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REQUIREMENTS FOR PHOTOMULTIPLIERS FOR DUMAND.

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ABSTRACT

We discuss the way in which the requirements of the DUMAND array affect the characteristics and design of the photomultipliers required. The size, sensitivity, background requirements, lifetime and other characteristics are considered. A summary describes the requirements concisely.

This paper lists and discusses the requirements for the PMT's needed for the DUMAND detector, as we now understand them. Some of these have already been discussed in some detail[1]. The requirements are sufficiently unusual to require a special PMT; the number of tubes required (1000 or more) is sufficient to warrant the design of a new type. This paper should not be regarded as a formal specification; it is intended as a general guide for PMT manufacturers interested in DUMAND.

It should be noted that there is at present no guarantee that the DUMAND detector will be constructed.

1.0 INTRODUCTION

The primary requirement for the DUMAND PMT is very high sensitivity. The DUMAND array is a lattice of PMT's designed to detect neutrino interactions. The larger the array, the more sensitive the experiment. It is consequently desirable to have as many detectors as one can afford, and to space them as widely as possible. The achievable lattice spacing depends upon the transparency of the ocean to Cerenkov light produced by the neutrino interactions, and also upon the sensitivity of the individual PMT sensors. It is accordingly highly desirable for the PMT's to be large, and as sensitive as possible. We have adopted as a measure of PMT sensitivity the number of photoelectrons delivered to the first dynode when the cathode is illuminated by a light flux of 100 quanta/m^2.

2.0 PHYSICAL CHARACTERISTICS.

The PMT is to be used at great depths in the ocean - up to 6 km - and must consequently be protected against hydrostatic pressure to about 600 atmospheres. This may be achieved either by a pressure-tolerant envelope or the use of an external pressure-tolerant transparent protective envelope. At this pressure only glass or ceramics are satisfactory; plastics creep. The largest presently available glass pressure container is a 17" O.D. (16"I.D.) Benthos[2] sphere, consisting of two hemispheres that seal together to form the envelope. Unless an economical source for larger spheres can be found, this limits the largest PMT that can be used to an O.D. of 16 inches.

A hemispherical cathode 16" in diameter has a radius 20.3 cm. Allowing a 3mm glass wall, we find an effective cross-section area perpendicular to the polar axis of $\pi \times 20^2$ cm^2 or 1256 cm^2. The response to a photon flux of 100 quanta/m^2 is then

$$N_e = .1256 \times 100 \times \varepsilon$$

where

N_e is the number of photoelectrons produced, and
ε is the average cathode efficiency, including collection efficiency.

At ε=.25, N_e = 3.14; and at ε=.20, N_e = 2.5. Computer simulations of DUMAND calculations have indicated that N_e = 2.5 is a satisfactory sensitivity, if we require a minimum of two electrons for a trigger, and 3.0 if a 3-electron trigger is used. A minimum of 2.5 is thus required, and implies a phototube of about 16" diameter.

The spectrum of light incident on the PMT from the source is that of Cerenkov light, as modified by absorption in the ocean. Fig. 1 (from Ref. 4) shows a plot of that spectrum, which quickly narrows down to the range 400-520 nm. Consequently, for low noise and high sensitivity, the choice of a bialkali cathode is indicated.

2.1 Uniformity of Cathode: Isotropy.

One function of the PMT is to distinguish small signals in the presence of noise. The PMT will be subject to continuous random background light, almost all at the single-quantum level; we need to distinguish events with two photoelectrons from the background of single-electron noise. The signals we seek will produce larger pulses as well; but we have no requirement for good uniformity of pulse height (as e.g. for gamma-ray spectrometry). Thus DUMAND has no special requirement for cathode uniformity of response; the requirement will be for high average sensitivity.

Ideally it would be desirable to have the PMT sensitivity independent of the direction of the incoming light. For a hemispherical tube, one expects the sensitivity to vary as a function of polar angle with the PMT axis. It would reach a maximum at $\theta = 0^\circ$, along the PMT axis, and about half as much at 90°. As shown in Fig. 2, if the envelope is transparent, appreciable sensitivity over the total solid angle should be present. For DUMAND purposes the variation over all angles should not exceed a factor of two. Other geometries (a spherical photomultiplier or a cylindirical photomultiplier) may be acceptable, but as of now, a hemispherical-cathode tube seems most practical, and should yield acceptable angular sensitivity variation.

