. Life	--	--	--	--	9.3	0.7	0.02
500 hr. Life	--	--	--	--	10	0.8	0.03
750 hr. Life	--	--	--	--	11	0.7	0.03
1000 hr. Life	10	9.5	10	17	11	0.7	0.02

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QUANTUM EFFICIENCY (%) - MODEL 541F - SERIAL NO. D802

Test	1236	1470	1600	1849	2537	3125	3650
Initial	--	--	--	--	14	2.2	0.04
Dry Heat #1	8.4	6.4	6.3	16	13	2.2	0.04
Dry Heat #2	13	7.5	7.5	12	14	2.2	0.03
Dry Heat #3	12	8.5	7.4	17	13	2.3	0.03
Gas Dec.	7.2	7.7	5.2	13	12	1.7	0.02
200 g	8.0	6.2	5.4	8.8	11	1.9	0.02
1000 g	8.7	4.2	5.0	9.6	10	2.0	0.02
+75 Therm.Vac.	4.6	6.2	8.6	13	11	1.9	0.02
-10 Therm.Vac.	6.1	5.5	6.4	14	10	1.7	0.02
50 hr. Life	--	--	--	--	9.9	1.8	0.02
100 hr. Life	--	--	--	--	10	1.9	0.02
500 hr. Life	--	--	--	--	11	1.7	0.02
750 hr. Life	--	--	--	--	12	1.8	0.03
1000 hr. Life	7.0	11	10	15	12	1.9	0.03

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QUANTUM EFFICIENCY (%) - MODEL 541F - SERIAL NO. D805

Test	1236	1470	1600	1849	2537	3125	3650
Initial	--	--	--	--	8.0	0.7	0.01
Dry Heat #1	5.0	3.6	4.5	15	9.0	0.9	0.01
Dry Heat #2	7.3	3.5	3.4	13	8.8	0.9	0.01
Dry Heat #3	8.6	4.6	3.9	16	8.2	0.7	0.01
Gas Dec.	5.1	4.7	4.5	14	7.2	0.6	0.01
200 g	7.9	2.5	2.3	14	7.0	0.7	0.01
1000 g	7.1	3.0	3.8	13	7.0	0.7	0.01
+75 Therm.Vac.	4.7	3.4	5.2	11	7.3	0.7	0.01
-10 Therm.Vac.	4.7	4.0	4.5	14	6.9	0.7	0.01
50 hr. Life	--	--	--	--	6.8	0.7	0.01
100 hr. Life	--	--	--	--	6.9	0.6	0.01
500 hr. Life	--	--	--	--	7.7	0.7	0.01
750 hr. Life	--	--	--	--	8.1	0.7	0.01
1000 hr. Life	7.0	7.2	6.5	17	8.3	0.7	0.01

QUANTUM EFFICIENCY (%) - MODEL 541F - SERIAL NO. D814

Test	1236	1470	1600	1849	2537	3125	3650
Initial	--	--	--	--	5.7	0.2	--
Dry Heat #1	6.3	2.3	4.8	18	6.2	0.2	0.01
Dry Heat #2	8.2	3.2	4.5	15	6.3	0.2	0.005
Dry Heat #3	8.7	3.5	4.8	18	5.9	0.2	0.004
Gas Dec.	6.2	3.5	3.2	13	5.3	0.2	0.003
200 g	7.0	2.8	3.9	16	5.6	0.2	--
1000 g	9.2	4.4	4.7	15	5.3	0.2	0.01
+75 Therm.Vac.	5.9	3.4	5.0	15	5.7	0.2	0.01
-10 Therm.Vac.	7.6	3.7	5.0	16	5.5	0.2	0.01
50 hr. Life	--	--	--	--	5.4	0.2	0.00
100 hr. Life	--	--	--	--	5.4	0.2	0.00
500 hr. Life	--	--	--	--	6.1	0.2	0.00
750 hr. Life	--	--	--	--	6.5	0.2	0.00
1000 hr. Life	8.0	7.5	7.7	16	6.2	0.3	0.00

