NEAR-INFRARED SENSITIZED PHOTOCATHODES AND FILM SENSITIVITIES FOR TYPICAL XENON-LAMP RADIATION AND RELATED SUBJECTS[1]

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ABSTRACT

Weighting or assessment factors of near-infrared photocathodes and Kodak 5424 film are determined for xenon-lamp illumination. These values are important for selecting detectors and determining the basic sensitivity for a given situation and instrumentation; for example, in medicine, when obtaining retinal pictures. Some other typical applications are also discussed. Charts showing the radiation from a xenon-arc lamp, with a 0.5 mm arc length and 800 watt input, and the typical efficiency values of photocathodes and film to xenon-lamp radiation are presented at spectral intervals of 20 nm for the range of 400 to 1100 nm, with and without Kodak Wratten filter 89b.

INTRODUCTION

Several new types of photo-emitters are now marketed which not only perform excellently in the visible region, but also possess considerable sensitivity to radiation within the near-infrared portion of the spectrum. These photo-emitters, having a broader spectral response than has been achieved before, are of quite some interest for imaging instrumentation for laboratory set-ups, medical investigations, and other purposes. An object to be detected may show brightness differences in its detail in the near-infrared spectrum but not in the visible, or vice versa, or in both, where the polarity of this contrast may reverse for the different spectral regions. These new near-infrared extended photocathodes permit experimentation with a larger variety of filters than older types not covering as wide a spectral range. Thus not only is contrast improved but selection of a more perceivable contrast polarity may also be possible in some cases.

When investigating phenomena having a sudden change in color and intensity, as for example explosions, which are accompanied by temporal as well as spatial temperature distributions, taking a sequence of pictures with a broad-band photodector, by utilizing a series of appropriately staggered spectral filters, would provide a sequence of images from which blackbody temperatures could be approximated (Gebel, 1969a and 1969c). Highly sensitive infrared image-converter tubes are needed in the medical field, in industrial health care, and for insurance claims, as can be seen from the following typical examples.

During certain eye examinations, for example, highly intense visual radiation has to be used for illumination, which would result in contraction of the pupil after 0.25 seconds (pupil delay time), but is usually prevented by paralyzing the muscles operating the pupil. This paralysis of the eye muscles typically persists for 24 hours and usually causes various discomforts and incapacitation to the patient. If this paralysis of the pupil is to be avoided, a photographic record of the condition of the retina has to be made in a time shorter than the pupil delay time, by utilizing a short flash of light. If optoelectronic means are used, an electronic storage tube must be employed for allowing instant and extended observation. To allow direct dynamic observation of the condition of the retina over an extended time, it would be advantageous to use infrared radiation, because the human eye does not detect this radiation and the pupil would not contract. Therefore, by employing a near-infrared sensitive converter tube, the patient would not experience bad after-effects as is the case following the present conventional

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examination. This would be especially welcome to personnel who, because of exposure to adverse conditions in their work, are required to take examinations repeatedly, which now results in renewed discomfort and incapacitation.

The use of such red extended photocathodes in image-converter tubes, with appropriate spectral filters in front of them timed sequentially and also with synchronously timed colored filters between the reproduced image on a white phosphor screen and the observer, allows reproduction of near-infrared scenes in color. Such a set-up may allow better and faster interpretation of details in the observed scene than could be achieved by normal black-and-white near-infrared image systems. In a laboratory set-up, the reproduced color in no way has to coincide with the natural color, because the main purpose of such a set-up is to improve scene discrimination; color fidelity in many such applications is of very little interest. It is not necessary to use a three-color set-up; a two-color arrangement, reproducing different spectral regions of the near-infrared in different colors, or the near infrared in red and the visible spectrum in blue, may be quite useful. Conversely, it may be of advantage to construct a simultaneous system by employing a beam-splitter arrangement in front of a large-sized image intensifier, thus placing two or more images side by side, or to utilize any usable pattern on the photocathode. The image reproduced on the phosphor screen, being oriented there in a suitable pattern, may be photographed on black-and-white film and analyzed individually, or the images, using appropriate color filters in front of each, may be combined optically to obtain a photographic record on color film (Gebel, 1958). In such a system, a phosphor-screen which produces white light, would have to be used for the last reproducer screen. Another image-reproduction possibility, which avoids these filters, is the dividing of the output screens into several sections covered with appropriate phosphors which produce the different colors. Thus, for example, when using green for the visible and red for the near-infrared light, depending on the intensity ratio between the visible and the near-infrared, any color located at the periphery of the color triangle between green and red may be reproduced (Gebel, 1964). In addition, many other applications and arrangements are conceivable.

Progress has also been made in the field of photographic emulsions sensitive to the visible radiation as well as to the near-infrared. Thus, it is of interest to compare the sensitivities of photo-emitters with that of near-infrared-extended photographic film. However, in order to compare the performances of the different available photo-emitters with that of near-infrared film from a practical point of view, their performances should be considered when using an illumination of practical interest. Because high-powered xenon-lamps that can be pulsed are readily available and provide a sufficiently broad spectral coverage (Engelhard Hanovia, Inc.) which adequately matches the spectral sensitivity distribution of the new improved photo-detectors, weighting factors are furnished in this paper for such illumination for the state-of-the-art of photo-emitters and film sensitive to the visible as well as to the near-infrared. The data are presented by spectral intervals, thus allowing easy comparison and evaluation. Utilizing these data, the design engineer may conveniently compute the numerical values for any suitable filter. As an example, the numerical values for Wratten-filter 89b (Eastman Kodak Company, 1965), which has a spectral transmittance as shown in Figure 1, and which suppresses the visible portion of the xenon-lamp radiation, are tabulated in this paper.

