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CALIBRATION OF THE PHOTOMULTIPLIERS USED FOR MEASURMENT OF BIOLUMINESCENCE BACKGROUND FOR DUMAND

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ABSTRACT

The calibration of the photomultiplier for the first measurment, TTR-1, used a single filter centered at 470 nm with a full width at half maximum of 85 nm. A calibrated photodiode was used to measure the light from a lamp which passed this filter and a 1 cm^2 aperture. This known light flux then served as a temporary standard to be used in calibrating the photomultiplier. For 1500 volts on the photomultiplier, we found that a current of 3.00 amps in the filament of our intermediate light source gave a level of light which could be read on the photodiode and which could reasonably (10^6) be attenuated to the limit of sensitivity of the photo tube. We then calculated a sensitivity of 1100 photons/sec per nanoamp of current at the anode of the photo tube. For the TTR-3 measurment we used a lower noise phototube[1] which had been protected from light and which had been monitored (note to Dan and Vince: monitored for what. Dark current?) over the last several years. In order to assess the dependence of the calibration on the spectrum of light used for calibration and to look for systematic errors, we used several filters and several operating temperatures of the intermediate light source. We describe here this more elaborate calibration procedure used for the TTR-3 measurment. We find a sensitivty of 78 photo-electrons per nanoanp. The efficiency of the photocathode is 0.178 photoelectrons per photon for a Gaussian spectrum[2] centered at 470 nm and having a standard deviation of 30 nm.. This gives a sensitivity of 438 photons per nanoamp for this spectrum. The possibility that infrared leaked through the filters used in the calibration makes this a lower limit on the sensitivity of the phototube. The small difference in the sensitivity calculated with data from two very different temperatures of the

bulb filament indicates that the error in sensitivity due to such a leak is probably not greater than 10 percent. The TTR-3 measurment used a selected phototube which had been protected from light, so this sensitivity cannot be compared directly with the sensitivity calculated for TTR-1. Application of the simplier procedure to the phototube used for TTR-3 gave 807 photons per nanoamp at the original setting of 3 amp filament current and 567 photons per nanoamp at the higher temperature provided by 4.2 amp of filament current. This indicates that the cruder procedure is quite satisfactory for $\simeq$ 40% accuracy (567/417 =1.36) in the calibration if one works at the higher filament current. In fact the optical density of the od=3 attenuator is somewhat less than 3 and the error from using the nominal value tends to cancel the error from the simple method to give quite an accurate answer. Combining the error from the simple procedure with the error from using nominal values for the attenuators, we conclude that the procedure used for the TTR-1 cruise led to an overestimate of the light level[3] in the ocean by a factor of 1.5.

We also present data which shows that the sensitivity of the photomultiplier changes by less than 5% for a temperature change from normal room temperature ($\simeq 22^{o}$C) to about 4^{o}C in the Wisconsin-in-Hawaii room.

We conclude that the sensitivity of the photomultiplier used in the TTR-3 cruise is 440 $\pm$ 70 photons per second per nanoamp.

I. INTRODUCTION

A calibrated photodiode[4] is a good, rugged, and stable device for measuring light fluxes in absolute units. We use a photodiode to measure the light transmitted through a fixed aperture and each of a series of color filters. We then replace the photodiode with a photomultiplier in a light tight box which is sealed to the filter system and which is positioned so that the photocathode of the photomultiplier intercepts all rays which previously hit the photodiode surface. The sensitivity of the photomultiplier can then be calculated from the measured photodiode and photomultiplier currents and the manufacturer's calibration curve for the photodiode and the transmission curves of the filters. One has to make reasonable assumptions about the spectrum of light from the incandescent filament, but the result is quite insensitive to these assumptions. The box[5] which holds the filters[6], attenuators[6] and light source[7] is shown in Fig. 1. All rays from the small filament area to the detector aperture are well within the 2 inch square filters and attenuators. In fact it is clear that smaller filters would have been adequate. We have verified that the photodiode current is independent of rotations of both source and detector, and the construction does not permit significant translations of either.

Fig. 2 shows the approximate transmission ranges of five filters which were used, the response curves of the photodiode[4], and photomultiplier cathode[8], and Planck radiation curves for several temperatures of interest here. Note that the diode sensitivity extends far into the infrared so that infrared leakage of filters will make a serious error in the calibration of the light source from the diode. The photomultiplier is much less sensitive to such a problem because its long wave length cut off is in the visible, so there is little cancellation of errors when the ratio is taken. The lowest temperature curve shows a relative rise which is several hundred times larger, between the visible and the infrared, than the rise of either of the two higher temperature curves: the infrared leakage problem should be <u>much</u> greater at the lower temperature. Note also that the photo diode and photomultiplier response curves are approximately constant over the ranges of filters 03FIB003 and 03FIB004.

II. General Discussion

The current, in nanoamps, in the photodiode is:

1) $$I^k_{pd} = \int f(\lambda)\ T^k(\lambda)\ R_{pd}(\lambda)\ d\lambda$$

where $T^k(\lambda)$ is the transmission of filter k, $f(\lambda)$ is the number of photons emitted by the source within the geometric acceptance of the detector and in the wavelength interval $d\lambda$, and $R_{pd}(\lambda)$ is the response of the photo diode in nanoamps per photon. Note that the response of the photodiode is quite constant over the ranges of several filters, so, if infrared leakage can be neglected, it will often be a good approximation to pull this function outside the integral and to obtain:

2) $$I^k_{pd} \simeq R^k_{pd} \int f(\lambda)\ T^k(\lambda)\ d\lambda.$$

For the photomultiplier it is convenient to split the response into two factors $G\ R_{pc}(\lambda)$ where G is the gain of the dynode structure, in nanoamps per photoelectron, and $R_{pc}(\lambda)$ is the conversion efficiency of the photocathode. In principal we could determine the form of R_{pc} by comparison with photodiode currents for several (narrow) filters. In practice there is sufficient concern about infrared leakage in the photodiode currents so that we a) use the expected values of R_{pc} from Learned[8] and use the comparison to set upper limits on the error due to such leakage and we also b) determine a small correction to Learned's curve. Fortunately both methods give consistent values for the sensitivity of the phototube. We thus write

3) $$I^k_{pm} = G \int f(\lambda)\ T^k(\lambda)\ R_{pc}(\lambda)\ d\lambda$$

4) $$I^k_{pm} \simeq G\ R^k_{pc} \int f(\lambda)\ T^k(\lambda)\ d\lambda$$

The crude form of calibration used for TTR-1 is based upon the fact that the integrals, and thus details of the spectrum, cancel when eq 2 and 4 are solved for G.