QUANTUM EFFICIENCY (%) - MODEL 541F - SERIAL NO. D817

Test	1236	1470	1600	1849	2537	3125	3650
Initial	--	--	--	--	12	0.4	0.01
Dry Heat #1	9.6	4.8	6.1	18	12	0.7	0.01
Dry Heat #2	11	5.5	6.0	16	12	0.7	0.01
Dry Heat #3	11	5.5	5.9	20	11	0.7	0.02
Gas Dec.	7.6	5.0	6.4	16	9.8	0.7	0.01
200 g	8.5	4.4	4.5	15	9.1	0.6	0.01
1000 g	13	5.6	6.8	15	9.4	0.4	0.01
+75 Therm.Vac.	5.6	5.1	6.1	16	9.5	0.6	0.01
-10 Therm.Vac.	9.6	6.4	5.7	16	9.9	0.5	0.01
50 hr. Life	--	--	--	--	9.5	0.5	0.01
100 hr. Life	--	--	--	--	9.0	0.5	0.01
500 hr. Life	--	--	--	--	9.9	0.4	0.01
750 hr. Life	--	--	--	--	11	0.5	0.01
1000 hr. Life	9.3	9.0	7.8	17	11	0.5	0.01

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GAIN - MODEL 541F - SERIAL NO. D799

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	1.3×10^5	1.2×10^6	5.8×10^6	2.3×10^7	5.4×10^7
Dry Heat #1	1.3×10^5	9.6×10^5	4.7×10^6	2.0×10^7	3.0×10^7
Dry Heat #2	1.2×10^5	9.1×10^5	4.4×10^6	1.6×10^7	2.9×10^7
Dry Heat #3	1.2×10^5	8.6×10^5	4.4×10^6	1.7×10^7	3.1×10^7
Gas Dec.	1.3×10^5	1.0×10^6	5.1×10^6	1.9×10^7	3.4×10^7
200 g	1.3×10^5	1.0×10^6	4.9×10^6	1.9×10^7	3.6×10^7
1000 g	1.2×10^5	9.4×10^5	4.7×10^6	1.8×10^7	3.4×10^7
+75 Therm.Vac.	1.1×10^5	8.0×10^5	4.0×10^6	1.5×10^7	2.8×10^7
-10 Therm.Vac.	7.6×10^4	7.3×10^5	3.5×10^6	1.3×10^7	2.5×10^7
50 hr. Life	9.9×10^4	6.9×10^5	3.3×10^6	1.2×10^7	2.2×10^7
100 hr. Life	9.5×10^4	6.6×10^5	3.1×10^6	1.2×10^7	2.2×10^7
500 hr. Life	9.5×10^4	6.5×10^5	3.1×10^6	1.2×10^7	2.1×10^7
750 hr. Life	9.3×10^4	6.4×10^5	3.2×10^6	1.2×10^7	2.2×10^7
1000 hr. Life	8.9×10^4	6.1×10^5	3.0×10^6	1.2×10^7	2.3×10^7

