CHARACTERISTICS OF SCINTILLATION PHOSPHORS

Foreword

It was not until 1944 that the use of a phosphor coupled to a photomultiplier tube was successfully used for detection of ionizing radiation. In the short period between that time and the present, however, the scintillation counter has become a familiar instrument for the detection of many types of ionizing radiation in a wide variety of applications. This growth has been accelerated by the inherent advantages of this type of detector over other means of measurement. These include high sensitivity to gamma rays, wide range of physical size, response proportional to the incident radiation, rapid response time, and fast decay times. Such characteristics have made this type of detector useful in geophysical surveys for uranium and oil, clinical measurement of radioisotopes, radiation monitoring of personnel exposure, as well as the many applications in nuclear physics and research.

Since the best choice of a scintillation counting system can only be made with the properties of the scintillation phosphor in mind, it was considered both desirable and necessary to consolidate some of the pertinent information that has been accumulated during the past years. It is the purpose of the following report to provide a partial compilation of some of the data which have been found useful in this respect.

Elements of a Scintillation Counting System:

The basis of a scintillation counting system is the ability of the phosphor to convert into light emission some fraction of the energy lost by ionization during the passage of a charged particle through the material. This emitted light is picked up by the sensitive photocathode of a photomultiplier tube producing an electrical pulse which can be similar to the light output from the crystal in both magnitude and duration. Depending upon the amplification achieved by the phototube alone, this pulse may be of sufficient size to activate a scaler or ratemeter directly or may require external amplification.

Characteristics of Various Photomultiplier Tubes:

The system depends upon the sensitivity of the photomultiplier tube photocathode to the light emitted from the phosphor, and hence it is necessary that the photocathode response occur in the range of the emission wavelength. Fig. 1 shows the spectral sensitivity characteristics of a phototube having S-11 response. This response is typical of most of the photomultipliers now utilized for scintillation counting, and adequately covers the emission spectra of two of the more common scintillation phosphors as illustrated in this figure.

Table I shows a classification of some of the more common phototubes with respect to photocathode response, size of photocathode, amplification, and manufacturer. This table does not include all the phototubes available but does illustrate a partial range of photocathode sizes.

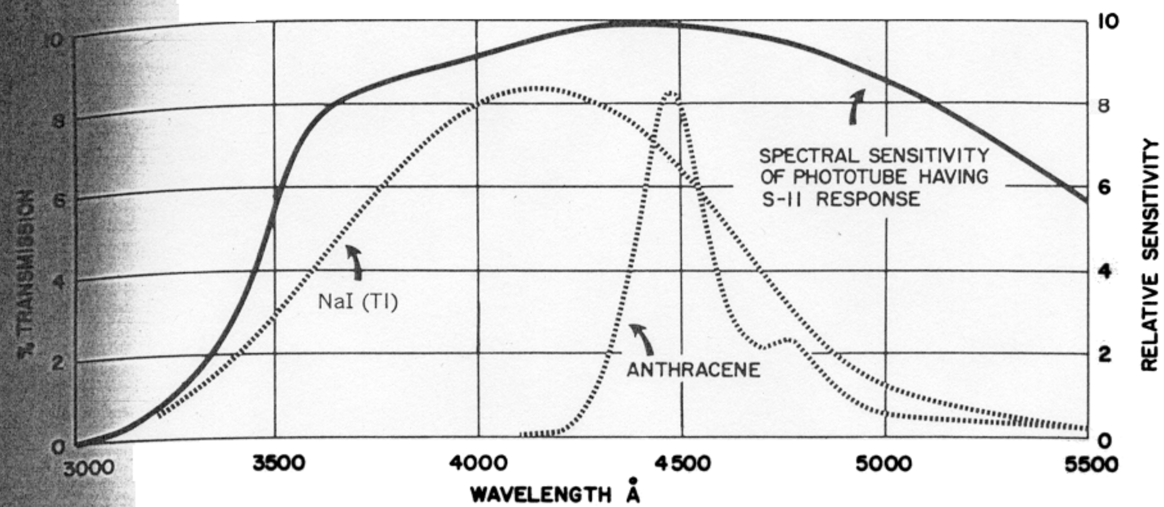

FIGURE 1

Emission **Spectra of Anthracene and Thallium Activated Sodium Iodide Crystals (P. R. Bell,** R. C. Davis, **J. E. Francis, J. Cassidy; ORNL Progress Report 1092; 6/20/51). This emission is** covered adequately by **a phototube with S-11 response. (Courtesy of Radio Corporation of America)**