5) $$G\ R^k_{pc} \simeq \frac{I^k_{pm}}{I^k_{pm}} R^k_{pd}$$

This is clearly a good approximation for filter 03FIB003, as used for the TTR-1 calibration, and gives a useful answer if the bioluminescence spectrum is also in the range of 400 to 500 nm. In order to improve upon this approximate treatment it is necessary to assume a form for the spectrum $f(\lambda)$ and to use the full set of equations 1 and 3 for each of several filters in order to verify that the assumed form of the spectrum is reasonable. In practice we have chosen the form $f(\lambda) = C\ L(\lambda;\lambda_c)$ where the function L, defined in the caption of Fig. 2, is proportional to the Planck blackbody differential photon spectrum and λ_c is inversely proportional to the temperature. The constant C is unknown because it includes as factors the area of the emitter and the angle subtended by the detector. It does not, however, depend upon the temperature. The sets of equations 1) and 3) then become:

6) $$I^k_{pd} = C \int L(\lambda)\ T^k(\lambda)\ R_{pd}(\lambda)\ d\lambda$$

7) $$I^k_{pm} = G\ C \int L(\lambda)\ T^k(\lambda)\ R_{pc}(\lambda)\ d\lambda$$

We assume a value for λ_c and adjust C in equations 6 to minimize the chi-square for the sum over all (good) filters and we do a similar, but independent, fit with equations 7 for the product G C. We then vary λ_c to find the minimum with respect to variation of λ_c as well as with respect to variation of C (or G C). In principal the minimum should occur at the same value of λ_c for both detectors, the value of C should be the same for both temperatures (filament currents) for which we obtained data, and G could be obtained by averaging the (equal within errors) values of (G C)/C from the different filters. Anticipating the data to be presented in the next section, we note that:

1) One of the filters, 03FCG001, is clearly <u>dominated</u> by infrared leakage. Data taken with this filter are presented to show the effect of leakage, but are not used in the calculation of the sensitivity.

2) The temperatures, or λ_c values, obtained for the photodiode and for the photomultiplier do not agree within errors. At the lower temperature (3 amps), this certainly indicates leakage of infrared through the various color filters. At the higher temperature (4.2 amps) there is enough light so that we can measure the photodiode response with several different attenuators and we find that the current with no attenuator is consistently higher than expected from the values with attenuators. We speculate that the attenuators are helping to remove the infrared. At this higher temperature the difference probably indicates that the photocathode response of this photomultiplier decreases with increasing wavelength slightly more rapidly than expected from Learned's curves. The relatively high value of chi-square at the minimum for the photodiode at 3 amps indicates a less succesful parameterization of the data than for the other three cases.

~~[illegible]~~

3) The "constant" C increases by ony 30% when the luminosity of the source is changed by a factor of ≃ 120 by increasing the current from 3.00 to 4.20 amps. The area of the emitting surface certainly increases as the appearance of the filament changes from the color of last nights coals in the fireplace to somthing more like the appearance of a light bulb, and this small change in C is quite satisfactory. Note to Dan: Is power supplied to filament consistent with this temperature change? See comments in footnote 7.

area increased by 20% if this change in temp is consistent with measured elect input power. 20% and 30% is good agreement

4) Despite the unsatisfactory aspects of the data, the calculated gain of the tube, G, changes by only a few percent as the temperature used in the calculation of the assumed spectrum is changed from the temperature preferred by the photo tube data to that preferred by the diode data, and decreases by only about 30 % when the temperature of the filament is increased to the higher temperature. Since the gain "determined" by the obviously leaky filter decreases by a factor of 40 with this change in temperature and the ratio of visible to infrared changes by a factor of nearly a hundred, we interpret these results as indicating modest problems with the data and/or model used for the analysis, but as indicatng that the gain which we set out to measure is not sensitive to these problems. The lower temperature calibration shows significant infrared leakage problems, but this effect is negligible for the higher temperature calibration. We conclude that the sensitivity has certainly been determined to 50%, and probably to 15%.

5) Fig. 3 shows the typical electronic gain expected from tubes with various numbers of dynodes as a function of voltage for EMI tubes[9]. At 1500 volts, the typical gain for an 11 stage tube is about 0.8×10^8. Our gain of 78 ± 12 photoelectrons/sec per nanoamp is a dynode gain of $(0.801 \pm 0.12) \times 10^8$: the carefully selected, low noise tube used for TTR-3 is normal and the tube used for TTR-1 is slightly below normal.

III. DATA AND QUANTITATIVE RESULTS

In this section we present the details of the measurments and describe the cross checks which have been made in order to insure the reliability of the calibration data as well as its applicability to the data taken with the phototube in the sphere at depth in the ocean.

A. Choice of Filters

Filter 03FIB003 was chosen for the simple calibration procedure because it covers the range of best transmission of seawater as well as the range of good efficiency of the photocathode. When we decided to improve the calibration by taking the spectrum of the calibration source into account, we searched for filters which would span the region of good efficiency of the photocathode and which would have sufficiently different regions of transmission to permit a determination of the shape of the source spectrum.

The approximate transmission regions are shown in Fig. 2 and the average wavelength of photons from a source at 1800° K, which pass the filter and which are detected by the photodiode, is given in Table II. The transmission curves were plotted for these particular filters by the manufacturer[6] and the numerical integrations for averages and for transmitted numbers of photons used the data from these curves. The measured curves typically covered a range which was several times the width of the transmission peak and the transmission was down to a few tenths of a percent on the measured wings of the curves, but the range was not adequate to give information about leakage well outside the pass band.

In addition to the color filters, neutral density filters are used to adjust the intensity of the light for the photomultiplier. The optical densities of these filters are nominally 3, 2, 1, 0.5, 0.3, 0.1, and 0.04. The manufacturers curves for these attenuators shows that the densities of these filters are reasonably close to the nominal densities in the range 500 to 700 nm, but show approximately 10 percent smaller optical density in the range from 350 to 500 nm. (transmission = $10^{-\text{optical density}}$, so an error of 0.02 in optical density is an error of 5% in transmission.) The manufacturer's optical density curves were converted to transmision curves and averaged over the detected spectrum for each detector with each filter and for each temperature of filament used for the calibration light source. The deviations from the nominal values are quite significant and the variations for the different color filters are of modest significance. The variations over the range of filament temperatures considered here is insignificant. Table I gives the effective optical densities for each of the attenuators for each color filter. The variations with filament temperature and the variation between the photomultiplier and photodiode are generally in the third decimal, so the photomultiplier response and a filament temperature of 2100°K has been used in computing this table, which has been used for all calculations presented here.

TABLE I EFFECTIVE OPTICAL DENSITIES OF ATTENUATORS

NOM OP DN	3.000	2.000	1.000	0.500	0.300	0.100	0.040
03FIB003	2.861	2.025	1.003	0.489	0.310	0.109	0.038
03FIB002	2.822	1.996	0.982	0.471	0.303	0.112	0.038
03FIB004	2.853	2.019	0.999	0.484	0.309	0.110	0.038
03FCG001*	2.777	1.973	0.946	0.449	0.292	0.122	0.040
03FIV027	2.877	2.040	1.011	0.498	0.312	0.105	0.036

The pass band of this filter extends below the range for which the manufacturer has supplied data on the optical density of the attenuators. Still another reason not to use this filter.

B. Importance of maintaining correct current in bulb filament

We expect ~~that~~ the emission of light from an incandescent bulb to depend upon the current in the bulb and that the dependence will be even stronger if the bulb is operated with the peak of the Wein curve at wavelengths which are much greater than the wavelengths at which the intensity is measured. We have varied the currents about the nominal 3.00 amps and measured the change in intensity with each filter and we have measured one filter at 4.20 amps. We find that a plot of the data on semilog paper is a straight line for deviations of < 0.2 amps and we present the data as changes in the filament current which produce a 5% change in the light transmitted through the filter.