GAIN - MODEL 541F - SERIAL NO. D802

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	2.4×10^4	1.6×10^5	8.2×10^5	2.9×10^6	5.4×10^6
Dry Heat #1	2.6×10^4	1.8×10^5	9.2×10^5	3.5×10^6	6.2×10^6
Dry Heat #2	2.6×10^4	1.7×10^5	8.4×10^5	3.2×10^6	5.7×10^6
Dry Heat #3	3.0×10^4	2.1×10^5	1.0×10^6	3.7×10^6	6.7×10^6
Gas Dec.	3.3×10^4	2.2×10^5	1.1×10^6	4.0×10^6	7.2×10^6
200 g	3.1×10^4	2.0×10^5	9.0×10^5	3.3×10^6	6.0×10^6
1000 g	2.8×10^4	1.8×10^5	8.8×10^5	3.3×10^6	6.0×10^6
+ 75 Therm.Vac.	2.4×10^4	1.6×10^5	7.8×10^5	2.9×10^6	5.2×10^6
-10 Therm.Vac.	2.6×10^4	1.7×10^5	8.5×10^5	3.0×10^6	5.4×10^6
50 hr. Life	2.4×10^4	1.4×10^5	6.6×10^5	2.4×10^6	4.2×10^6
100 hr. Life	1.8×10^4	1.1×10^5	4.9×10^5	1.8×10^6	3.1×10^6
500 hr. Life	1.1×10^4	6.8×10^4	3.1×10^5	1.1×10^6	1.9×10^6
750 hr. Life	1.0×10^4	6.1×10^4	2.7×10^5	9.6×10^5	1.6×10^6
1000 hr. Life	7.7×10^3	4.8×10^4	2.1×10^5	7.4×10^5	1.3×10^6

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GAIN - MODEL 541F - SERIAL NO. D805

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	1.8×10^4	1.2×10^5	5.5×10^5	2.0×10^6	3.5×10^6
Dry Heat #1	1.8×10^4	1.2×10^5	5.9×10^5	2.1×10^6	3.8×10^6
Dry Heat #2	1.8×10^4	1.2×10^5	5.6×10^5	2.0×10^6	3.6×10^6
Dry Heat #3	2.1×10^4	1.3×10^5	6.6×10^5	2.4×10^6	4.2×10^6
Gas Dec.	2.1×10^4	1.3×10^5	6.7×10^5	2.6×10^6	4.7×10^6
200 g	2.2×10^4	1.4×10^5	6.4×10^5	2.4×10^6	4.3×10^6
1000 g	2.0×10^4	1.3×10^5	6.3×10^5	2.4×10^6	4.3×10^6
+75 Therm.Vac.	1.9×10^4	1.2×10^5	5.6×10^5	2.1×10^6	3.6×10^6
-10 Therm.Vac.	2.0×10^4	1.2×10^5	5.9×10^5	2.1×10^6	3.7×10^6
50 hr. Life	1.5×10^4	9.5×10^4	4.2×10^5	1.5×10^6	2.5×10^6
100 hr. Life	1.3×10^4	8.2×10^4	3.6×10^5	1.3×10^6	2.2×10^6
500 hr. Life	8.4×10^3	5.1×10^4	2.3×10^5	7.8×10^5	1.3×10^6
750 hr. Life	7.7×10^3	4.8×10^4	2.1×10^5	7.2×10^5	1.2×10^6
1000 hr. Life	6.7×10^3	4.1×10^4	1.8×10^5	6.1×10^5	1.1×10^6

GAIN - MODEL 541F - SERIAL NO. D814

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	1.2×10^5	9.5×10^5	5.0×10^6	2.1×10^7	3.7×10^7
Dry Heat #1	1.2×10^5	9.6×10^5	5.0×10^6	2.1×10^7	3.9×10^7
Dry Heat #2	1.2×10^5	9.5×10^5	5.1×10^6	2.1×10^7	3.7×10^7
Dry Heat #3	1.4×10^5	1.1×10^6	5.9×10^6	2.4×10^7	4.6×10^7
Gas Dec.	1.5×10^5	1.1×10^6	6.2×10^6	2.6×10^7	5.0×10^7
200 g	1.2×10^5	9.3×10^5	4.9×10^6	2.0×10^7	3.8×10^7
1000 g	1.3×10^5	9.5×10^5	5.0×10^6	2.0×10^7	3.7×10^7
+75 Therm.Vac.	1.1×10^5	8.4×10^5	4.4×10^6	1.8×10^7	3.5×10^7
-10 Therm.Vac.	1.0×10^5	8.1×10^5	4.2×10^6	1.7×10^7	3.1×10^7
50 hr. Life	8.8×10^4	6.2×10^5	3.1×10^6	1.1×10^7	1.9×10^7
100 hr. Life	7.4×10^4	5.0×10^5	2.6×10^6	9.6×10^6	1.7×10^7
500 hr. Life	5.0×10^4	3.6×10^5	1.7×10^6	6.7×10^6	1.2×10^7
750 hr. Life	4.5×10^4	3.2×10^5	1.6×10^6	6.0×10^6	1.0×10^7
1000 hr. Life	3.9×10^4	2.8×10^5	1.3×10^6	5.0×10^6	9.2×10^6