3.0 TYPES OF PMT BACKGROUND.

The DUMAND PMT presents a unique design problem. We want to trigger on infrequent, very short (ns), signals from a weak, diffuse light source; the signals may produce a total of 250 individual sensor triggers per second, comprising perhaps 25-50 events. These must be detected in the presence of a background that includes three major components, all much stronger than the signal: PMT noise, Cerenkov light from natural radioactivity in the ocean, and occasional interference from bioluminescent organisms. We consider these in turn, though not in the same order.

3.1 Bioluminescence.

The light from bioluminescent organisms is not expected to be a serious background, even though few measurements of it at the relevant depths or location exist. In the first place, few organisms of any sort are expected, because of the absence of any plant life in the eternal darkness of the depths. Available food includes the resident lifeforms, and the detritus that falls from above; and the major life forms resident at these depth are expected to include one-celled biota, and worms that live in the sediment. However, occasional visitors from lesser depths can be expected, especially if there are flashing lights, sheltering structures, and sources of heat.

The time scale of bioluminescent flashes from large organisms is such that flashes have risetimes of many milliseconds. The shortest risetime we have heard quoted is about 50 microseconds for bacterial colonies. These are all too long to be confused with the nanosecond Cerenkov signals. The intensities may be high enough to temporarily jam nearby sensors; but the frequencies of such events are not so great as to give serious alarm.

3.2 PMT Noise.

It is to be expected that PMT noise will consist of a spectrum of pulse heights, of which the greater part will be single electrons from thermionic emission by the photocathode. In bialkali cathodes at the ambient temperature expected - 0^{o} C. - a good bialkali cathode will have a thermionic emission rate of not over 10 electrons/cm^2 sec. As we will see, this is considerably lower than the rate produced by the external K^{40} signal.

Another component of tube noise consists of delayed large pulses due to positive ions produced by the accelerated photoelectrons, either in the residual gas, from the first dynode, or from the electron multiplier. These will be accelerated in the opposite direction and strike the cathode. On the average a positive ion will produce several photoelectrons[3], and thus the PMT will exhibit the phenomenon of afterpulsing; the presence of large pulses delayed a few microseconds from an initiating signal. It is not clear whether all large pulses arise in this way, but certainly a large fraction do. Such afterpulses of large size will prove to be critical in the performance of PMT phototubes for DUMAND.

3.3 Background light from K^{40} in the Ocean.

Of the many radioactivities present in ocean water, the only one of serious concern to DUMAND is that due to the potassium content; all potassium on earth contains a small amount of the isotope K^{40}, which has a lifetime of something under a billion years. It concerns us because it is a potent beta-emitter, its electrons producing in seawater, on the average, 43 Cerenkov quanta between 300 and 650 nm per disintegration. Consequently the ocean is everywhere a weak light-source, and it can be shown[4] that if the ocean transparency is such that the attenuation length for light at the wavelength of peak transparency is 25 meters -i.e. 25m water - a flux of about 120 quanta/sec cm^2 is present. At a mean cathode efficiency of 20%, this will produce a background rate of 24 photoelectrons/sec cm^2 from the photocathode. Since most decays are far away, the probability of two photons from the same disintegration striking the photocathode is small, and the background will consist mostly of single photoelectrons; there will be, however, a small but significant number of true two- or more electron counts from the K^{40}.[5]

The sum of tube noise and K^{40} background will be a net single-electron background rate of about 30-40/sec cm^2. Since a 16" hemispherical cathode has an area of 2610 cm^2, the expected single-electron background rate will be around 100K/sec. In addition, the large afterpulse rate will be 1/2 to a few percent of this amount, if we extrapolate from the behavior of present tubes, or 500-2500 counts per second.

4.0 REDUCTION OF PMT BACKGROUND.

The weak diffuse Cerenkov light produced by muons or neutrinos must be detected in the presence of the backgrounds just discussed. For that purpose we must first set a threshold signal of at least two photoelectrons reaching the first dynode, or the K^{40} background will swamp us. Our arrays have been designed to date on the assumption of a two-electron trigger. If the threshold were three photoelectrons, the array spacing might have to be decreased.

Elimination of the single-electron background is in itself not necessarily the complete answer to our problem. The residual rate of large pulses, due to the tail of internal tube noise, estimated above at several thousand per second, is also a serious difficulty.