CONVERSION EFFICIENCY OF SIGNIFICANT INFRA-RED EXTENDED PHOTO-EMITTERS

The spectral conversion factor η_{PC} of the most significant near-infrared extended photocathodes which are marketed are shown in Figure 2. These data were calculated from the sensitivity, S_{PC} in A W^{-1} incident radiation, using internationally accepted spectral response values (Electron Tube Division—ITT, Ft.

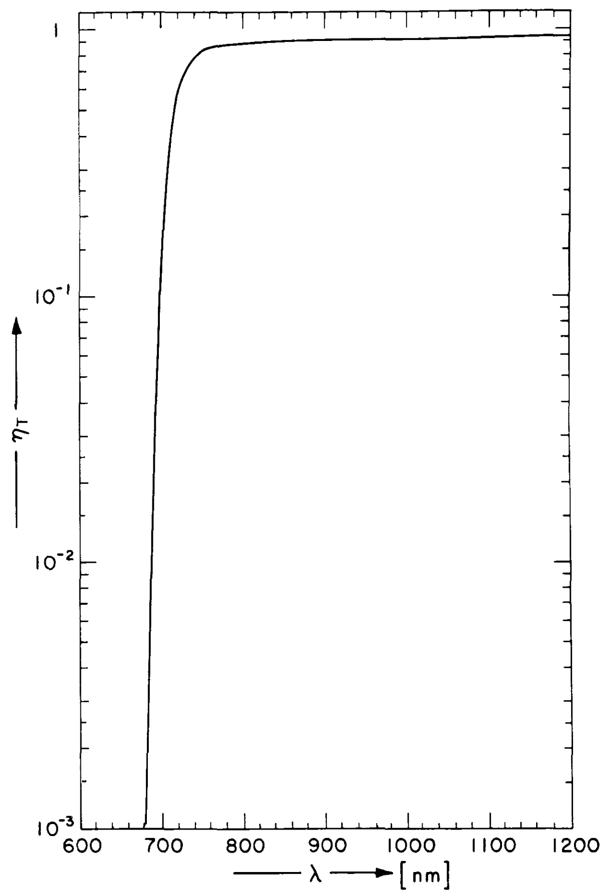

FIG. 1. SPECTRAL TRANSMITTANCE η_T OF KODAK WRATTEN FILTER 89b.

Wayne). Since one ampere equals 0.624×10^{19} electrons per second, and the energy E_Q in joules of one quantum is given by the relation

$$E_Q = hc/\lambda = 1.98631 \times 10^{-25} \lambda^{-1}, \tag{1}$$

then the flux Q, in quanta s^{-1} corresponding to the power N_Q in watts at wavelength λ, is given by

$$Q = \frac{N_Q}{E_Q} = \frac{\lambda N_Q}{1.99 \times 10^{-25}} = 5.034 \times 10^{24} \lambda N_Q, \tag{2}$$

where λ is in meters. Hence, for the spectral conversion factor η_{PC}, in electrons per quantum incident to the photocathode, the relation

$$\eta_{PC} = 6.24 \times 10^{18} S_{PC} \times 1.99 \times 10^{-25} \lambda^{-1} = 1.24 \times 10^{-6} \lambda^{-1} S_{PC} \tag{3}$$

is found.

The term "quantum efficiency", as used by physicists, expresses a number of events, for example electrons emitted per quantum absorbed by a photodetector, and is of no particular interest here, and thus is not further treated in this paper. Normally, only the average number of events a detector will yield resulting from the average number of events incident to a device are of interest in engineering sciences, a value called the "conversion efficiency". However, the term "quantum efficiency" is often used incorrectly for the term "conversion efficiency", which can cause considerable confusion, as shown by the following example. A photocathode may have a conversion yield η_{PC} of 20%, but a quantum efficiency η_Q of 80%, which, by the terminology accepted by the physicists, means that for 100 quanta incident to the device, an average of 20 eletrons is emitted; out of the 100