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GAIN - MODEL 541F - SERIAL NO. D817

Current Gain

Test	1800 V	2200 V	2600 V	3000 V	3200 V
Initial	2.0×10^4	1.3×10^5	5.8×10^5	2.1×10^6	3.6×10^6
Dry Heat #1	2.2×10^4	1.4×10^5	6.6×10^5	2.4×10^6	4.2×10^6
Dry Heat #2	2.1×10^4	1.3×10^5	6.3×10^5	2.3×10^6	3.9×10^6
Dry Heat #3	2.6×10^4	1.6×10^5	7.9×10^5	2.9×10^6	5.0×10^6
Gas Dec.	2.8×10^4	1.8×10^5	8.6×10^5	3.1×10^6	5.6×10^6
200 g	3.2×10^4	2.0×10^5	1.0×10^6	3.7×10^6	6.6×10^6
1000 g	3.1×10^4	2.0×10^5	9.7×10^5	3.5×10^6	6.3×10^6
+75 Therm.Vac.	2.1×10^4	1.3×10^5	6.1×10^5	2.0×10^6	3.5×10^6
-10 Therm.Vac.	2.2×10^4	1.4×10^5	6.3×10^5	2.2×10^6	4.0×10^6
50 hr. Life	2.1×10^4	1.3×10^5	5.9×10^5	2.1×10^6	3.6×10^6
100 hr. Life	1.8×10^4	1.1×10^5	4.8×10^5	1.6×10^6	2.8×10^6
500 hr. Life	1.4×10^4	9.0×10^4	3.9×10^5	1.3×10^6	2.3×10^6
750 hr. Life	1.1×10^4	7.3×10^4	3.2×10^5	1.1×10^6	1.8×10^6
1000 hr. Life	1.0×10^4	6.6×10^4	2.9×10^5	1.0×10^6	1.7×10^6

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APPENDIX C

TEST REPORT NO. TR-34 NO. OF PAGES 14

PRINCETON DIVISION

ELECTRO-MECHANICAL RESEARCH, INC.

REPORT OF ENVIRONMENTAL TEST

ON

MULTIPLIER PHOTOTUBE

PROJECT 2641-3456

Date: July 16, 1965

Prepared by: K. Lenghaan

Reliability Engineering

Approved by: H. Butterworth

Quality Control Manager

TABLE OF CONTENTS

ADMINISTRATIVE DATA

1.0 PURPOSE OF TEST: To subject multiplier phototubes to a series of environmental tests as outlined in this report.

2.0 MANUFACTURER: Electro-Mechanical Research, Inc., Princeton Division.

3.0 MANUFACTURER's MODEL NO.:
541F-08-18, Serial Numbers D799, D802, D805, D814, and D817 (Stainless Steel Shell).
541D-01-14, Serial Numbers D833, D839, D873, and D877 (Fiber-glass Shell).

4.0 DRAWING SPECIFICATION: 541F-08-18, 541D-01-14 and special directions by Project Engineer 2641-3456.

5.0 QUANTITY OF ITEMS TESTED: Nine

6.0 SECURITY CLASSIFICATION OF ITEMS: Unclassified

7.0 DATE TEST COMPLETED: July 12, 1965

8.0 TEST CONDUCTED BY: Reliability Section, Reliability and Quality Assurance Department, Electro-Mechanical Research, Inc., Princeton Division.