TABLE I

Characteristics of Representative Photomultipliers

Type	Manufacturer	Photocathode Size (Min. dia. inches)	Spectral Class	Average Sensitivity μa/lumen	Gain	Dia. (in.)	Overall Dimensions (Length, in.)
6342-A	RCA	1.5	S-11	50	2.3 x 10^6*	2¼	5 13/16
6655-A	RCA	1.7	S-11	50	2.3 x 10^6*	2¼	
6810-A	RCA	1.7	S-11	60	6.3 x 10^8**	2⅜	
6199	RCA	1.24	S-11	45	2.8 x 10^6*	1 9/16	
6292	Dumont	1.5	S-11	60	2 x 10^6***	2 1/16	
6363	Dumont	2.5	S-11	60	2 x 10^6***	3	
6364	Dumont	4.2	S-11	60	2 x 10^6***	5¼	
6291	Dumont	1.25	S-11	60	2 x 10^6***	1½	
CL 1012	CBS	1.348	S-11	60	2.25 x 10^5*	1½	
CL 1002	CBS	1.745	S-11	60	2.25 x 10^5*	2	
CL 1003	CBS	2.703	S-11	60	2.25 x 10^5*	3	
CL 1015	CBS	4.250	S-11	70	1.90 x 10^5*	5¼	
9536B	EMI	1.75	S-11	50	6 x 10^5	2 1/16	
9578B	EMI	2.5	S-11	50		3 3/32	
9579B	EMI	4.37	S-11	50		5	
8054	RCA	2.59	S-11	75	8 x 10^4	3	

* 1250 v. supply **voltage** **** 2300 v. supply voltage** ***** At 145 volts/stage**

3 *Characteristics of Various Scintillation Phosphors:*

In general there are four categories of phosphors used for beta-gamma detection: inorganic crystals, organic crystals, plastic phosphors, and liquid phosphors. Table II tabulates the more prominent examples of each type.

While there are many desirable characteristics of a luminescent material as illustrated by the above table, the more important include (1) a higher density for greater absorption of gamma rays, (2) increased pulse height for detection of low energy interactions, and (3) short decay times for fast counting.

TABLE II

Characteristics of Representative Scintillation Phosphors

Material	Wavelength of maximum emission (A°)	Decay Constant μsec.	Density gm/cc^3	Relative Pulse Height*
Inorganic Crystals				
NaI (Tl)	4100	.25	3.67	210
CsI (Tl)	4200-5700**	1.1	4.51	55
KI (Tl)	4100	1.0	3.13	50 (approx)
LiI (Eu)	4400	1.4	4.06	74
Organic Crystals				
Anthracene	4400	.032	1.25	100
Trans-Stilbene	4100	.006	1.16	60
Plastic Phosphors	3500 to 4500	.003 to .005	1.06	28 to 48
Liquid Phosphors	3550 to 4500	.002 to .008	0.86	27 to 49

*With 10 μsec. anode time constant (Robert Swank—"Annual Review of Nuclear Science", Vol. 4 (1954)

**Unpublished data of Bonomomi and Rossel quoted by B. Hahn and J. Rossel in "Helv. Phys. Acta" 26 (1953)

Gaseous detectors such as the conventional Geiger-Müller counter and the gas flow counter exhibit close to 100% efficiency for beta detection; consequently there is no general need for scintillation counters for this purpose. In some cases, however, the unique geometric shapes available in a scintillation counter will make this a special advantage and for this application the organic crystals, plastics, and liquid scintillators have generally been selected. The heavier inorganic crystals are not desirable for this application since the high atomic number may result in excessive scattering of the incident beta particles before they have lost all of the energy in the crystal.

The primary advantage of the inorganic crystals is their higher density which is mainly responsible for the higher stopping power and thus the greater counting efficiency for gamma rays. Inorganic substances such as the tungstates, are relatively transparent but have such high indices of refraction that the light output is low because of internal reflection, particularly in powder form. Since the alkali halides, and in particular NaI (Tl), exhibit such desirable characteristics as high density, high light output, transparency, and suitable index of refraction, it is with this material that most of the specifications will be concerned.