4.1 Required Degree of Background Reduction.

The obvious and simplest mode of generating an array-wide event trigger is as follows: open a gate, whose duration is the transit time through the array, whenever a suitable sensor trigger is received, and declare an event trigger if within the gate time the proper number of sensor triggers is received. For a 500m array, the maximum transit time for a muon is of the order of two microseconds. An acceptable tentative event trigger may therefore be defined as at least k sensor triggers within 2 microseconds. The number k and the threshold for sensor triggering will have to be adjusted to keep the gate rate G at a tolerable level. Computer simulations indicate a desirable value of k=3.

4.2 Elimination of Single-Electron Background.

The usual method of discriminating against small background pulses is the use of pulse-height discrimination at the PMT output. With conventional dynodes the separation between 1, 2, 3..etc. photoelectrons is imperfect; Wright[6] estimates that 30% of the single-electron counts remain if the discriminator is set to accept all two-electron pulses. It would be hopeless to try uniquely to select two-electron pulses from a strong one-electron background. The problem can be much ameliorated - even solved, in principle - if a sufficiently high-gain first dynode is used. Existing tubes with high-gain first dynodes[7] provide much improved discrimination between one- and two-electron signals. Unfortunately, with the very high background we have, this procedure does not appear practical for us, especially in view of the fact that manufacturers tell us that high-gain first dynodes are difficult and expensive to produce in tubes with large dynode apertures. We therefore seek another method to reduce the single-electron background by the required factor of 100 to 1000, while losing as little as possible in sensitivity.

The light signals we detect are due to diffuse light, and consequently the photons that strike the PMT are uniformly and randomly distributed over the cross-section presented to the incident beam by the cathode. If we require two photoelectrons for a trigger, they will originate from uncorrelated and separate locations on the tube face.

4.2.1 Segmentation of multiplier structure and anode.

Another potential method of eliminating the single-electron background is through segmentation of the multiplier structure and the anode. If the multiplier consists of m separate segments, each isolated from all others so that the multiplication of any photoelectron is confined to a single segment, then separate anodes on each segment will contain signals from independent electrons. A single-electron initiating signal will produce only one output anode signal; two independent simultaneous input electrons in different segments will produce two simultaneous output signals. Signals due to two initial electrons can then be recognized by requiring a coincidence between any two output anodes. If there are m segments, there will be a loss of 1/m of the true event rate by the accidental coincidence of the two initiating electrons in the same segment. Depending on the geometry of the dynodes, there may also be some loss due to crossover from one segment to another. Leakage between segments is tolerable to the extent that it does not unduly increase the random coincidence rate between segments.

The required multiplier property, of segregating each cascade to a single segment, we will refer to as confinement. This procedure is of course particularly applicable to micro-channel plate (MCP) multiplier structures. For traditional tubes it may mean multiple dynode stacks, or conceivably, one dynode stack with a segmented anode.

4.2.2 Calculation of Single-Electron Background.

If the total single electron counting rate is R, and the resolving time for coincidences between segments is τ,, then the rate R_c of random coincidences between any two segments will be

$$R_c = m(m-1)/2 \times 2(R/m)^2\tau$$

$$= (m-1)/m \times R^2\tau$$

which is almost independent of m for large m. For the value $R = 1.0 \times 10^5$/sec, $\tau = 10^{-8}$sec, the random coincidence rate is

$$R_c = (m-1)/m \times 100/\text{sec}.$$

Without segmentation, the background rate would be tens of thousands per second.

4.3 True two-fold triggers from K^{40}.

Those K^{40} disintegrations that occur very close to the photocathode can occasionally produce true coincidences of two or more electrons. Their number has been calculated[5] in DUMAND Note 81-19, and for the 16" PMT is in the vicinity of 120/sec, just under 10^{-3} of the singles rate. We will reconsider this quantity when we consider background reduction.

4.4 Background Summary.

The contributing components of the background will be

1. True twofolds from K^{40}.
2. Random background from single K^{40} counts; reduced by coincidences if segmentation is used, by pulse-height discrimination alone if it is not.
3. Large background pulses occurring in more than one segment.

Our present estimates for Nos. 1 and 2 are respectively 120/sec and 100/sec, assuming segmentation. The third depends too much upon tube design to estimate. It must obviously be minimized.

5.0 TIMING ACCURACY.

Uniformity of collection time over the entire photocathode is clearly desirable; minimizing time jitter will decrease the resolving time for eliminating random twofold coincidences between segments, and will improve true event reconstruction accuracy. On the basis of computer simulations, we set a maximum FWHM on the output pulse in the vicinity of 10 nsec. Experience indicates that this is an achievable resolution at the single-photoelectron level.