TABLE II. PERMITTED ERROR IN BULB FILAMENT CURRENT FOR 5% CHANGE IN LIGHT THROUGH THE FIVE FILTERS

Filter	Mean Wave Len	Nominal Filament Current 3.00 amp	4.20 amp
03FIV027	522.0 nm	0.011 amp	
03FIB003	494.2	0.0085	0.019 amp
03FIB004	476.1	0.0079	
03FIB002	436.8	0.0079	
03FCG001	373.7	0.012	

All of the tolerences are small enough to require care in maintaining a constant current throughout the calibration procedure, but reproducible results are obtained if the current is monitored with a digital volt meter which reads to 0.01 amp and if it is watched attentitively. The problem is easier at 4.2 amps than at 3.0 amps. Note that the experimentally observed sensitivity of 03FCG001 is more like that of a red filter than that of a blue filter. This supports our contention that the transmission of this filter is dominated by leakage in the near infrared rather than transmission in the pass band in the near ultraviolet.

C. Temperature Dependence of Phototube and High Voltage Power Supply

The temperature in the deep ocean is 2^{o} to $5^{o}C$, so it is important[10] to establish the calibration at this temperature. The TTR instrument was designed to work in the ocean environment and has previously been demonstrated to be adequately stable against this temperature change. The Wisconsin-in-Hawaii room at the Hawaii Institute of Geophysics provides ample space for checking equipment and is maintained at this temperature. We first established that the emission from the bulb was independent of temperature of the environment for changes from room temperature to approximately $0^{o}C$. We packed the neck of the calibration device, which contained the bulb, with ice bags and wrapped the neck and ice bags in an insulating jacket. This is the part above the region labeled filters in Fig. 1. The filament power supply, digital ammeter, photodiode, and the sensitive voltmeter used to measure the anode current were kept at room temperature. We estimate an upper limit of 1% on the change in emission in the region of the 03FIB003 Filter over a period of 2.5 hours. Since we were looking for a small change, we periodically swept the current slowly through the region in which the digital ammeter changed from 2.99 to 3.00 and from 3.00 to 3.01 amps and found no measurable change in the photodiode currents for these points as the ice, in plastic bags, cooled the plastic housing surrounding the bulb. This test established that the emission from the bulb did not depend upon the temperature of the environment of the bulb housing within the range of interest here, so we could complete our check of temperature dependence of the phototube and power supply by taking the assembly of light box and sphere into the Wisconsin room. The photomultiplier and high voltage power supply were taken into the Wisconsin room about 10:00 August 11 and the calibration source and light box were taken into the room early in the afternoon. The battery for the high voltage and all meters were left outside at normal temperature. In late afternoon a calibration run was taken with 3.00 amps filament current. The tube was removed from the cold room and the calibration run was repeated on the 12 and on the 13 of August. The current vs od (optical density of the attenuator) curves for these three runs are shown in Fig. 4(a) The dark currents show a decrease for the later runs and we interpret this as a decay since last exposure to light rather than as a temperature effect, since dark current is generally thought to decrease with temperature. There are no other differences which show on this plot. In order to look more critically for differences which might be related to temperature, we have fitted each of the three sets to the form $I = dc + I_o 10^{-od}$. We find negligible variation in the fitted parameters I_o for the three sets, so we have selected $I_o = 1.12\ 10^7$ nanoamps as typical and Fig. 4(b) shows the deviations of each of the data sets from the assumed form with I_o fixed at this value but the dark currents adjusted individually for each set. Again there is no evidence for any systematic difference between the cold data and the other two. We conclude that the upper limit on any temperature effects is probably less than 2% and certainly less than 5% for this particular phototube. Fig. 3(b) is a reproduction of comments from EMI on thermal effects and indicates that this result is reasonable.

D. Calibration Assuming Photocathode Efficiency Is Known

Data were obtained with 3.00 amp filament current in the bulb and with 4.20 amp. The intensity at 3 amp gave currents in the photodiode as given in Table III. (a). These values were ≃ 1 nanoamp and it was not practical to introduce attenuators in the light beam in order to obtain several different points on a light curve. For the photomultiplier currents given in Table II. (b), attenuators were chosen to give anode currents (measured as voltages across 10 kOhm resistor with high resiatance voltmeter) in the range of 70 to 300 nanoamperes. The dark current (≃ 20 na) was subtracted and the resulting current for each measurment was multiplied by the attenuation as obtained from the optical densities of the filters given in Table I. The three to five values obtained for each filter were found to agree to about 5% and were averaged together.

At 4.2 amp filament current the greater light intensity permitted the use of attenuators of optical density 0.5 to 2 for the photodiode and the four values were averaged after correction for attenuation. The currents with no attenuation were not used because they were about 10% higher than the values calculated from the four attenuators. Filter 03FCG001 in particular gave a value without attenuation which was 25% higher than the values obtained from measurments with attenuation. The variation in the measurments for a given filter indicate that the error on the average of four values is about 5%. For the photomultiplier, this higher light intensity gave anode currents of a few hundred to a few thousand nanoamps with attenuators of 3 to 6 and again dark currents were subtracted and the currents were converted to currents for no attenuator. The agreement among the three values is again consistent with 5% errors for the averages.

The currents, scaled for no attenuation, are given in Table III. (a)-(d) for the photo diode and photomultipler at 3 amp and then at 4.2 amp. The column labeled "integral" is the right hand side of equation 6 or 7 with C or G adjusted to minimize the fractional differences between the measured currents and the integrals for all four filters. (Filter 03FCG001 is omitted from the fit.) Errors of 5% in each measured current for purposes of the fits and chi-squared calculations. The calculations which are presented in Table III are for the value of λ_c, or temperature, which give the best fit for the <u>photomultiplier</u> at each filament current. "Phot/sec" is the same as the "integral" except that the factor of R has been omitted from the integrand so that it represents the number of photons per second incident on the detector for the photodiode and G times the number of photons per second incident on the photomultiplier. "Ratio" is the quantity which has been adjusted to be one for the four good filters. If the 5% errors were correct and if the model were correct, "ratio" should show a 5% scatter about 1. The chi-squared measure of the quality of the fit for these, and additional temperatures, is given in Table IV.

TABLE III. (a) Photodiode at 3 amp. λ_c = 8635.0

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	496.	9.277E-01	9.200E-01	8.320E+09	9.917E-01
03FIB002	438.	7.954E-02	7.200E-02	8.098E+08	9.052E-01
03FIB004	478.	4.187E-01	3.800E-01	3.820E+09	9.077E-01
03FCG001	375.	1.186E-03	8.550E+00	3.396E+07	7.209E+03
03FIV027	522.	2.286E-01	3.700E-01	2.012E+09	1.619E+00

TABLE III. (b) Photomultiplier at 3.0 amps. λ_c = 8635.0

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	489.	1.019E+07	1.052E+07	6.914E+07	1.033E+00
03FIB002	434.	1.438E+06	1.397E+06	6.729E+06	9.712E-01
03FIB004	472.	5.408E+06	5.636E+06	3.175E+07	1.042E+00
03FCG001	371.	6.769E+04	5.330E+04	2.822E+05	7.875E-01
03FIV027	522.	1.930E+06	1.860E+06	1.672E+07	9.639E-01

TABLE III. (c) Photodiode at 4.2 amp. λ_c = 6475.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	489.	6.790E+01	7.665E+01	6.134E+11	1.129E+00
03FIB002	433.	1.030E+01	9.100E+00	1.093E+11	8.835E-01
03FIB004	472.	3.609E+01	3.453E+01	3.325E+11	9.569E-01
03FCG001	371.	3.520E-01	1.141E+02	1.082E+10	3.241E+02
03FIV027	522.	1.289E+01	1.443E+01	1.134E+11	1.119E+00

TABLE III. (d) Photomultiplier at 4.2 amp. λ_c = 6475.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	481.	1.155E+09	1.248E+09	7.376E+09	1.081E+00
03FIB002	427.	2.868E+08	2.782E+08	1.314E+09	9.699E-01
03FIB004	466.	7.113E+08	7.181E+08	3.998E+09	1.010E+00
03FCG001	367.	3.095E+07	1.974E+07	1.301E+08	6.378E-01
03FIV027	522.	1.576E+08	1.509E+08	1.364E+09	9.572E-01

In order to investigate the dependence of the sensitivity of the photomultiplier on the filter and on the assumed temperature of the source, we show in Table IV. (a) and (b) the reciprocal of G (in eq 7) for each filter, for several assumed temperatures of the source, and for each the two data sets. These are estimates of the number which must be multiplied by the average photocathode efficiency, for the source in the ocean, to yield the sensitivity of the tube. Immediately under the temperature (TEMP) line in the table are given the chi-squared values and the fitted C or CG coefficients for each detector. The AV PM GN is the reciprocal of G calculated from these two fitted numbers.