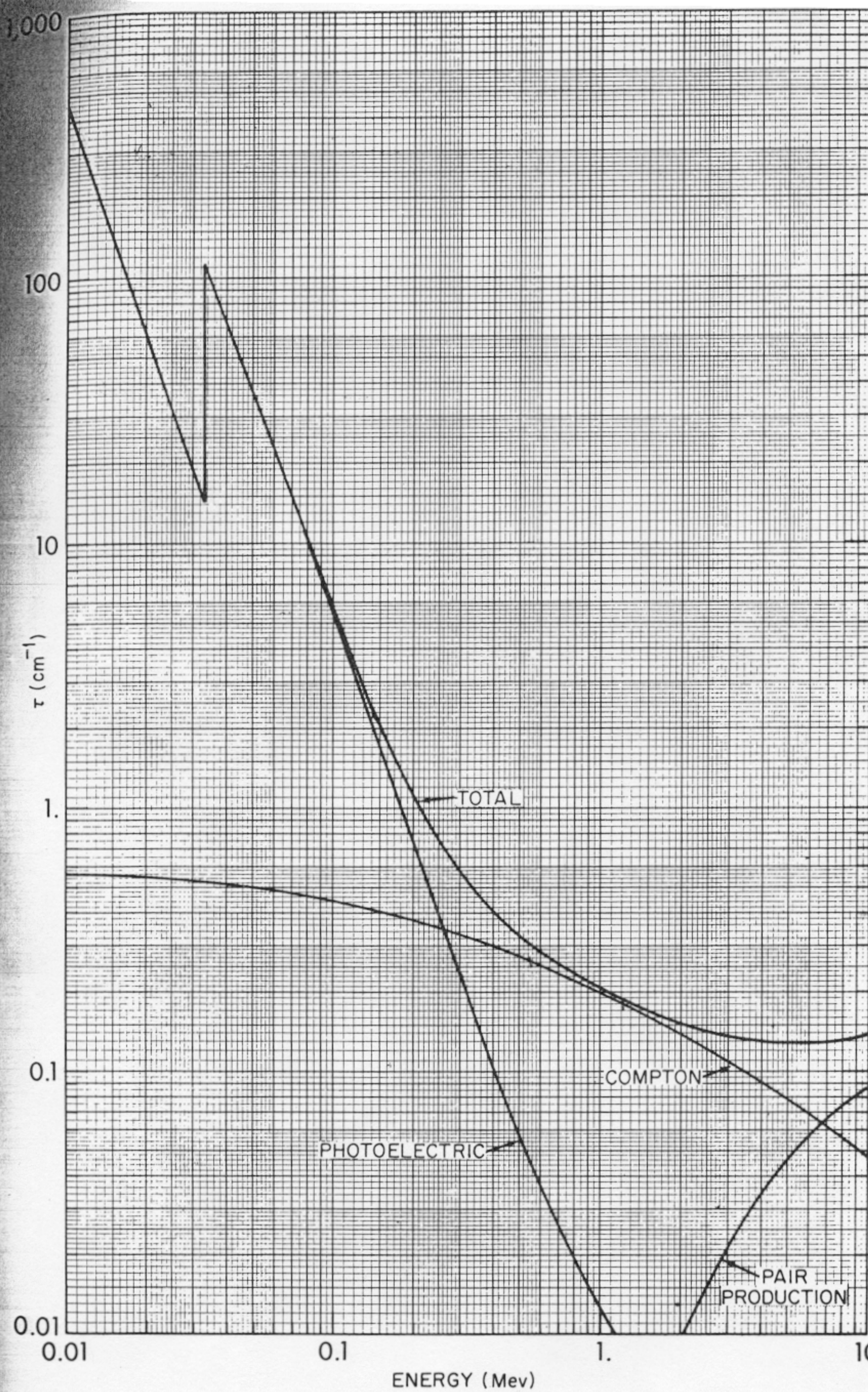

FIGURE 2

Complete cross sections of sodium iodide showing total absorption and fractional components due to Compton absorption, photoelectric absorption, and pair production. All curve ratios have been corrected for coherent scattering. Data from NBS circular No. 583.