6.0 LIFETIME AND GAIN.

It is desirable that the DUMAND array operate for ten years without the failure of more than 10% of the sensors. This requires a mean lifetime of 100 years for the PMT's. This requirement is unprecedented; it is difficult to measure or predict lifetimes in this range.

There is no obvious reason why most PMT's, properly treated, should not last indefinitely, following an initial burn-in of several hundred hours. Experience at Fermilab, CERN, and elsewhere indicates that conventional PMT's, so treated, do indeed have lives of the required order. However, experience to date with MCP's in PMT's has been that lifetime has been limited. Recent work seems to indicate that this can be ameliorated - perhaps even eliminated - by covering the MCP with a thin coat of aluminum[8]; this seems to eliminate the positive ion bombardment of the cathode that shortens its life.

MCP plates also seem to have a lifetime defined by the total charge transmitted by the plate. When this reaches values of the order one coulomb/cm^2, significant gain losses are observed. It seems possible that the gain can be restored by raising the voltage, and since we have no absolute signal requirements, this procedure would be acceptable. Reducing the overall gain demanded from the MCP would also increase the lifetime. It is to be hoped that some combination of such procedures will achieve the desired longevity.

7.0 SUMMARY.

We summarize the required properties of the DUMAND PMT as follows:

1. Size: Approximately hemispherical photocathode to fit inside 16" I.D. glass sphere.

2. Spectral sensitivity: Bialkali cathode or equivalent, with uniform and high sensitivity in the range 400 - 500nm.

3. Sensitivity: the average number of photoelectrons reaching the first dynode when the cathode is uniformly illuminated (wide beam) along the axis by a flux of 100 quanta/m^2 should be at least 2.5, preferably 3.

4. Uniformity of cathode sensitivity: not critical. Average cathode quantum efficiency (including collection efficiency) from 400 nm to 520 nm at least 20%.

5. Angular variation of sensitivity. There should be no gaps in angular coverage; it is desirable that the ratio of maximum to minimum response not exceed 2 (see Fig. 2). If the tube is of the hemispherical type it should not be silvered on the back hemisphere.

6. Tube noise: not to exceed 10 electron/sec cm^2 of cathode, at 0^oC. Large pulse (>1 photoelectron) signal-induced background to be minimized: preferably not over 1% of total counting rate.

7. Means must be found to decrease the single-photoelectron rate by a factor of 100 to 1000. Possible methods include pulse-height discrimination, with a high-gain first dynode, and/or segmentation. In the latter case a segmented anode is required with 6 to 15 segments. If parallel dynode structures are used, or a single dynode structure with segmented anodes, crossover between segments must be minimized. An MCP multiplier would satisfy this requirement ideally, provided it meets the other requirements.

8. The transit time of electrons through the PMT must be such that single photoelectron pulses shall have an output FWHM time jitter not to exceed 10-12 nsec. Tails of the time distribution should be minimized.

9. The lifetime of the tube under the specified operating conditions should be about 100 years; methods for specifying and measuring lifetime need to be agreed upon. The tube will be operated in an environment of 150-200 photons/cm^2 sec continuously.

10. The overall gain of the PMT under conditions satisfying requirement 6 shall be at least 10^6. A gain of 10^8 is desirable, since then no amplifier would be needed.

11. Magnetic Field Sensitivity. The tube must operate with no magnetic shielding whatever, in the earth's magnetic field. Variation of sensitivity with orientation will be unavoidable.

12. Output linearity is not important. In fact, for large pulses (> about 5 electrons) a logarithmic response would be desirable.