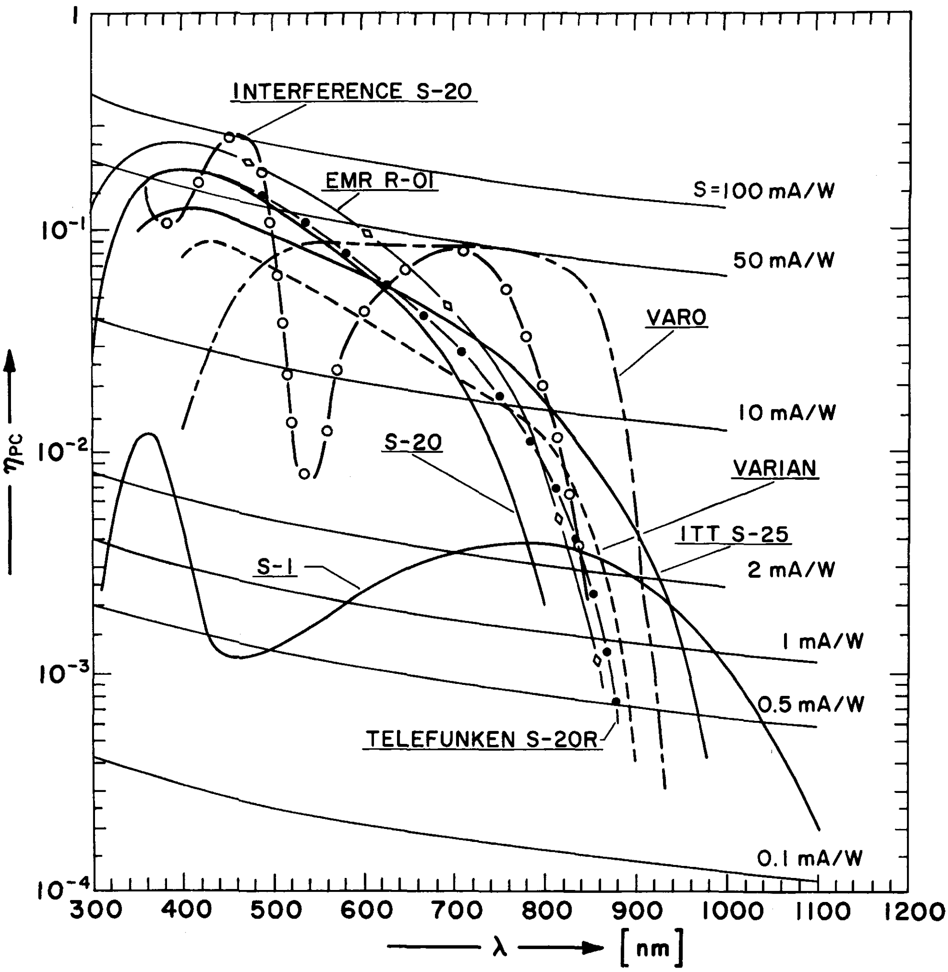

FIG. 2. SPECTRAL CONVERSION FACTORS η_{PC} OF REPRESENTATIVE PHOTOCATHODES: SENSITIVITY S AS PARAMETER.

incident quanta, 25 were absorbed and these resulted in the 20 emitted electrons. Thus, the ratio of 20 electrons to the 25 absorbed quanta yields a quantum efficiency η_Q of 0.8 and an absorption factor η_A of 0.25. Knowing η_{PC}, η_Q, and η_A permits determination as to whether there is a reasonable possibility of improving the performance of a particular photocathode. If, for example, a semi-transparent photocathode has $\eta_{PC}=0.2$, $\eta_A=0.25$, and $\eta_Q=0.8$, achieving unity of η_Q would only improve η_{PC} to 0.25, assuming that the other factors were not changed. So the absorption factor η_A would have to be increased by reducing reflection or by increasing the thickness of the photocathode. Increasing the thickness of the photocathode, however, may not increase the conversion factor η_{PC}, because the quantum efficiency η_Q will usually be lower, and then the result is a lower η_{PC}. This decrease of η_Q is usually caused by the fact that the excited electrons, having to travel through a thicker or denser layer, may lose too much of their energy before reaching the physical vacuum-photocathode boundary where emission occurs. In other words, only a certain thickness of the photocathode will assure optimum η_{PC}. These facts are utilized in interference photocathodes, where a high absorption factor is obtained without having to increase the thickness of the photocathode to such an extent that too many electrons will have lost too much of their excitation energy before having reached the physical vacuum-photocathode boundary (Deutscher, 1958; Kossel, 1961).

Because the dark current of photocathodes varies considerably in different production runs, especially for photocathodes of the S–1 type, it is difficult to collect enough representative data on this subject. Actually, the dark current can be practically eliminated if proper cooling of the photocathode is achieved, so the dark current is neglected in this paper. Under this assumption, the basic detection capability of photocathodes is governed by the conversion noise (Gebel, 1964).

CONVERSION EFFICIENCY OF KODAK 5424 NEAR-INFRARED SENSITIVE PHOTOGRAPHIC FILM

Manufacturers usually express the sensitivity of a film emulsion by the amount of energy per unit area (i.e., erg cm^{-2}) needed to achieve a certain density. However in order to compare the basic detection capability of photographic film with that of image intensifiers using a photocathode as the primary detector, the spectral conversion yield of the photographic emulsions, that is, the average number of photographic grains resulting from a certain number of incident quanta, must be known.

For determining the conversion yield by means of mathematical derivations, the average grain size must be known (Gebel and Duke, 1967a; Gebel, Duke, and Mestwerdt, 1967b). The average grain size and the conversion efficiency as a function of density and other pertinent factors were investigated by the authors for the near-infrared sensitized film emulsions Kodak 5218 and 5424 (Gebel, Hayslett, and Mestwerdt, 1968a). It was found that, for a developing time of 12 minutes and using Kodak developer D–19, the average grain size of Kodak 5424 near-infrared film is $3.8\times10^{-6}mm^2$. This should be taken as a typical value only and may vary considerably, due mostly to differences in development conditions, variations in production runs, and counting accuracy. The data for the Kodak 5424 emulsion will be used in this paper for comparison with the photocathodes, because this emulsion has a very good sensitivity for near-infrared radiation, is available on the open market, and has a reasonable lifetime even when stored at room temperature.

If the spectral sensitivity S_L of the film is expressed in ergs cm^{-2}, then the conversion efficiency η_L of the film emulsion, in grains $quantum^{-1}$, is given by

$$\eta_L = \frac{1.99\times10^{-22}\left(\frac{1}{10^{D_F}} - \frac{1}{10^{D}}\right)}{\lambda S_L A_g} \qquad (4)$$

(Gebel and Duke, 1967a; Gebel, Duke and Mestwerdt, 1967b), in which A_g equals $\pi d_L^2/4$ and is the average grain size in m^2, d_L is the average grain diameter in m, D is the total density, and D_F is the fog density of the emulsion. Using this equation for Kodak 5424 near-infrared film yielded the graph shown in Figure 3, which shows the spectral conversion factor η_L as a function of the wavelength, with D as parameter [$D = 1.0$ (D–19); $D = 0.3$ (H–110, $A = 4.75 \times 10^{-6}$ mm^2)].