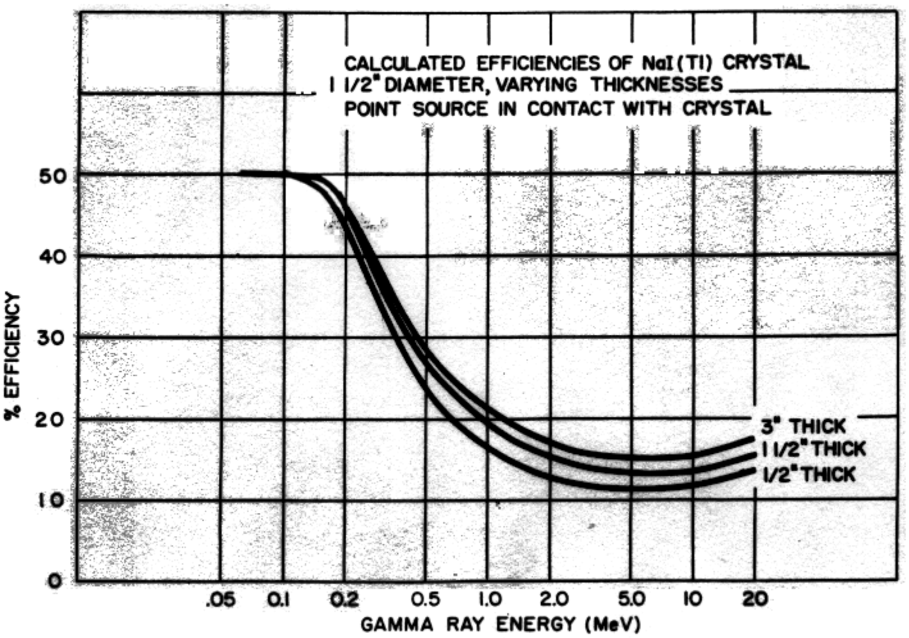

FIGURE 3

Efficiency in the above figure has been defined as $N/N_0 \times 100\%$, where N_0 represents the number of gamma rays per second radiated by the source and N represents the total number of interactions in the crystal. See also Figs. 5, 6, 7, and 8. (From "Calculated Efficiencies of NaI Crystals" by E. A. Wolicki, R. Jastrow, and F. Brooks, NRL Report 4833)

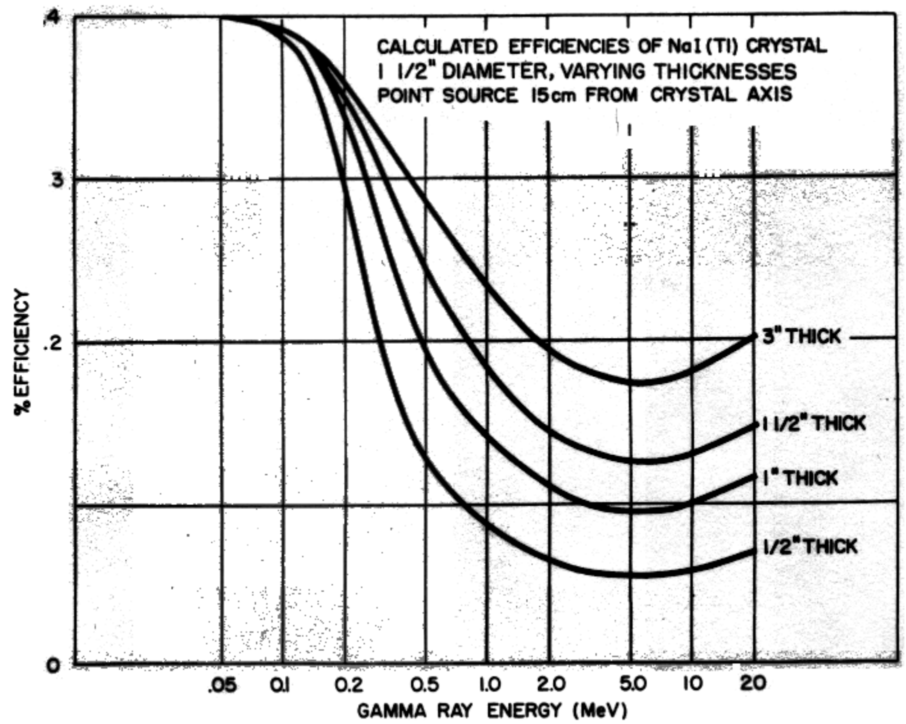

FIGURE 4

From "Calculated Efficiencies of NaI Crystals" by E. A. Wolicki, R. Jastrow, and F. Brooks, NRL Report 4833. See also Figs. 4, 6, 7, and 8.

4 *Counting Efficiency of Thallium Activated Sodium Iodide Crystals*

For gamma ray detection where the high atomic number aids in photon conversion, these inorganic crystals have been employed extensively. In Fig. 2, theoretical cross sections for sodium iodide are presented showing the total absorption as well as separate contributions of photoelectric effect, Compton effect, and pair production. In Figures 3 and 4, the theoretical efficiencies of varying thicknesses of NaI (Tl) crystals are plotted to show the absorption as a function of both crystal thickness and gamma ray energy for two differing source geometries.

In Fig. 4, the efficiency has been defined as $N/N_o \times 100\%$, where N_o represents the number of gamma rays per second radiated by the source and N represents the total number of interactions in the crystal. This is the theoretical efficiency. Actual efficiency must account both for the absorption of the crystal container and also for the fraction of the total interactions, N, that are actually counted. This latter is, of course, dependent on the discrimination level and would approach 100% only when set so that even weak interactions were detected. If only photopeak pulses were detected, this theoretical efficiency must be multiplied by the photopeak-to-total ratio.

In Fig. 3 slight difference is noted in the efficiency of the varying thicknesses, since with the source situated in contact with the crystal, the emission is isotropic and thus a large number of interactions will occur laterally in the crystal. When the source is further away, as in Fig. 4, the passage of gamma rays is perpendicular to the crystal so that increase is roughly exponential as expected.