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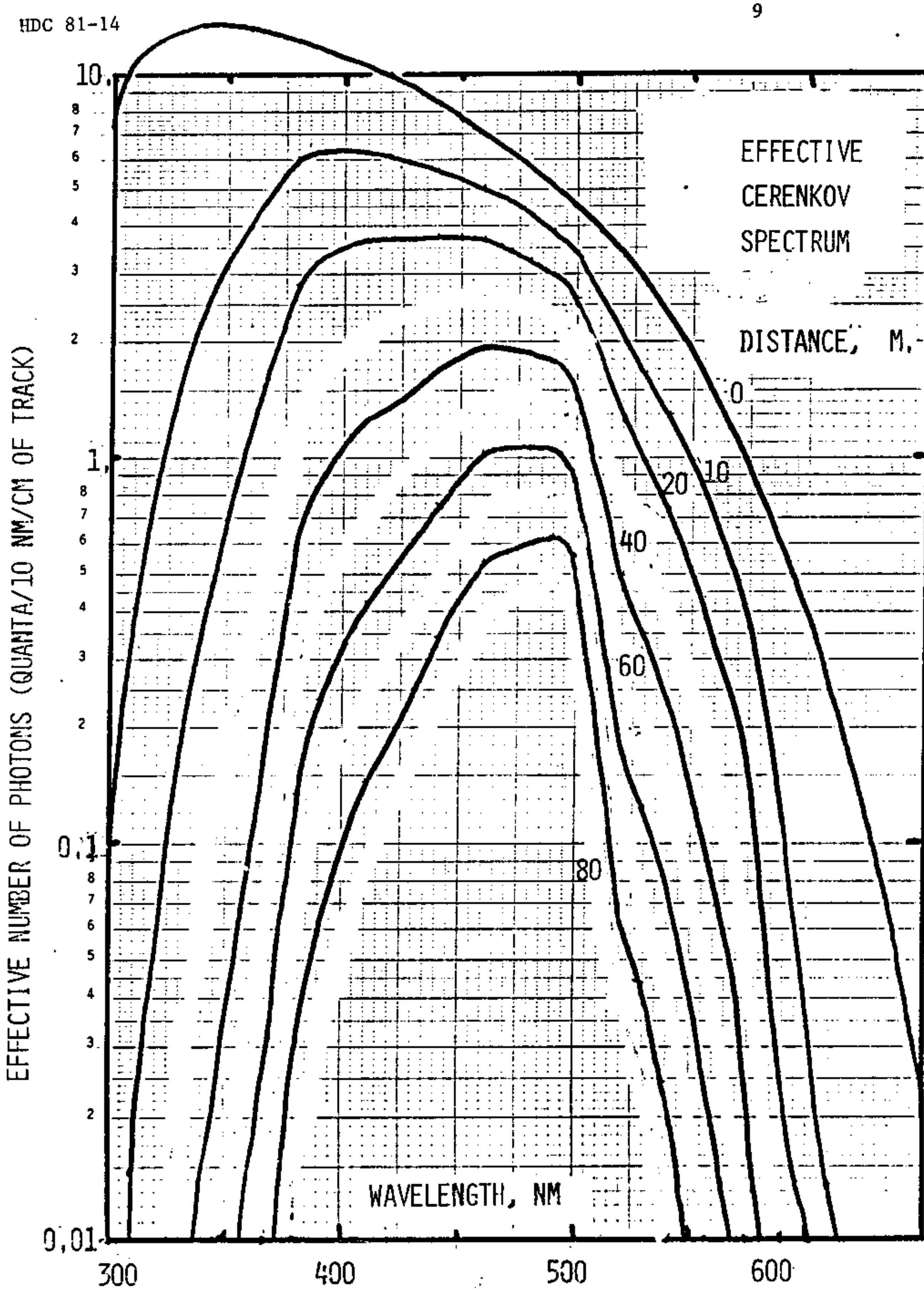

Fig. 1. Effective intensity variation of the Cerenkov spectrum with distance from the source, in water with 25m attenuation length; water and glass attenuation, PMT spectral sensitivity included. From Ref. 4.