The basic limit in contrast detection at threshold density is mainly determined by the unavoidable deviations in the number of background grains per resolution

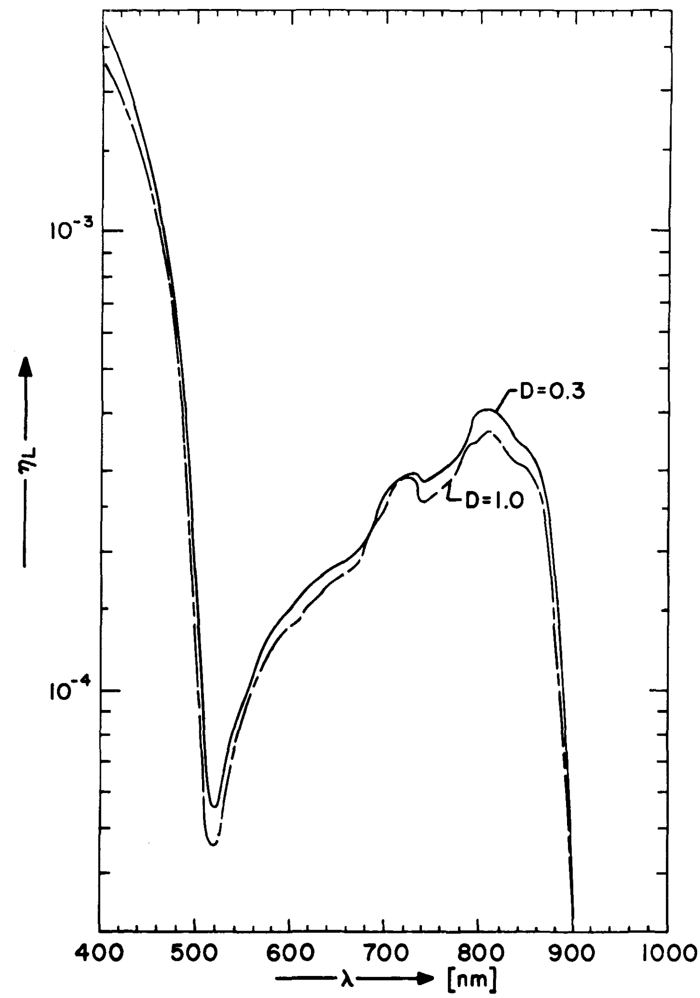

FIG. 3. SPECTRAL CONVERSION FACTORS η_L OF KODAK NEAR IR FILM 5424: DENSITY D AS PARAMETER.

element, and at higher densities by the deviation in the number of grains occurring in equally exposed resolution elements. In addition, for an effective conversion yield of $\eta_L \ll 1$ but under otherwise ideal conditions, the spatial and temporal statistical deviations in the numbers of grains cannot be less than that of a Poisson distribution; i.e., the standard deviation from the average number of grains is the square root of the average, and clearly the larger the average number, the smaller the statistical percentage deviation (Gebel, 1968b). However, because of inhomogeneities in the film emulsion and certain effects occurring during the development, the above ideal detection limit is not feasible and can only be more or less approached. Nevertheless, it is customary and appropriate, in opto-electronic calculations, to use as the detection limit the spatial and temporal standard deviation of a Poisson distribution in the number of photoelectrons, neglecting any other noise effects (Gebel, 1968b).

THE SENSITIVITY WEIGHTING OR ASSESSMENT FACTORS AFFECTING XENON RADIATION

The sensitivity of representative photocathodes and of film of the state-of-the-art are analyzed in this paper, as stated in the introduction, assuming radiation from a xenon-lamp as illumination. Since light from a xenon lamp has an irregular but continuous spectrum (Engelhard Hanovia, Inc.; Oliver and Barnes, 1969), the spectrum of the representative lamp used for this paper was divided into 20-nm (nanometer) intervals and the integrated percentage power fraction P_X and quantum flux Q_X were tabulated, as given in Table 1. The spectral distribution curves of xenon-lamp radiation at lower current densities usually show a considerable amount of energy in the near-infrared region (Oliver and Barnes, 1969). An increase in the current density may favor the visible and the ultraviolet regions at the expense of the near-infrared radiation (Goncz and Newell, 1966) and predominant spectral bands in the near-infrared may become less distinct. This paper is concerned only with xenon-lamp radiation which is temporally stable in its spectrum (as shown in Table 1) or with radiation similar to that. The data presented by Oliver and Barnes (1969) indicate that the spectra of pulsed-flash lamps are sufficiently similar to dc-operation, if reasonable current densities are used, so that the tables of this paper can be used for pulsed-flash lamp operations. The pulse-forming network must be designed in such a manner that the current is kept effectively within a range which assures full use of the favorable spectral distribution of the arc during the pulse time.

From equation (2), and using the midmost point of the interval values λ_{av} for the wavelength,

$$Q_X = 5.034 \times 10^{22} \lambda_{av} P_X, \tag{5}$$

where QZ (as tabulated in Table 1) constitutes the total radiation flux of the lamp per watt of electrical input to the lamp. When using these values, not only as spectral weighting factors but also for calculating any particular scene illumination, normally only a fraction of these values will have to be used, mostly depending on the optical arrangement and lamp configuration (Engelhard Hanovia, Inc.).

The pertinent photocathode-output weighting factors $I_{PC,X}$ (no filter) and $I_{PC,X,T}$ (for filter 89b) in mA $W^{-1}_{\text{input-Xenon}}$, applying to the quantum flux Q_X (no filter) and $Q_{X,T}$ (filter 89b), respectively, in quanta s^{-1} $W^{-1}_{\text{input-Xenon}}$ falling within the selected spectral intervals are given by

$$I_{PC,X,(T)} = \frac{Q_{X,(T)} \eta_{PC,av}}{6.24 \times 10^{15}} = 1.6021 \times 10^{-16} Q_{X,(T)} \eta_{PC,av}. \tag{6}$$

The factor $\eta_{PC,av}$ is the average photocathode conversion yield for the interval under consideration. Numerical values for $Q_{X,(T)}$ are listed in Table 1 and values for $\eta_{PC,av}$ may be obtained from the spectral conversion factor η_{PC} (fig. 2) by averaging the boundary values of the interval used. The weighting factors $I_{PC,X,(T)}$ for typical state-of-the-art photocathodes are tabulated by 20-nm intervals in Tables 2a and 2b.