5 *Variation of Efficiency with Geometry:*

The efficiency of a cylindrical thallium activated sodium iodide crystal as shown in Fig. 3 has been calculated for the case of a point isotropic gamma ray source situated in immediate contact with the crystal on its central axis. In most practical cases of gamma ray detection, this proximity cannot be attained. More commonly, the source may be situated on the axis of the crystal cylinder but at some distance from the outer face. In Figures 5,6,7, and 8, curves are plotted to show this decrease of counting efficiency as the source is moved farther away from the crystal face. Only three of the more common crystal sizes are plotted here.

As would be expected, the greatest total efficiency is obtained when the source and crystal are in contact. While source size may often prevent this, there are some cases of special crystal construction where the source may actually be inserted in the crystal itself. Fig. 11 illustrates a crystal which has been drilled through the longitudinal cross section and fitted with concentric tubing so that radioactive material may be passed through the tubing with close to 100% geometric efficiency. This adaptation gives the highest detection efficiency for flow systems.

A similar method of improving geometric efficiency for radioactive assay has been the construction of various sized well counters in which the sample may be inserted deep within the crystal. This construction is illustrated in Fig. 12.

While well counters may be of various dimensions, the most common has been

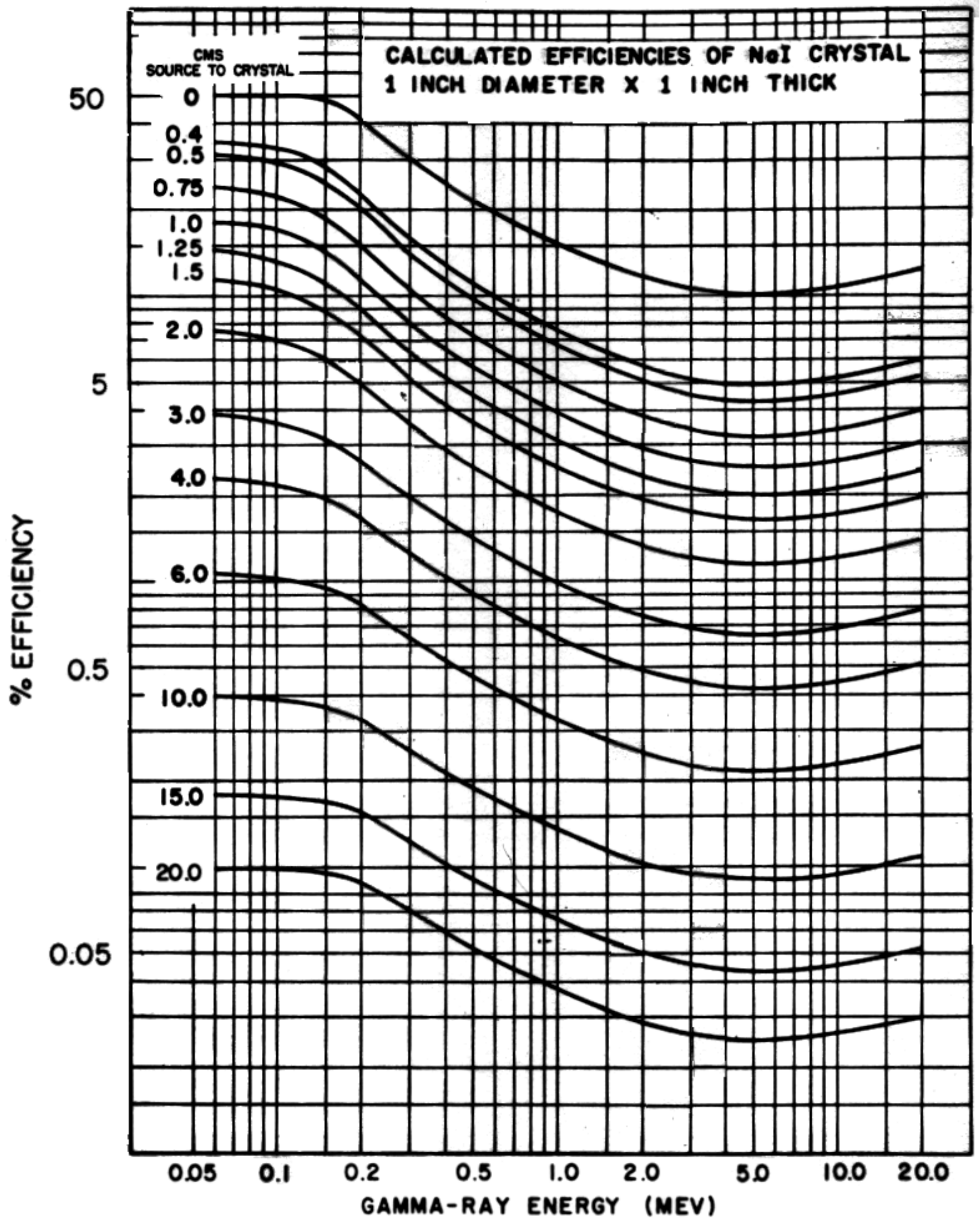

FIGURE 5

From "Calculated Efficiencies of NaI Crystals" by E. A. Wolicki, R. Jastrow, and F. Brooks, NRL Report 4833. See also Figs. 4, 5, 6, and 8.