TABLE IV. (a) SUMMARY FOR MEASURMENT SET NO. 1 (3.00 AMPS)

LAMC =	FLAT	8460.	8635.	8810.	9250.	9850.	11000.
TEMP =	SPECTRUM	1702.	1668.	1635.	1557.	1462.	1309.
PD CHISQ	8.32E+02	7.67E+01	6.70E+01	5.87E+01	4.38E+01	3.66E+01	5.83E+01
PD COEF	2.64E+07	2.97E+10	4.32E+10	6.27E+10	1.59E+11	5.56E+11	5.84E+12
PM CHISQ	8.50E+02	3.06E+00	1.97E+00	3.05E+00	1.47E+01	4.83E+01	1.49E+02
PM COEF	1.80E+05	2.48E+08	3.59E+08	5.17E+08	1.29E+09	4.37E+09	4.32E+10
AV PM GN	1.46E+02	1.20E+02	1.20E+02	1.21E+02	1.23E+02	1.27E+02	1.35E+02
PHOT MULT SCALE FACT IN PHOTO ELECT/SEC PER NANOAMP							
03FIB003	1.433E+02	1.162E+02	1.156E+02	1.150E+02	1.135E+02	1.115E+02	1.079E+02
03FIB002	1.461E+02	1.127E+02	1.122E+02	1.117E+02	1.105E+02	1.090E+02	1.064E+02
03FIB004	1.244E+02	1.052E+02	1.048E+02	1.044E+02	1.032E+02	1.018E+02	9.902E+01
03FCG001	1.367E+06	1.107E+06	1.102E+06	1.096E+06	1.083E+06	1.065E+06	1.033E+06
03FIV027	2.028E+02	2.021E+02	2.021E+02	2.021E+02	2.020E+02	2.020E+02	2.018E+02

TABLE IV. (b) SUMMARY FOR MEASURMENT SET NO. 2 (4.2 AMPS)

LAMC =	FLAT	6300.	6475.	6650.	6945.	7120.	7295.
TEMP =	SPECTRUM	2286.	2224.	2165.	2073.	2022.	1974.
PD CHISQ	6.32E+02	2.64E+01	1.75E+01	1.08E+01	4.14E+00	2.96E+00	3.77E+00
PD COEF	3.58E+09	2.66E+10	3.88E+10	5.64E+10	1.06E+11	1.52E+11	2.20E+11
PM CHISQ	6.21E+02	4.76E+00	3.46E+00	4.74E+00	1.25E+01	2.01E+01	2.99E+01
PM COEF	3.89E+07	3.21E+08	4.67E+08	6.76E+08	1.26E+09	1.81E+09	2.59E+09
AV PM GN	9.21E+01	8.29E+01	8.32E+01	8.35E+01	8.40E+01	8.44E+01	8.48E+01
PHOT MULT SCALE FACT IN PHOTO ELECT/SEC PER NANOAMP							
03FIB003	1.007E+02	8.735E+01	8.686E+01	8.637E+01	8.556E+01	8.509E+01	8.462E+01
03FIB002	9.270E+01	7.619E+01	7.576E+01	7.533E+01	7.464E+01	7.424E+01	7.385E+01
03FIB004	8.872E+01	7.918E+01	7.883E+01	7.849E+01	7.791E+01	7.758E+01	7.724E+01
03FCG001	4.925E+04	4.248E+04	4.225E+04	4.204E+04	4.167E+04	4.146E+04	4.125E+04
03FIV027	9.747E+01	9.726E+01	9.725E+01	9.724E+01	9.723E+01	9.722E+01	9.721E+01

First consider the last set of entries in TABLE IV. (b). These are remarkably constant over the whole table except for the filter 03FCG001. The dependence upon the spectrum used in computing the integrals is so slight that a flat spectrum differs from any reasonable spectrum by only about 30%. The difference between the temperature estimated from the photodiode and from the photomultiplier best fits is only about 1%. Of course these use the same measurments, so only model dependence and not measurment error is reflected in these changes. The differences among different filters is about 20% where 5 to 10% is expected from the propagation of errors from the measurments. Since infrared leakage would increase these numbers, we tend to take the lower ones and would take 75 to 80 photoelectrons per nanoamp as our best estimate. We have used the average, 78, in the introduction and general discussion. Bradner[2] suggests that the spectrum in the ocean may be aproximately described as a Gaussian with mean at 470 nm and rms of 30 nm. Such a spectrum would give a photocathode efficiency of 0.178 and thus a sensitivity of 78/0.178 = 438 photons per nanoamp. An error of 15% or 65 photons per nanoamp seems to be consistent with this calibration.

This scale factor is about 30% higher at 3 amps than at 4.2 amps, except for two filters. The "very leaky" filter is a factor of 100 higher. The ratio of infrared to visible is also of the order of 100 higher at 3 than at 4.2, so a filter which is dominated by a leak should be a factor of 100 higher at 3. Filter 03FIV027 is a factor of two higher than the three "best" filters at 3 and about 15% higher than the three "best" filters at 4.2. The factor of 100 in ratio of infrared to visible ratio between the two temperatures should make the leakage negligible at 4.2 for 03FIV027 as well as for the remaining three filters. We observe 15% and expect 3% from this simple argument. We may conclude that the leak is much closer to the pass band or that the photomultiplier response is incorrect. We have taken the first alternative in the preceeding paragraph. We explore the second alternative in the next section.

We note that the coefficients for both the photodiode and the photomultiplier vary by only about 30% although the intensity increases by a factor of 120 when the filament current is increased from 3 to 4.2 amps. The change in coefficient is much greater at other temperatures such as the temperature indicated by the photodiode best chi-square. This small increase in the coefficient is easily explained by a small increase in effective area at the higher temperature.

E. Calibration with Adjustment of Photocathode Efficiency

The most unsatisfactory aspect of the preceeding analysis is the disagreement between the temperatures computed from the photodiode and photomultiplier data at 4.2 amp. At the lower current there is sufficient evidence of infrared leakage that one should not be disturbed by the difference in the temperature estimates. At 4.2 the difference is driven by filter

03FIV027. In order to investigate the significance of this difference, we have explored the possibility that the response of our photocathode is slightly different from the response we took from Learned's curve. We find that we can move the photomultiplier temperature estimate to agree with the photodiode temperature estimate at 4.2 amps if we multiply the photocathode efficiency by a small linear correction which we have arbitrarily chosen to be unity at 450 nm: $1-0.00283*(\lambda-450)$. Fig. 5. shows the photocathode efficiency taken from Learned and this modification to it. Table V. (a-d) is similar to Table III. except that the modified photocathode efficiency is used. Table VI. (a-b) shows the sensitivity of the photomultiplier at the new minima.