TABLE I. RADIATION FROM A HANOVIA COMPACT XENON ARC LAMP WITH A 6.5 mm ARC LENGTH AND 800 WATT INPUT.

SPECTRAL INTERVAL Λi $\lambda 1$ to $\lambda 2$		XENON ARC LAMP RADIATION			
		Fraction of Input Power	Total Quanta Flux	Fraction of Input Power	Total Quanta Flux
		NO FILTER		WRATTEN FILTER 89b	
$\lambda\ [\times 10^{-9}m]$		P_X [%]	Q_X $\left[\frac{10^{17}\text{Quanta/s}}{W_{\text{Input-Xenon}}}\right]$	$P_{X,T}$ [%]	$Q_{X,T}$ $\left[\frac{10^{17}\text{Quanta/s}}{W_{\text{Input-Xenon}}}\right]$
400	420	0.59	0.122		
420	440	0.65	0.141		
440	460	0.70	0.159		
460	480	0.86	0.203		
480	500	0.69	0.170		
500	520	0.73	0.187		
520	540	0.72	0.192		
540	560	0.68	0.188		
560	580	0.69	0.198		
580	600	0.82	0.244		
600	620	0.88	0.270		
620	640	0.89	0.273		
640	660	0.94	0.308		
660	680	0.97	0.327		
680	700	0.98	0.340	0.035	0.012
700	720	0.96	0.343	0.334	0.119
720	740	0.86	0.316	0.588	0.216
740	760	0.85	0.321	0.699	0.264
760	780	0.83	0.322	0.714	0.277
780	800	0.70	0.278	0.613	0.244
800	820	0.72	0.294	0.636	0.260
820	840	1.46	0.610	1.456	0.609
840	860	0.81	0.347	0.723	0.309
860	880	0.61	0.267	0.547	0.239
880	900	1.94	0.869	1.744	0.782
900	920	2.05	0.939	1.847	0.843
920	940	1.66	0.777	1.499	0.702
940	960	1.81	0.866	1.638	0.783
960	980	0.72	0.352	0.653	0.319
980	1000	3.33	1.660	3.027	1.589
1000	1020	0.95	0.483	0.865	0.440
1020	1040	0.82	0.425	0.749	0.388
1040	1060	0.92	0.486	0.842	0.445
1060	1080	0.89	0.479	0.816	0.440
1080	1100	0.99	0.543	0.910	0.499
400	1100	35.67	14.948		
680	1100	24.86	11.318	21.364	9.778

The analogous film-emulsion weighting factors G_X (no filter) and $G_{X,T}$ (filter 89b) in grains s^{-1} $W^{-1}_{\text{input-Xenon}}$ is given by

$$G_{X,(T)} = Q_{X,(T)}\eta_{L,av}, \tag{7}$$

where $\eta_{L,av}$ is the average film-conversion efficiency and may be obtained from the spectral values in Figure 3. The weighting factor $G_{X,(T)}$ of the Kodak 5424 near-infrared film in response to xenon-lamp illumination is tabulated by spectral intervals in Table 3.

TABLE 2a. TYPICAL EFFICIENCY VALUES OF PHOTOCATHODES IN RESPONSE TO COMPACT XENON ARC LAMP RADIATION.

SPECTRAL INTERVAL Δi λ1 to λ2		PHOTOCATHODE TYPES: STANDARD (a) S-1	STANDARD (a) S-20	TELE-FUNKEN (b) S-20R	INTER-FERENCE (c) S-20	VARIAN 80/40 INTENS. (d)	EMR (e) E-01	EMR (e) R-01	ITT (f) S-25	VARO 25mm INTENS. (g)
λ [x10^{-9}m]		$I_{PC,x}$ [10^{-4}mA/W$_{input-Xenon}$]								
400	420	54	3829	3829	2712	1663	4593	4828	2516	353
420	440	31	4257	4257	4378	2064	4970	5309	2843	667
440	460	29	4398	4398	6707	2233	5095	5604	2999	1144
460	480	36	5038	5038	8887	2629	6179	6830	3570	2012
480	500	32	3808	3808	5210	2006	4698	5175	2762	1993
500	520	40	3712	3887	1451	1990	4644	5243	2782	2483
520	540	46	3366	3600	328	1825	4306	4922	2655	2718
540	560	51	2890	3077	315	1608	3765	4367	2383	2711
560	580	61	2688	2878	756	1515	3489	3965	2313	2829
580	600	86	2827	3052	1417	1668	3714	4300	2623	3444
600	620	106	2717	2970	2079	1672	3677	4109	2653	3784
620	640	121	2402	2680	2649	1554	3171	3718	2491	3916
640	660	145	2162	2455	3372	1518	2862	3577	2479	4230
660	680	167	1827	2254	3966	1437	2253	3039	2412	4462
680	700	186	1489	1960	4459	1337	1798	2615	2217	4618
700	720	196	1113	1608	4560	1200	1484	2088	1968	4704
720	740	189	728	1161	3891	984	962	1519	1601	4300
740	760	199	490	932	3208	875	797	1183	1445	4250
760	780	199	295	732	2282	765	593	929	1245	4067
780	800	171	136	476	1137	565	379	535	892	3351
800	820	174		356		482	283	283	747	3393
820	840	350		470		730	489	313	1241	6424
840	860	189		149		255	211	72	536	2895
860	880	136		51		105	111		314	1166
880	900	403					70		737	1697
900	920	388							553	371
920	940	275							311	
940	960	255							205	
960	980	84							38	
980	1000	314								
1000	1020	69								
1020	1040	43								
1040	1060	35								
1060	1080	25								
1080	1100									
400	1100	4885	50172	56072	63764	32680	64593	74523	51529	77982
		WEIGHTING FACTORS REFERENCED TO THE VARO PHOTOCATHODE (=1)								
400	1100	0.063	0.643	0.719	0.818	0.419	0.828	0.956	0.661	1

(a) Standard curves published by ITT.
(b) AEG-Telefunken, Ulm
(c) Westinghouse, Elmira
(d) Varian Associates, Palo Alto
(e) EMR, Div. of Inst., A. Schlumberger Co., Princeton
(f) ITT-IL, Fort Wayne
(g) Varo Inc., Garland, Tex.