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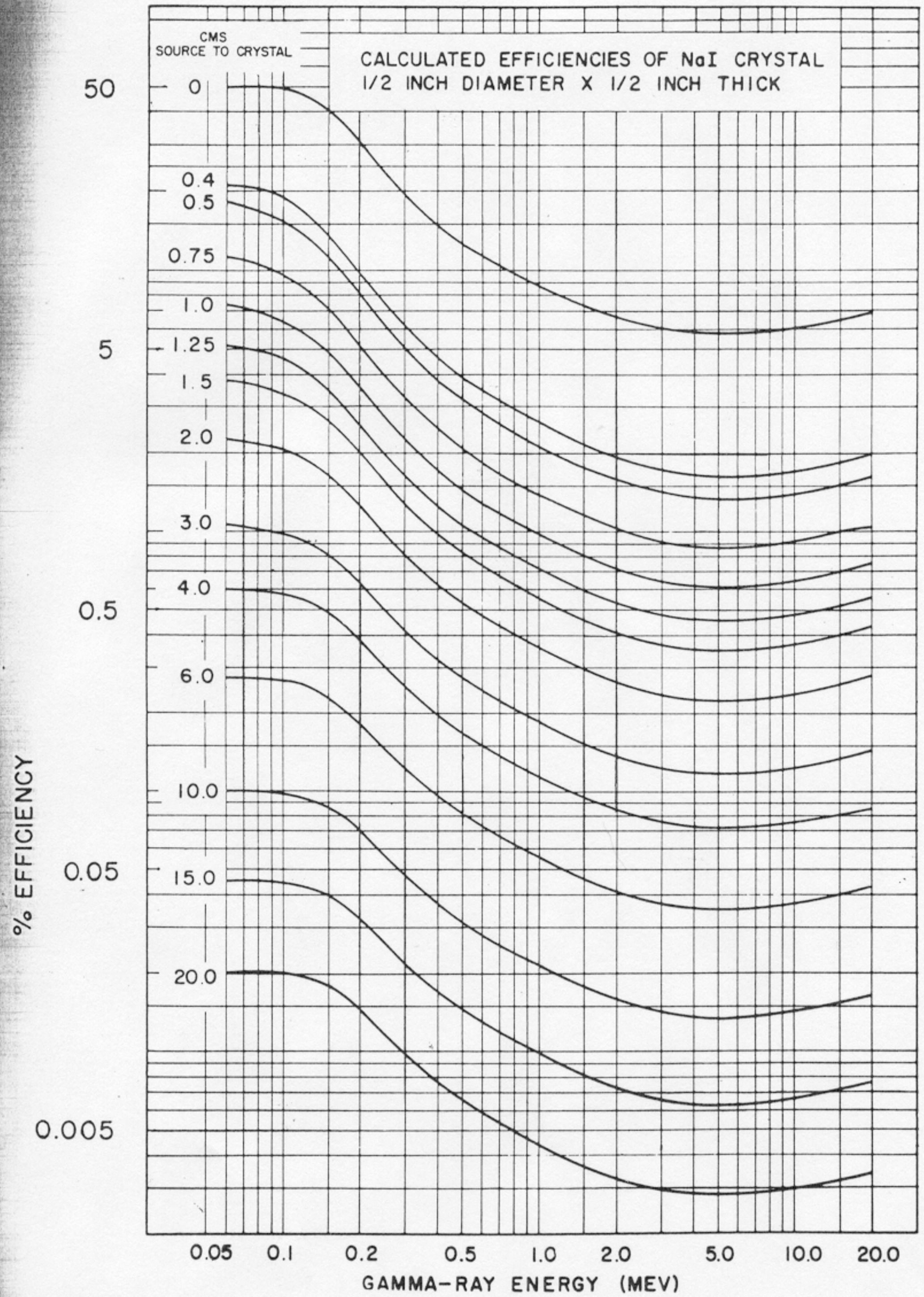

FIGURE 6

From "Calculated Efficiencies of NaI Crystals" by E. A. Wolicki, R. Jastrow, and F. Brooks, NRL Report 4833. See also Figs. 4, 5, 7, and 8.