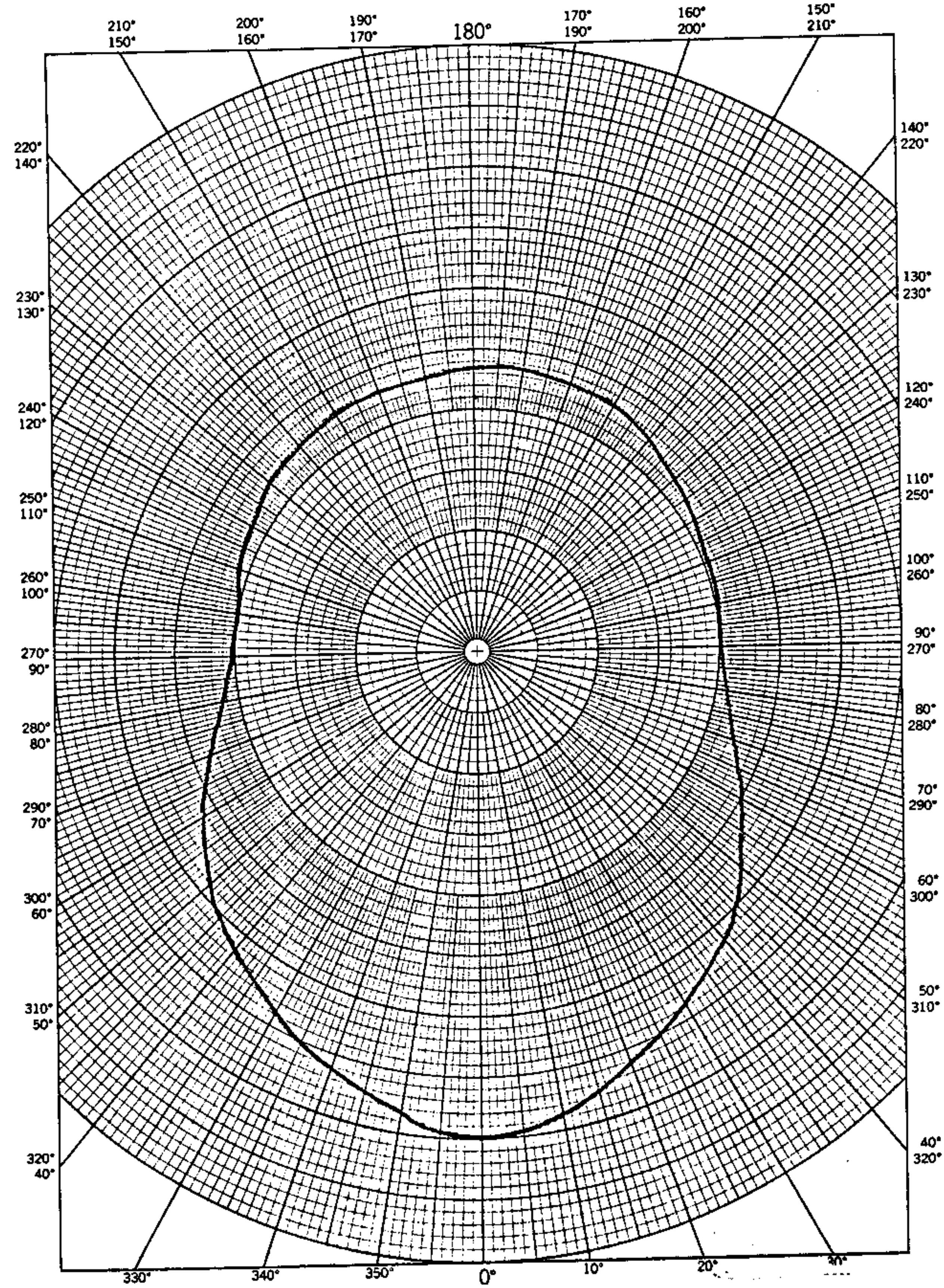

Fig. 2. Hypothetical variation of sensitivity with angle of a hemispherical-cathode PMT, measured with parallel beam of light wider than the PMT. There should be no gaps in the coverage. Polar angle is measured from PMT axis.

Addendum to HDC 81-14.

Since this report was written, HDC 81-15 has appeared. That report modifies some of the conclusions of the present paper, and the following supplement indicates how the conclusions of 81-14 should be changed.

1.0 Allowable Background Rate.

The major problem in DUMAND PMT design is getting rid of the K^{40} background. In this report, 81-14, we saw no feasible way of accomplishing that, aside from segmentation of the multiplier structure. In 81-15, it is shown that by raising the trigger threshold to three photoelectrons and using a high-gain first dynode, with uniformly high collection efficiency, the K^{40} background can perhaps be reduced to manageable proportions. While this is not an easy task to accomplish, it offers at least in principle an alternative to segmentation.

Raising the trigger threshold is not desirable; it reduces the effective sensitivity of the PMT and requires the array to have closer spacing than would otherwise be necessary. Investigation of that effect shows it to be tolerable. Fig. 5 of report 81-15 indicates the degree of contraction required: from a spacing of 50 x 50 x 22.7m to 45 x 45 x 17.5m.

The requirement for low noise can perhaps best be stated as follows: When operated in the ocean, where the expected K^{40} counting rate of single photoelectrons is expected to be about 10^5/sec, it must be feasible to reduce the total residual noise plus signal counting rate to ~1000/sec, by either setting the pulse-height discrimination threshold no higher than at three photoelectrons, or by segmentation and coincidence background reduction.