TABLE V. (a) Photo diode at 3.0 amp. λ_c = 9325.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	498.	9.939E-01	9.200E-01	8.897E+09	9.257E-01
03FIB002	440.	7.094E-02	7.200E-02	7.148E+08	1.015E+00
03FIB004	480.	4.254E-01	3.800E-01	3.871E+09	8.933E-01
03FCG001	375.	8.099E-04	8.550E+00	2.271E+07	1.056E+04
03FIV027	522.	2.626E-01	3.700E-01	2.311E+09	1.409E+00

TABLE V. (b) Photomultiplier at 3.0 amps. λ_c = 9325.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	489.	1.026E+07	1.052E+07	8.031E+07	1.026E+00
03FIB002	434.	1.426E+06	1.397E+06	6.452E+06	9.794E-01
03FIB004	473.	5.463E+06	5.636E+06	3.494E+07	1.032E+00
03FCG001	371.	6.016E+04	5.330E+04	2.050E+05	8.860E-01
03FIV027	522.	1.919E+06	1.860E+06	2.086E+07	9.692E-01

Table V. (c) Photodiode at 4.2 amps. λ_c = 7120.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	491.	7.117E+01	7.665E+01	6.415E+11	1.077E+00
03FIB002	435.	9.110E+00	9.100E+00	9.532E+10	9.990E-01
03FIB004	474.	3.604E+01	3.453E+01	3.311E+11	9.581E-01
03FCG001	372.	2.433E-01	1.141E+02	7.316E+09	4.690E+02
03FIV027	522.	1.471E+01	1.443E+01	1.294E+11	9.811E-01

TABLE V. (d) Photomultiplier at 4.2 amps; λ_c = 7120.

FILTER	AV WL	INTEGRAL	MEAS I NA	PHOT/SEC	RATIO
03FIB003	481.	1.164E+09	1.248E+09	8.372E+09	1.072E+00
03FIB002	428.	2.857E+08	2.782E+08	1.244E+09	9.738E-01
03FIB004	466.	7.201E+08	7.181E+08	4.321E+09	9.972E-01
03FCG001	368.	2.804E+07	1.974E+07	9.549E+07	7.041E-01
03FIV027	522.	1.556E+08	1.509E+08	1.689E+09	9.696E-01

TABLE VI. (a) SUMMARY FOR MEASURMENT SET NO. 1 at 3.00 amp

LAMC =	9200.	9325.	9450.
TEMP =	1565.	1544.	1524.
PD CHISQ	4.50E+01	4.21E+01	3.97E+01
PD COEF	1.43E+11	1.86E+11	2.42E+11
PM CHISQ	1.64E+00	1.21E+00	1.84E+00
PM COEF	1.29E+09	1.68E+09	2.18E+09
AV PM GN	1.11E+02	1.11E+02	1.11E+02

PHOT MULT SCALE FACT IN PHOTO ELECT/SEC PER NANOAMP

03FIB003	1.005E+02	9.999E+01	9.949E+01
03FIB002	1.152E+02	1.148E+02	1.144E+02
03FIB004	9.632E+01	9.593E+01	9.554E+01
03FCG001	1.325E+06	1.320E+06	1.315E+06
03FIV027	1.611E+02	1.610E+02	1.610E+02

TABLE VI. (b) SUMMARY FOR MEASURMENT SET NO. 2 at 4.2 amp.

LAMC =	7050.	7120.	7250.
TEMP =	2043.	2022.	1986.
PD CHISQ	3.19E+00	2.96E+00	3.38E+00
PD COEF	1.32E+11	1.52E+11	2.00E+11
PM CHISQ	2.81E+00	2.50E+00	2.99E+00
PM COEF	1.71E+09	1.99E+09	2.62E+09
AV PM GN	7.68E+01	7.66E+01	7.63E+01

PHOT MULT SCALE FACT IN PHOTO ELECT/SEC PER NANOAMP

03FIB003	7.718E+01	7.695E+01	7.653E+01
03FIB002	7.881E+01	7.860E+01	7.821E+01
03FIB004	7.378E+01	7.361E+01	7.329E+01
03FCG001	5.115E+04	5.103E+04	5.081E+04
03FIV027	7.753E+01	7.752E+01	7.752E+01

The agreement among the four filters is very good after having chosen a single fudge factor to make the shape of the photomultiplier spectrum agree with the shape of the photodiode spectrum. The fits to C and to G C are not used in calculating the gains for the individual filters. The agreement is now so good that a simple average is appropriate and gives 77 photoelectrons per nanoamp. The average photocathode efficiency is also down very slightly for the Bradner Gaussian used in Sec. D and gives 0.171 instead of 0.178. The net result is 448 photons per nanoamp instead of 438 as in Sec. D. This difference is clearly too small to be worth exploring.

IV. CONCLUSIONS

The conversion from anode current to photons per second for the TTR-3 cruise is 440 ± 70 photons per second per nanoamp.

V. ACKNOWLEDGEMENTS

We wish to express our gratitude to Prof. John Holmes and to Prof. Robert Hardie for helpful discussions.

FOOTNOTES AND REFERENCES

1) The Photomultipliers used were 5 inch diameter EMI tubes with bialkali photocathodes. The tube used for TTR-3 was one of the tubes which had been evaluated over the past several years by the Irvine Group.

2) WHAT WE CAN PREDICT ABOUT SHAPES OF BIOLUMINESCENT SPECTRA. Note from Hugh Bradner, 7/10/83. References to David Karl, presentation to DUMAND collaboration meeting, 6/28/83, and to George Wilkins, Biology and the DUMAND Experiment, pp543-470 in DUMAND 1976. (Proceedings of the Hawaii Summer Workshop.)

3) Preliminary Report Ocean Light Levels at 1600 Meters Depth.C. E. Roos, S. Matsuno, M. Webster, D. O'Conner, G. Blackinton, V.G. Stenger, K. McArthur June 1, 1983 DUMAND Internal Report

4) United Detector Technology,3939 Landmark St., Culver City, CA 90230 Photodiode PIN 10D/SB, Calibration Certificate 95268, 25 Feb. 81. We actually determined the temperature dependence of the photomultiplier without taking the photodiode into the cold room, but we called the manufacturer (213-978-0516) and obtained the following information about the change in responsivity (amp per watt) of the photodiode:

> Upon cooling the photo diode from 22°C to 15°C, the responsivity increases as follows, for λ = 390 nm, R increases 2.5%; for λ = 450 nm, R increases 1.5%; for λ = 560 nm, R increases less than 1%.

5) Reference on Box to hold filters- Dan or Vince fill in. It is great, but I don't know who made it or designed it. We should express our appreciation for a job well done.

6) Filters and attenuators were obtained from Melles Griot, Arnhiem, Ca. A phone call to the technical staff confirmed that filter type 03FCG001, which is an ultraviolet filter, does in fact show transmission above 700 nm.

7) Model 245C Irradiance Standard bulb, Optronic Laboratories, Inc. 7676 Fenton Street, Silver Spring, Maryland 20910. The bulb is rated at 140 footcandles for the design current of 6.50 amps. In order to

reduce the light output, we have used the bulb at 3.00 and at 4.20 amps. If we knew the voltage at 3 and at 4.2 amp, we could see if the power supplied is consistent with the power radiated. $(2224/1668)^4 = 3.16$. Does the resistance increase by a fator of 1.6? Seems reasonable, but I neglected to measure it.