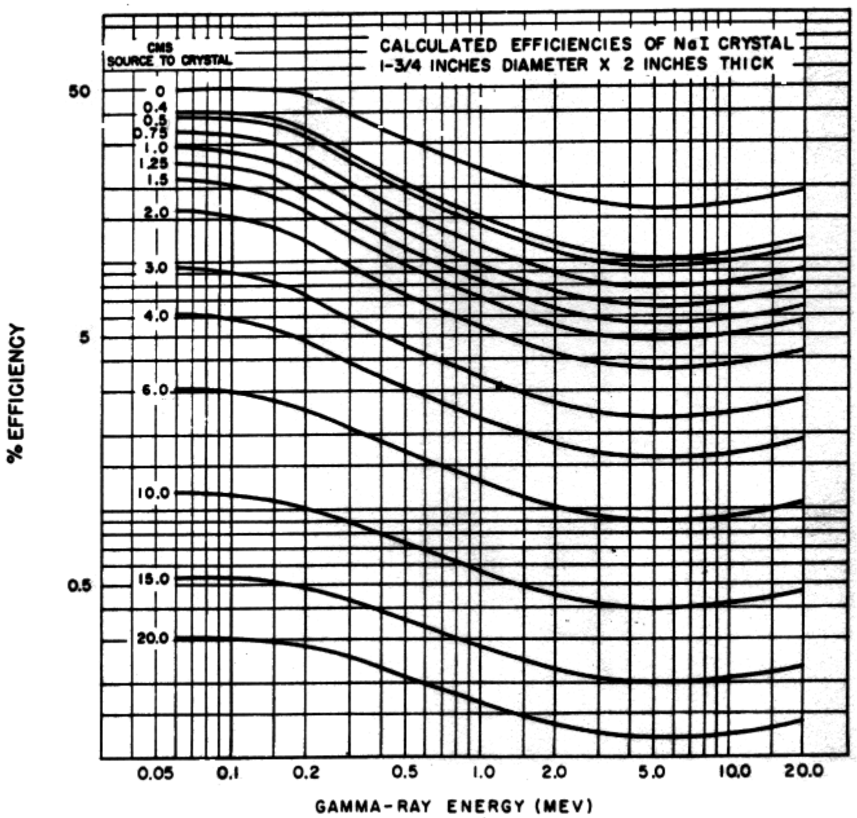

FIGURE 7

Calculated efficiencies of NaI crystal 1¾ inches diameter × 2 inches thick.

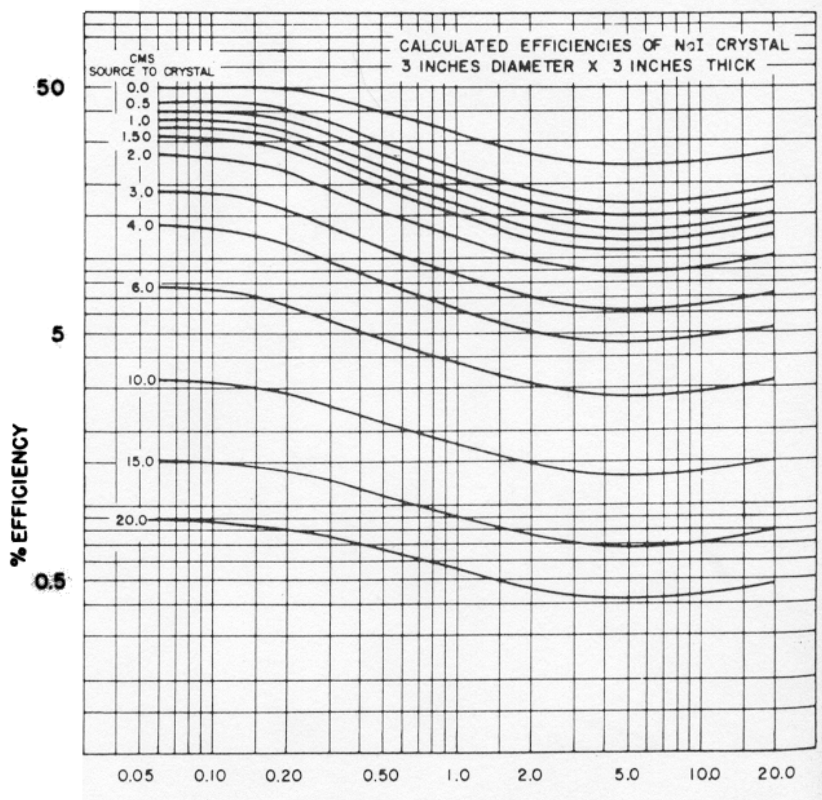

FIGURE 8

From "Calculated Efficiencies of NaI Crystals" by E. A. Wolicki, R. Jastrow, and F. Brooks, NRL Report 4833. See also Figs. 3, 4, 5, 6, and 7.