9.0 DISPOSITION OF SPECIMEN: Returned to Project Engineer, 2641-3456

10.0 ABSTRACT: The series of environmental tests described herein were conducted. No significant electrical parameter changes were noted as a result, except on tube Serial Number D839 (see page 11 for details). Slight indentations on all stainless steel type shell cases (Serial Numbers D799, D802, D805, D814, and D817) were caused by applied forces during the test, and one tube (Serial Number D817) slipped partially from its mount during static acceleration thus having its face flattened while hitting against the accelerator wall.

LIST OF APPARATUS

1. Calidyne Shaker System, Model A-174, S/N 21, modified with B&K Automatic Vibration Exciter Control, Type 1039, S/N 123830.

2. Shaevitz Rotary Accelerator, Model G-6-A, S/N 106, with Beam Extension.

3. Tektronix Oscilloscope, Model 535, S/N 2512, with companion Preamplifier, Model 53/54C, S/N 6988.

4. Barry Component Shock Machine, Type 20 VI.

5. Glennite Accelerometer, Model A320, S/N 1620.

6. EMR Low Pass Filter, 250/750 cps.

7. EMR Band Pass Filter 15-2000 cps.

8. General Radio Random Noise Generator, Type 1390-B, S/N 2395.

9. Tektronix Oscilloscope Camera, C-19, S/N 001492.

10. EMR Tube Clamping Fixture, 4 x 541.

SEQUENCE OF TESTS

All multiplier phototubes were subjected to a series of tests in the order shown below.

1. Static Acceleration.
2. Sinusoidal Vibration.
3. Wide Band Noise.
4. Shock 150 g
5. Shock 200 g

NOTE: 1. Electrical functional tests were conducted by Project Engineering immediately after each of the above tests.

2. All tests were divided into two groups of four tubes and one group of one tube, thus limited by the clamp capacity of the fixture (item 10, page 2).

IDENTIFICATION OF AXES

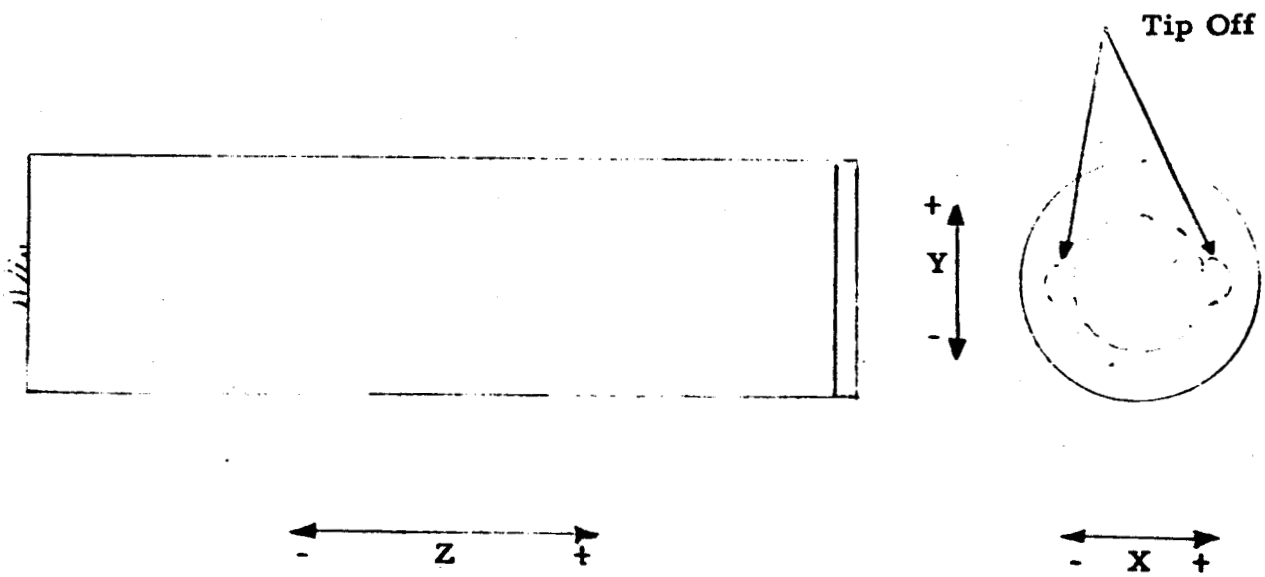

FIGURE 1

STATIC ACCELERATION

TEST PROCEDURE

The items under test were mounted on the beam extension of the rotary accelerator as shown in Figure 2, and subjected to a static acceleration as follows:

AXIS	UNITS OF GRAVITY	TIME
Z +	190 g ± 10%	20 minutes
Z -	190 g ± 10%	20 minutes
Y +	190 g ± 10%	20 minutes
Y -	190 g ± 10%	20 minutes
X +	190 g ± 10%	20 minutes
X -	190 g ± 10%	20 minutes

TEST RESULTS

Tube serial number D817 slipped from its initial mounting position approximately 3/4" along the Z + axis after 6 minutes of 190 g in Z + direction, thus having its face flattened while hitting against the accelerator wall. All stainless steel type shell cases (Serial Numbers D799, D802, D805, D814, and D817) experienced a slight out of round distortion and/or case indentation as a result of the applied acceleration and clamping forces. These tubes were re-mounted with fine grade emery cloth to reduce slippage, and the test was completed with no further discrepancies noted.

FIGURE 2

Four multiplier phototubes shown mounted inside the housing of the rotary accelerator.

SINUSOIDAL VIBRATION

TEST PROCEDURE

The test items were mounted on the shaker as shown in Figure 3, and subjected to a sinusoidal vibration as follows:

AXIS	CPS	MAGNITUDE	TIME *
Z	5-17	± .5 inch ± 10%	3.4 minutes
Z	17 50	5 g rms ± 10%	3.0 minutes
Z	50-100	15 g rms ±10%	2.0 minutes
Z	100-2000	35 g rms ± 10%	8.4 minutes
X	5-17	± .5 inch ± 10%	3.4 minutes
X	17-50	5 g rms ± 10%	3.0 minutes
X	50-100	15 g rms ± 10%	2.0 minutes
X	100-2000	35 g rms ± 10%	8.4 minutes
Y	5 17	± .5 inch ± 10%	3.4 minutes
Y	17-50	5 g rms ± 10%	3.0 minutes
Y	50 100	15 g rms ± 10%	2.0 minutes
Y	100 2000	35 g rms ± 10%	8.4 minutes

TEST RESULTS

There was no apparent damage to the multiplier phototubes as a result of this test.

* The rate of sweep was constant at 1/2 octave/minute with an automatic crossover set at 17 cps, switching from displacement-velocity to acceleration monitoring.

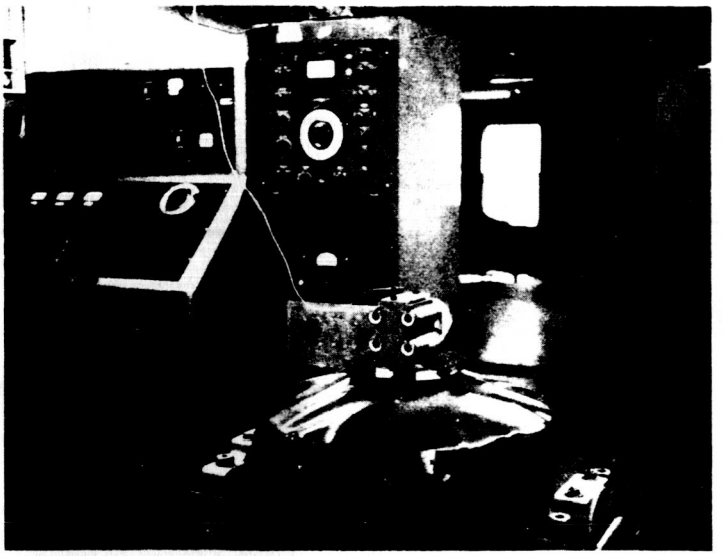

FIGURE 3

Test set up, sinusoidal vibration showing four tubes mounted in the clamping fixture on the shaker.