COMPARISON OF THE BASIC PHOTOCATHODE AND FILM SENSITIVITIES

In order to obtain a true "figure of merit" (similar to the "detective quantum efficiency") for photocathodes and for film, many factors must be considered, such as conversion noise, dark current, proper voltages for the photocathode, and proper storage conditions for the films to keep the fog level at a minimum. However, this paper is not concerned with the determination of such a figure of merit, but rather considers a comparison factor $M_{PC/L}$, which expresses the basic detection capability of different devices in respect to each other by comparing the number of primary species (electrons, photographic grains) obtained by the conversion process.

Since the weighting factors in Tables 2a and 2b are expressed in mA $W^{-1}_{input\text{-}Xenon}$ these values must be converted into the pertinent number E_{PC} of electrons s^{-1} $W^{-1}_{input\text{-}Xenon}$ in order to be able to compare the basic capability of photocathodes with that of film. This is done by multiplying these values by the factor 6.2418×10^{15}, as the unit 1 mA constitutes this rate of electrons $\sec^{-1}$. The comparison factor $M_{PC/L}$ may be expressed by

$$M_{PC/L} = \frac{6.2418 \times 10^{15} I_{PC,X,(T)}}{G_{X,(T)}} = \frac{E_{PC}}{G_{X,(T)}}. \tag{8a}$$

By using the above definitions and considering the total interval of 680–1100 nm, the figure-of-merit ratio of the Varo, Inc., photocathode to film, for $D_\Delta = 1$, is given by

$$M_{Varo/film} = \frac{2.88 \times 6.24 \times 10^{15}}{7.76 \times 10^{13}} \sim 232. \tag{8b}$$

The illumination for a typical set-up for investigating dynamic events is presented in the following example. It is assumed that the instrumentation requires constant visual observation and that, for analyzing a specific time interval of the dynamic event, a gated recording system, which is synchronized with the individual pulses of a light source, is required. Recording thus occurs effectively only during a sufficiently short flash of light, resulting in a smear-free record. During a single flash of light, the image-converter tube may be gated several

TABLE 2b. TYPICAL EFFICIENCY VALUES OF PHOTOCATHODES IN RESPONSE TO COMPACT XENON ARC LAMP RADIATION THROUGH KODAK WRATTEN 89b FILTER

SPECTRAL INTERVAL Λ_i $\lambda 1$ to $\lambda 2$		PHOTOCATHODE TYPES: STANDARD (a) S-1	STANDARD (a) S-20	TELE-FUNKEN (b) S-20R	INTER-FERENCE (c) S-20	VARIAN 80/40 INTENS. (d)	EMR (e) E-01	EMR (e) R-01	ITT (f) S-25	VARO 25mm INTENS. (g)
λ [$\times 10^{-9}$m]		$I_{PC,X,T}$ [10^{-5}mA/W$_{Input-Xenon}$]								
680	700	68	512	681	1639	475	634	923	784	1679
700	720	659	3635	5287	15230	3980	5148	7245	6517	15767
720	740	1295	4948	7903	26544	6717	6575	10382	10931	29390
740	760	1638	4024	7659	26340	7192	6556	9728	11870	84935
760	780	1715	2524	6300	19628	6587	5103	7988	10711	34994
780	800	1499	1195	4169	9963	4952	3323	4691	7819	29365
800	820	1543		3149		4262	2499	2499	6601	29985
820	840	3108		4180		6481	4878	3122	11019	57043
840	860	1694		1336		2275	1881	644	4786	25827
860	880	1222		457		942	996		2814	10450
880	900	3623					626		6627	15258
900	920	3500							4986	3342
920	940	2484							2810	
940	960	2313							1842	
960	980	770							346	
980	1000	2860								
1000	1020	633								
1020	1040	396								
1040	1060	326								
1060	1080	230								
1080	1100									
680	1100	31576	16838	41121	99344	43863	38219	47222	90463	288035
		WEIGHTING FACTORS REFERENCED TO THE VARO PHOTOCATHODE (=1)								
680	1100	0.110	0.058	0.143	0.345	0.152	0.133	0.164	0.314	1

(a) Standard curves published by ITT.
(b) AEG-Telefunken, Ulm
(c) Westinghouse, Elmira
(d) Varian Associates, Palo Alto
(e) EMR, Div. of Inst., A. Schlumberger Co., Princeton
(f) ITT-IL, Fort Wayne
(g) Varo Inc., Garland, Tex.