V	I	Pow
1.89	3	5.67
3.57	4.2	14.99

1.35 measured

no 2.64

2.64 average 1.19

8) <u>Attenuation of Cerenkov Photons in the Ocean</u>, John Learned, Memo HDC 81-10, 4-81. The shape of this curve is in good agreement with curves published by EMI[9] above 450 nm, and is about 10% higher than the curves from EMI in the region of 350 to 400 nm. The EMI curves are for quartz windows, so the curves diverge below 350 nm where absorption in the window is the dominant effect for our tube.

9) The curve shown in Fig. 3 and the paragraph which are reproduced were taken from pages 5 and 8 of a technical brochure <u>EMI Photomultipliers</u> which was copright by EMI Industrial Electronics LTD in 1979.

10) Vince told me that some of the papers he had been reading on bioluminescence made claims about the care needed in measuring temperature dependence of the apparatus. I did not keep the reference. If Vince has it, we can put it in. If not we can simply omit this reference. It isn't essential to our argument, but it sounds "scholarly".

FIGURE CAPTIONS

Fig. 1. Sketch of box which holds filters, light source, attenuators, and photodiode. The photodiode can be removed and the box sealed to the light tight box in which the photomultiplier is tested. The cathode of the photomultiplier is about 6 inches below the 1 cm^2 aperture which replaces the photodiode. The colored filters are mounted in a wheel so that any one can be positioned in the light path.
(note to Dan and Vince: Obviously we could have used smaller filters and the proposal to purchase new filters from Corion Corp. is for 1 inch diameter filters.

Fig. 2. Plots of several important quantities as a function of wavelength. The left axis is the photoelectron conversion efficiency for our photocathode and is taken from an internal report by Learned[8]. The right axis is the calibration curve of the photodiode, converted to nanoamps per photon. The region below 600 nm is taken from the measured calibration curve for our photodiode[4] and the region above that is taken from general curves in the product description brocure for the 10 DB/541 Silicon Photodiode by the same manufacturer. The approximate pass bands of the five filters which we used are shown and are within the calibration portion of the photodiode curve. The remaining three curves are plots of the emittance of a black body at three temperatures: 1800°, which corresponds to the approximate temperature of the filament of the bulb at 3.00 amps; 2400°, which corresponds to the approximate temperature of the filament with 4.20 amps; and 2800°, the normal temperature of the filament of a tungsten bulb. Note that lowest temperature curve has been multiplied by 100 to permit plotting it with the other two. The form of the curves is:

$$L(\lambda)d\lambda = \left(\frac{10\ 000.}{\lambda}\right)^4 \frac{1.}{e^{(\lambda_c/\lambda)} - 1} \qquad \lambda_c = \frac{h\ c}{k\ T} = 1.44\ 10^7/T$$

The factor 10 000 simply gives values in a convenient range; the correct Planck normalization is not applicable here because we do not accept the full solid angle and because we do not know the area of the emitting surface. Note, however, that the normalization needed to apply this formula to our aperture in the light box is independent of the temperature.

Fig. 3(a) Graph of typical electronic gain for phototube and (b) paragraph on thermal sensitivity of tubes. Taken from an EMI publication[9].

Fig. 4(a) Photomultiplier anode current, I, vs optical density, od, of attenuator.

(b) The same data plotted as fractional deviations from the curve $I = dc + I_o\ 10^{-od}$ where $I_o = 1.12\ 10^7$ nanoamps and dc is adjusted for each data set. This fitted value is given on the figure along with the definition of symbols used in plotting.

Fig. 5. Photocathode efficiency from Learned[8] and as modified by the factor $1.0-0.00283*(\lambda-450.)$.

20 Aug 83
Marty Bartlett
3 amps - very red hard to see — like embers of dying fire
4.2 yellow much easier to see

~~Melles et~~
Melles Griot
Anaheim Calif.