WIDE BAND NOISE

TEST PROCEDURE

The test items were mounted on the shaker in the usual way as shown in Figure 4, and subjected to a random noise spectrum as follows:

AXIS	SPECTRUM	MAGNITUDE	TIME
Z	15-2000 cpes	25 g rms ± 10%	9 minutes
X	15-2000 cps	25 g rms ± 10%	9 minutes
Y	15-2000 cps	25 g rms ± 10%	9 minutes

TEST RESULTS

There was no apparent damage to the multiplier phototube as a result of this test.

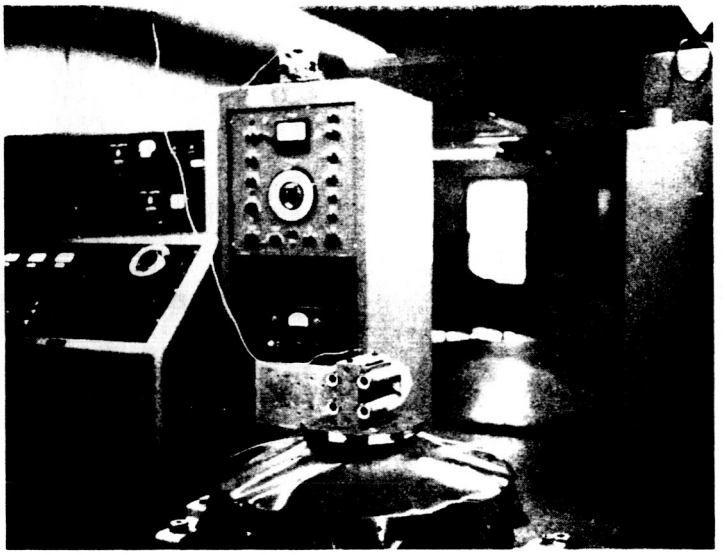

FIGURE 4

Test set up, wide band noise, depicting the main instruments used and four tubes in typical mounting positions.

SHOCK

TEST PROCEDURE

The test items were mounted on the drop table of the shock machine and subjected to the following shocks:

AXIS	G pk	RISE TIME	NUMBER OF SHOCKS
X +	150 ± 10%	5 ms	5
X -	150 ± 10%	5 ms	5
Y +	150 ± 10%	5 ms	5
Y -	150 ± 10%	5 ms	5
Z +	150 ± 10%	5 ms	5
Z -	150 ± 10%	5 ms	5
X +	200 ± 10%	.5 ms	5
X -	200 ± 10%	.5 ms	5
Y +	200 ± 10%	.5 ms	5
Y -	200 ± 10%	.5 ms	5
Z +	200 ± 10%	.5 ms	5
Z -	200 ± 10%	.5 ms	5

TEST RESULTS

There was no apparent damage to eight of nine multiplier phototubes as a result of this test. One tube, Serial Number D839, showed a dislocation of the focusing electrode toward the X - axis. The discrepancy was noted upon Y - axis reversal from + to - in the 200 g test. The tube was removed for a complete electrical test, which indicated a slight degradation.

Subsequently, tube Serial Number D839 was subjected to the remaining shock in Y -, Z +, and Z - axis at 200 g. The first shock in the Z - axis caused the focusing electrode to shift again now pointing toward the Y + axis. The final test after completion of all shock testing showed the tube still operational.