TABLE 3. TYPICAL NUMBER OF GRAINS OF KODAK NEAR IR FILM 5424 IN RESPONSE TO COMPACT XENON ARC LAMP RADIATION WITH AND WITHOUT KODAK WRATTEN 89b FILTER

SPECTRAL INTERVAL Λi $\lambda 1$ to $\lambda 2$		KODAK NEAR IR FILM 5424 IN RESPONSE TO TOTAL XENON LAMP RADIATION			
		NO FILTER		WRATTEN FILTER 89b	
		Values of η_L used for intervals correspond to:			
		D=0.3	D=1.0	D=0.3	D=1.0
$\lambda\ [\times 10^{-9} m]$		$G_X [10^{13} Grains\ s^{-1} W^{-1}_{Input-Xenon}]$		$G_{X,T} [10^{13} Grains\ s^{-1} W^{-1}_{Input-Xenon}]$	
400	420	3.067	2.605		
420	440	2.607	2.377		
440	460	2.059	1.936		
460	480	1.628	1.512		
480	500	0.488	0.461		
500	520	0.149	0.136		
520	540	0.126	0.109		
540	560	0.176	0.158		
560	580	0.238	0.219		
580	600	0.338	0.316		
600	620	0.433	0.390		
620	640	0.476	0.435		
640	660	0.574	0.535		
660	680	0.662	0.614		
680	700	0.810	0.780	0.0293	0.0282
700	720	0.967	0.941	0.3365	0.3275
720	740	0.922	0.883	0.6304	0.6037
740	760	0.933	0.852	0.7670	0.7003
760	780	1.011	0.933	0.8700	0.8025
780	800	1.018	0.936	0.8924	0.8200
800	820	1.185	1.054	1.0474	0.9313
820	840	2.285	2.032	2.2764	2.0240
840	860	1.158	1.049	1.0327	0.9358
860	880	0.670	0.599	0.6001	0.5325
880	900	0.637	0.564	0.0573	0.0507
400	900	24.616	22.425		
680	900	11.598	10.624	8.540	7.757

times and, during the blanking time, the image may be deflected into a new position, so that a sequence of images can be obtained (Reed, 1961). The experimental set-up may be illuminated by a constant room light-source for the visual observations, and a pulsed xenon-lamp with a suitable filter such as the Wratten 89b filter may be used as the IR source for delivering single or repetitive pulses (the filter is necessary to prevent the observer from being annoyed by the flashes). For the calculations in this paper, it is assumed that the attenuation factor

$K_{X,S}$ of the light delivered by the xenon lamp is 10^{12}, thus $K_{X,S}$ is determined by the transmission coefficient of the medium, the reflection coefficient of the object, and the optical imaging arrangement. This means that each resolution element of the image converter in the focal plane receives one out of 10^{12} quanta emitted by the lamp. This value was calculated for a feasible set-up with the following specifications: lamp utilization, 10%; light focused on 1000 cm^2 at the scene; reflection, 10%; lens-scene distance, 200 cm; lens diameter, 10 cm; scene-resolution element size, 10^{-4} cm^2. Such a set-up should be possible by the state-of-the-art in instrumentation. Then for a resolution element the number $E^*_{PC,(T)}$ of electrons s^{-1} $W^{-1}_{input\text{-}Xenon}$, i.e., the number of electrons per second a resolution element of the photocathode would emit per watt of xenon lamp input, would be given by using $I_{PC,X,(T)}$ from Table 2, i.e.,

$$E^*_{PC,(T)} = \frac{6.24 \times 10^{15} I_{PC,X,(T)}}{K_{X,S}}. \tag{9a}$$

Thus, for λ_1 to $\lambda_2 = 680$ to 1100 nm and using the Varo photocathode,

$$E^*_{PC,(T)} = \frac{6.24 \times 10^{15} \times 2.88 \times 10^{5} \times 10^{-5}}{10^{12}} \sim 1.8 \times 10^4 \text{ electrons s}^{-1} \text{ W}^{-1}_{input\text{-}Xenon} \cdot \tag{9b}$$

Manufacturers' data, from which the tables in this paper were computed, were readily available only for continuous operation, the conditions under which the above equations apply. If the lamp is to be pulsed, then it is of interest to know the number of electrons occurring at a resolution element as the result of a pulse. It may be assumed that the xenon lamps built for pulsed operation have essentially the same spectral distribution as non-pulsed lamps and that thus the tables may be used for pulsed operation by replacing the dimension, electrons s^{-1} $W^{-1}_{input\text{-}Xenon}$ by electrons $J^{-1}_{input\text{-}Xenon}$, representing the number of electrons for a pulse. The possible repetition-rate range has to be known and considered in a practical design. Therefore, for the purpose of this paper, it will be considered justified to rewrite the above value as

$$1.8 \times 10^4 \text{ electrons per joule}_{input\text{-}Xenon}, \tag{9c}$$

from which the lamp input may be calculated.

The number E_Z of electrons or grains caused by radiation from the object and needed at a detector resolution element for achieving detection with a certain signal-to-noise ratio, may be derived in the following manner. For the useful signal E_S, the following equation may be written as

$$E_S = |E_{BF} - E_{ZF}| = |E_B - E_Z|, \tag{10}$$

where, in reference to a detector-resolution element, E_{BF} is the number of electrons or grains resulting from the background plus foreground, E_B is the number of electrons or grains caused by the background at a pertinent resolution element, E_F is the number of electrons or grains resulting from the foreground only, and E_{ZF} is the number of electrons or grains resulting from the object to be detected plus the foreground. For the above, the background is defined as any radiation which comes from any source other than the object and from an equal or greater distance than the object. Any radiation coming from any distance lying between the object and the detector is defined as foreground and is usually caused by scattering.

For the theoretical signal-to-noise ratio δ, considering only the conversion noise, one may write

$$\delta = \frac{E_S}{(E_B + E_F + E_Z)^{1/2}}. \tag{11}$$

Letting

$$\rho = \delta \frac{E_B}{E_Z}, \tag{12}$$

and using ρ for substitution in equation (11), yields

$$\delta = \frac{E_Z(\rho - 1)}{[E_Z(\rho + 1) + E_F]^{1/2}}. \tag{13}$$

Depending on whether the background is more or less radiant than the object, ρ can be $\gtrless 1$, but if $\rho = 1$, no effective difference in radiation intensity between background and object exists and detection becomes impossible. The ratio between the number of electrons or grains produced by a detector element which receives radiation from both the background and the foreground, and the number of electrons or grains produced by another detector element which receives radiation from both the object and the foreground, is E_{BF}/E_{ZF}. If there is no foreground, this ratio becomes equal to E_B/E_Z, i.e., it is equal to ρ. Solving equation (13) for the number E_Z of electrons or grains required for achieving detection with a given δ and ρ yields.