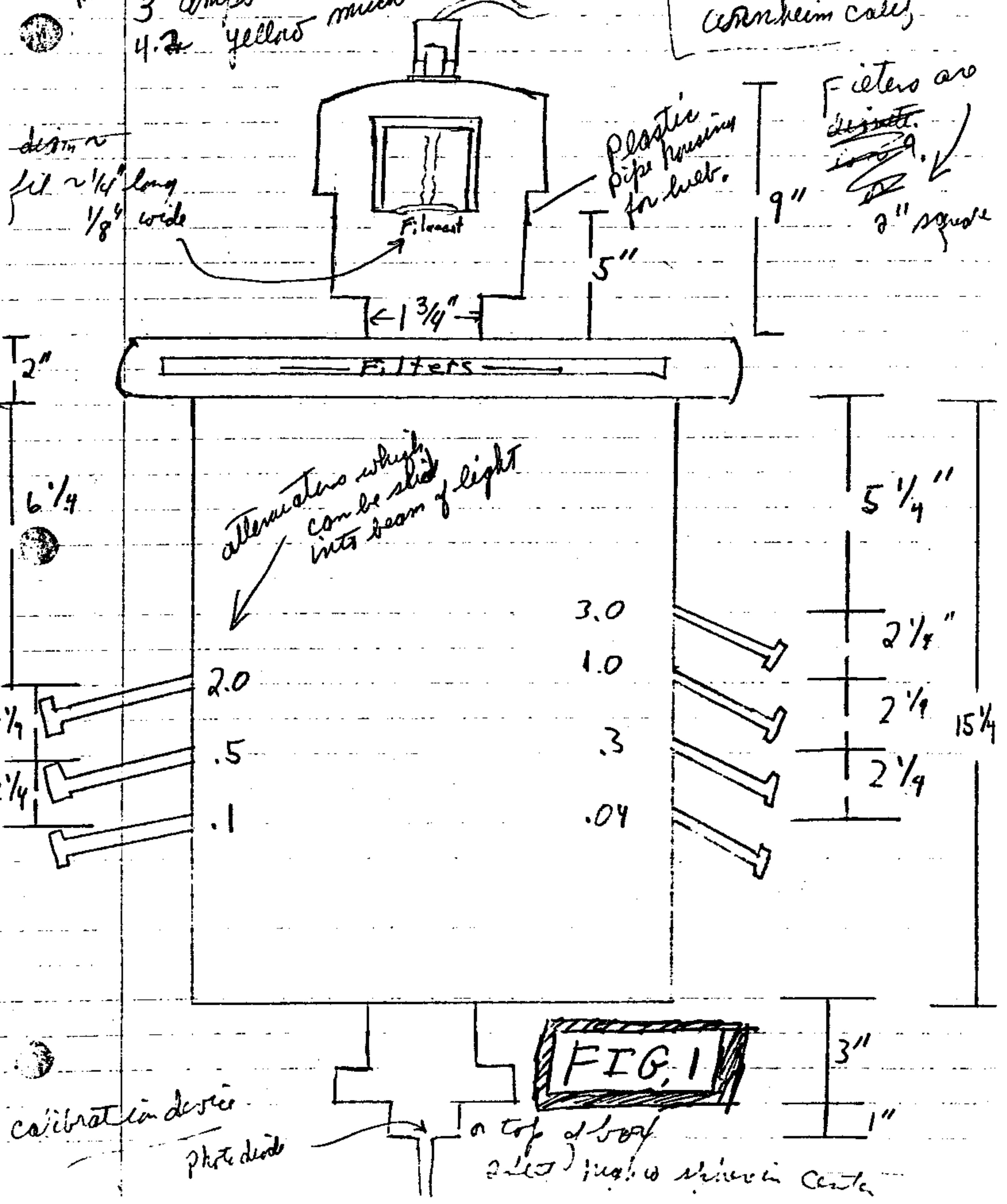

FIG. 1

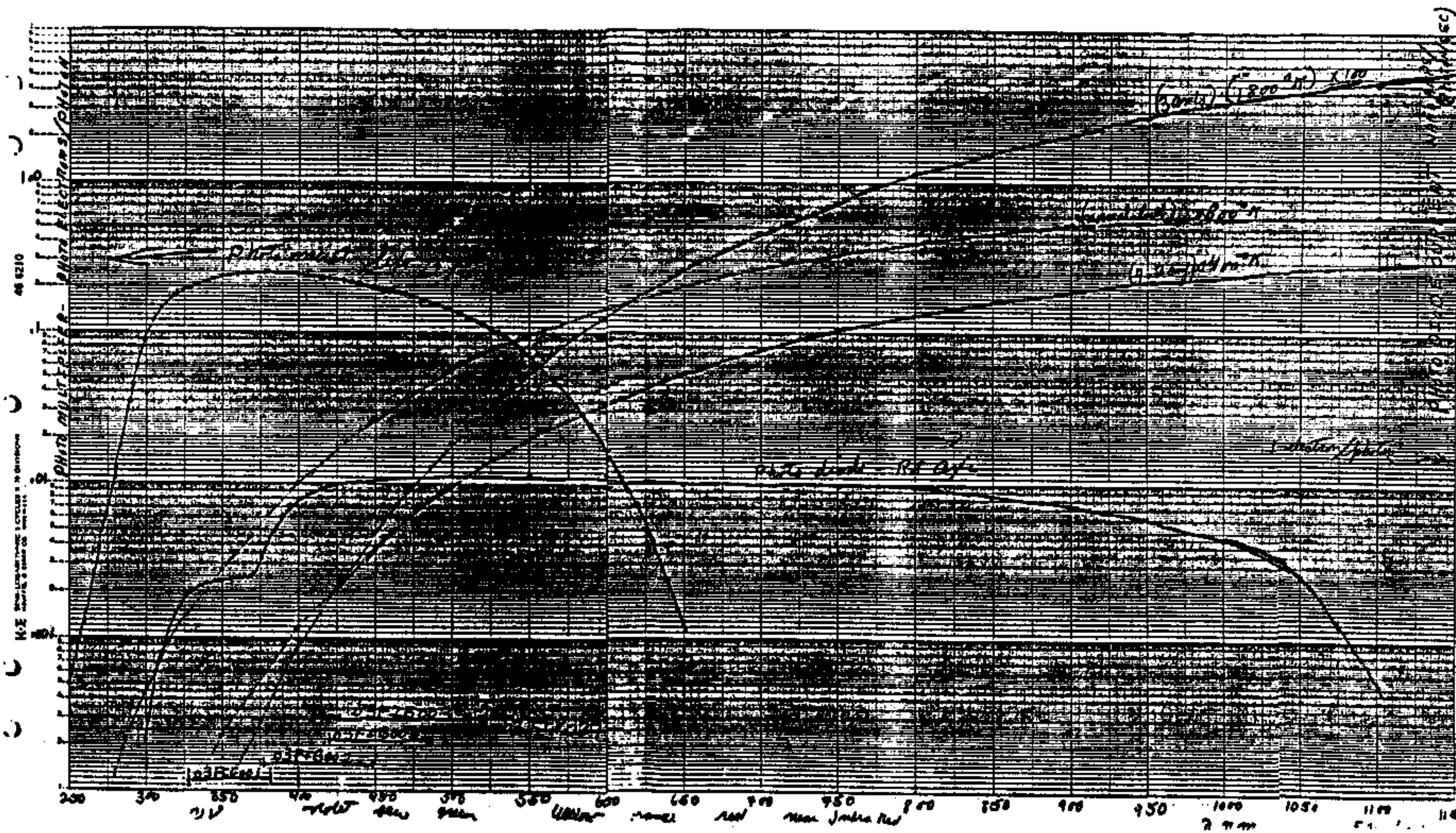
PHOTO MULTIPLIER- PHOTO ELECTRONS/PHOTON
1.0
.1
.01
.001
200
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
UV
violet
blue
green
yellow
orange
red
near Infra Red

Fig 2

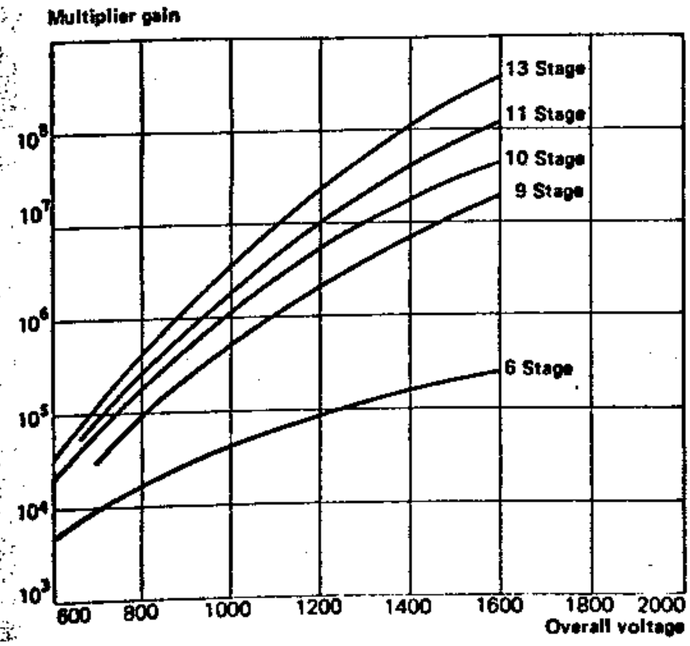

FIG. 6 Gain versus overall voltage for multipliers with various numbers of SbCs stages.

a

8.5 Thermal Effects

The spectral response and the cathode sensitivity vary with temperature. Temperature co-efficients generally reported are incomplete and discordant, with measurements varying between ±0.1 to 1.0% $^{\circ}C^{-1}$. In critical applications, therefore, it is necessary to determine the temperature co-efficient for the particular photomultiplier used and allow for it. The alternative is to use a temperature stabilized housing, details of which can be sent on request.

b

Fig. 3.