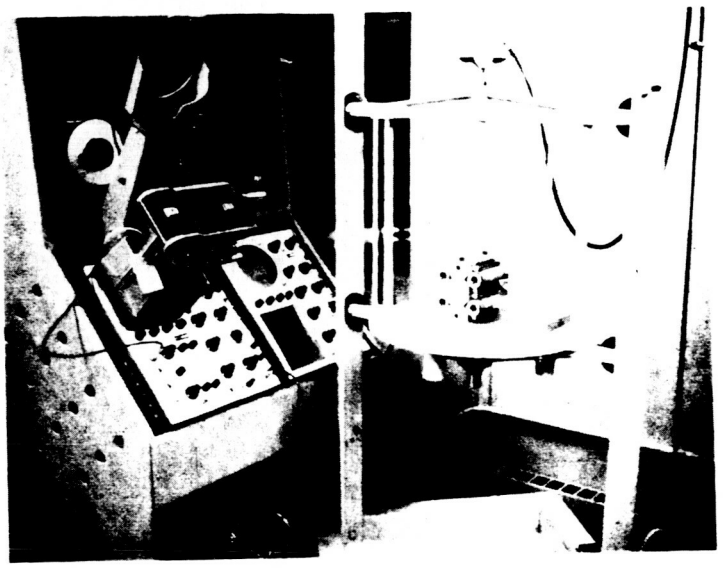

FIGURE 5

Depicting shock test set up with four tubes shown mounted on the drop table.

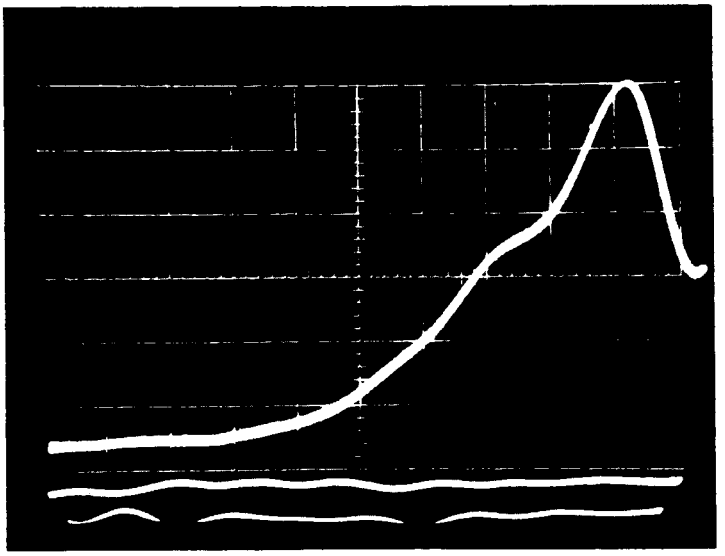

FIGURE 6

Showing photographed shock impulse of 150 g.
Vertical Scale: 25 g/cm
Horizontal Scale: 1 ms/cm
(a low pass filter of 750 cps was used)

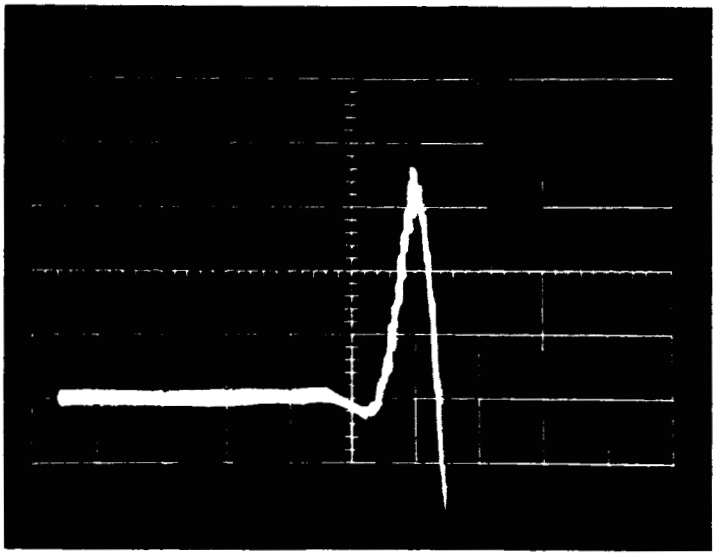

FIGURE 7

Showing photographed shock impulse of 200 g
Vertical Scale: 60 g/cm
Horizontal Scale: 1 ms/cm
(a low pass filter of 750 cps was used)