$$E_Z \sim \frac{\delta^2(\rho + 1)}{2(\rho - 1)^2} \left\{ 1 + \left(1 + \frac{(\rho - 1)^2 E_F}{\delta^2(\rho + 1)^2} \right)^{1/2} \right\}. \tag{14a}$$

In order to use this equation, E_F has to be known, determined by measurement, estimation, or calculation. If, for example, $\delta = 10{:}1$, $\rho = 0.15$, and E_F is assumed to be negligible, then for each pulse and involved resolution element, the number E_S of electrons needed is

$$E_Z = \frac{10^2(0.15 + 1)}{2(0.15 - 1)^2}(1 + 1) \sim 159 \text{ electrons.} \tag{14b}$$

Since the necessary xenon-lamp input $X_{W,PC}$ is given by

$$X_{W,PC} = \frac{E_Z}{E^*_{PC}}, \tag{15a}$$

then, in this example, the energy needed is

$$X_{W,PC} = \frac{159}{1.8 \times 10^4} \sim 0.0088 \text{ joules.} \tag{15b}$$

If a photographic record is to be obtained on Kodak 5424 emulsion, Table 3 reveals ($D_\Delta = 1$, Wratten 89b) that, by replacing the dimension grains s^{-1} $W^{-1}_{\text{input-Xenon}}$ with the dimension grains $J^{-1}_{\text{input-Xenon}}$, 7.75×10^{13} grains $J^{-1}_{\text{input-Xenon}}$ are obtained. The number E_G of grains $J^{-1}_{\text{input-Xenon}}$, obtained at the photographic film, considering the utilization factor $K_{X,S}$, is given by

$$E_{G,(T)} = \frac{G_{X,(T)}}{K_{X,S}}, \tag{16a}$$

which, by using the values of Table 3 for $G_{X,(T)}$ and with the assumed $K_{X,S}=10^{12}$, is

$$E_{G,T}=\frac{7.757\times10^{13}}{10^{12}}\sim78 \text{ grains per joule.} \tag{16b}$$

For achieving the same signal-to-noise ratio, $\delta=10{:}1$, and the same ratio, $\rho=0.15$, as in the opto-electronic case, there have to be about 159 grains instead of electrons per resolution element for each pulse. Thus

$$X_{W,L}=\frac{E_Z}{E_G}, \tag{17a}$$

which requires for one pulse

$$X_{W,L}=\frac{159}{78}\sim2 \text{ joules.} \tag{17b}$$

The above number of grains has to be distributed over such an area that a density of $D_\Delta=1$ is achieved. In this example the fog of the film is neglected and therefore the data given constitute the basic capability. The grain size of Kodak film 5424 is $A_g=4.75\times10^{-12}$ m^2 and the coverage factor F_C is 0.9 when the density $D_\Delta=1$ (Gebel and Duke, 1967a; Gebel, Duke, and Mestwerdt, 1967b). Thus, the area A_G covered by 159 grains would be

$$A_G=E_ZA_g=159\times4.75\times10^{-12}\sim7.6\times10^{-10} \text{ square meters.} \tag{18}$$

The actual size of a resolution element A_F is therefore

$$A_F=\frac{E_ZA_g}{F_C}=\frac{A_G}{F_C}. \tag{19a}$$

Thus, here

$$A_F\sim\frac{7.6\times10^{-10}}{0.9}\sim8.4\times10^{-10} \text{ square meters,} \tag{19b}$$

that is, a resolution element with a diameter of about 30 μm is needed. This example is a very good illustration of the relationship between the required resolution element size and the signal-to-noise ratio (Gebel, 1968a).

Using an image intensifier-film combination instead of direct film recording not only reduces the lamp-input requirement, as in this example from 2 joules to 0.008 joules, but the 159 primary electrons (for which $\delta=10{:}1$ and $\rho=0.15$ are fulfilled) can be multiplied to such an extent that a reasonably larger number of grains is produced. This then makes it possible to obtain the same density by using a finer grained emulsion, which is usually less foggy and which gives a better texture and visual appearance. This larger number of grains will not improve δ, because in a chain of events the percentage of the fluctuation is always determined by the smallest number (Gebel, 1968b), which, in a well-designed image intensifier-film combination is the number of primary photoelectrons. However, if the intensifier has insufficient amplification, and the number of grains produced becomes smaller than the number of primary photoelectrons, then the statistical deviations are determined by the number of grains (Gebel, 1968b). Assuming that the number of grains in the optoelectronic case is increased to 2000 and that an emulsion with $\eta_L=2\times10^{-3}$ is used, about $2000/2\times10^{-3}=10^6$ quanta are needed (Gebel, 1967a, 1967b, and 1968a). Assuming 33% coupling efficiency, about 3×10^6 quanta have to be emitted by the image-intensifier phosphor screen. This requires an electron-to-quanta intensification factor of $3\times10^6/159\sim2\times10^4$. However, this cannot be achieved in a single tube; several tubes have to be cascaded, in which case a convolution of the phosphor responses of the different tubes occurs (Gebel, 1969b).

Performance data on photocathodes are commonly supplied by manufacturers without regard to the degree of reproducibility or possible deviations from the spectral curves. It should further be realized that, since these data come from different sources, the measurements were made with arrangements which were not necessarily directly comparable with each other. Also, the data used for the analysis of the photo-emitters are representative values as available to date; so this paper cannot reflect in any way on their availability in large numbers.

The authors trust that the material presented in this paper will enable the design engineer to estimate sufficiently closely threshold sensitivity of the different arrangements of practical interest, and that this paper will also prevent any unrealistic speculations concerning detectivity in any planned design.

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