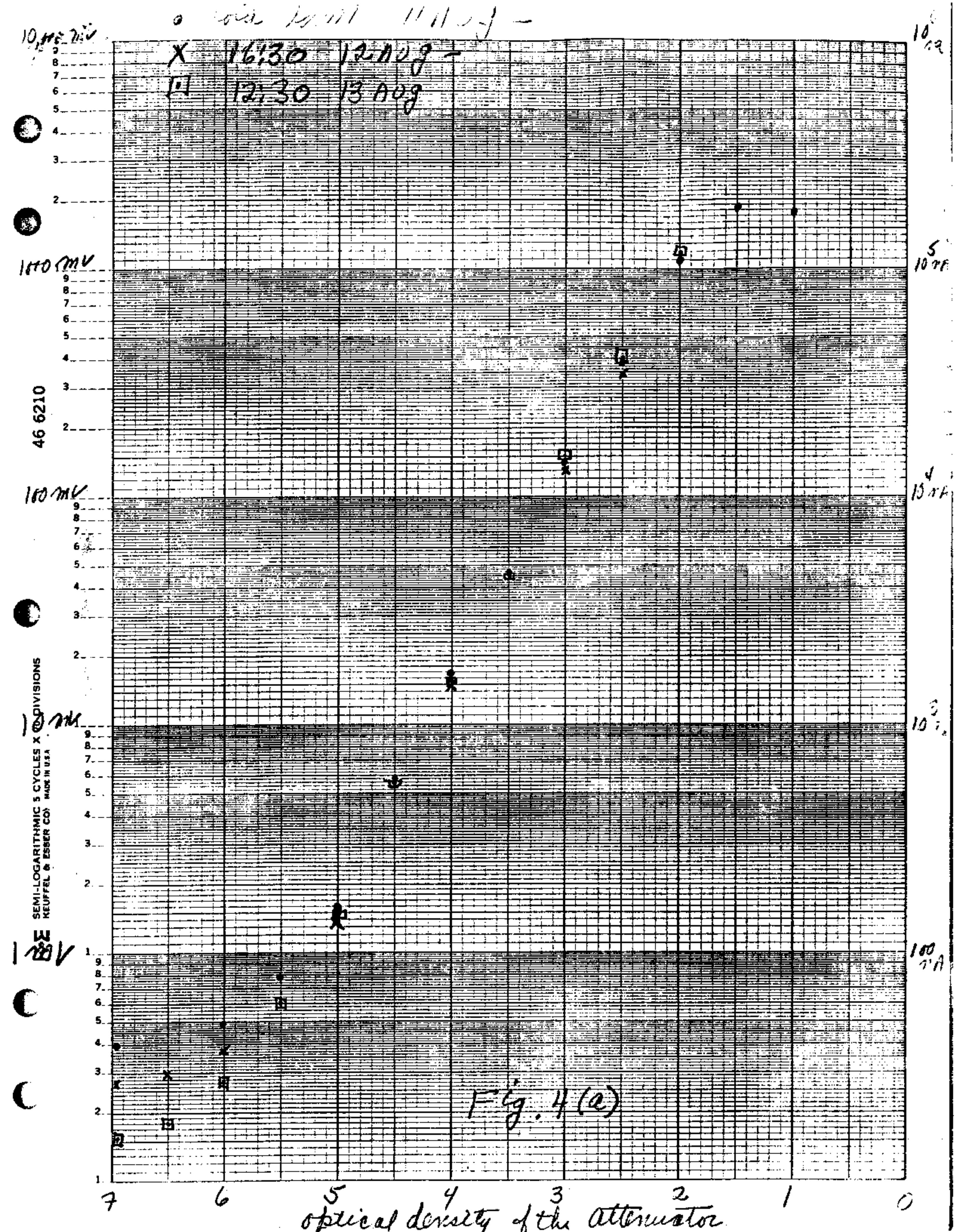
X 16:30 12 Aug
12:30 13 Aug
10 mV
100 mV
10 mV
1 mV
10^6
10^5 nA
10^4 nA
10^3 nA
100 nA
7
6
5
4
3
2
1
0
optical density of the attenuator
SEMI-LOGARITHMIC 5 CYCLES X DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6210

Fig. 4(a)

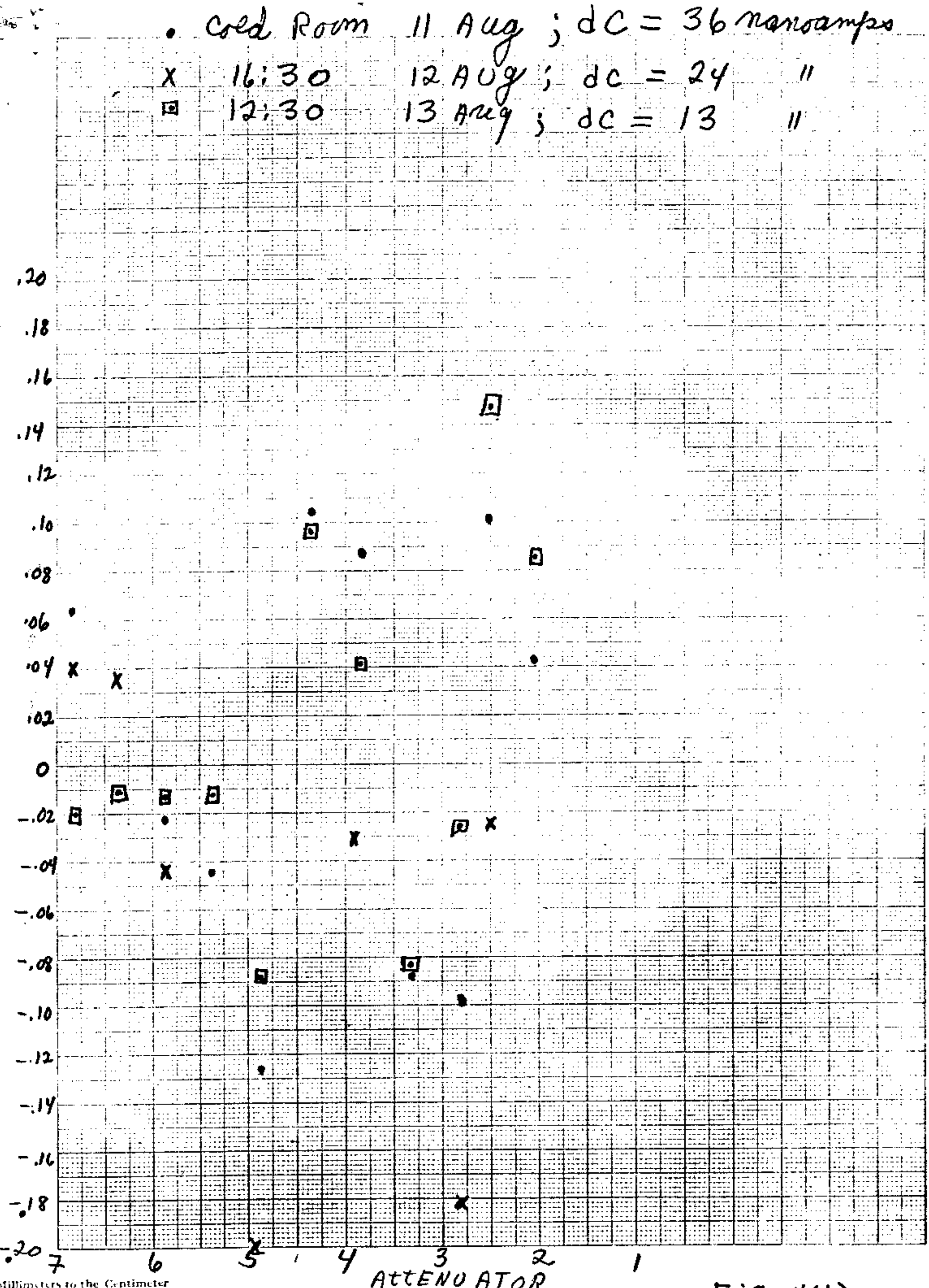
• Cold Room 11 Aug ; dC = 36 nanoamps
X 16:30 12 Aug ; dC = 24 "
⊡ 12:30 13 Aug ; dC = 13 "
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
-.02
-.04
-.06
-.08
-.10
-.12
-.14
-.16
-.18
-.20
7
6
5
4
3
2
1
ATTENUATOR
10 Millimeters to the Centimeter

Fig. 4(b)

Fig. 5.

Photo Cathode Efficiency

• Seamed's Curve 8

X Seamed's curve modified to obtain agreement with the photo diode at 4.2 amps