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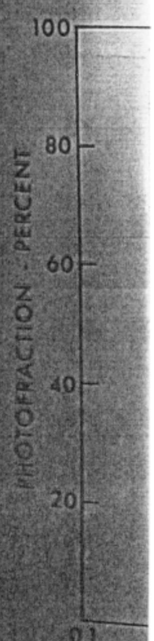

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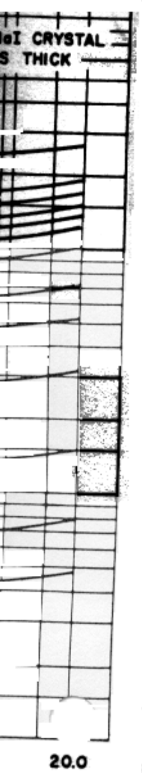

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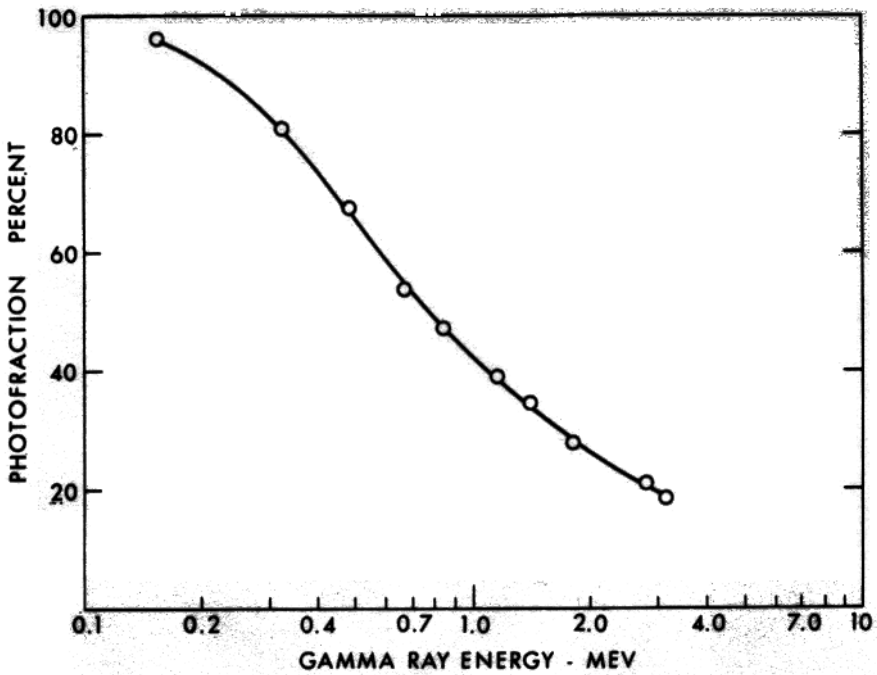

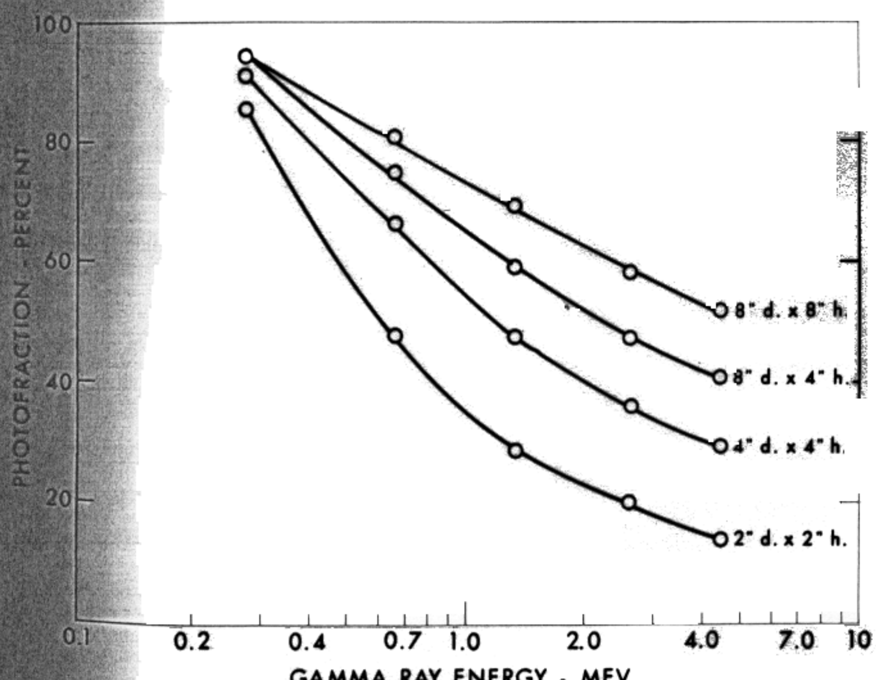

FIGURE 10

Calculated Efficiencies and Photofractions for Various Size Thallium Activated Sodium Iodide Crystals, W. F. Miller, John Reynolds, W. J. Snow, REVIEW OF SCIENTIFIC INSTRUMENTS, *28*, 717 (1957)