

HEXAFLUOROBENZENE LIQUID SCINTILLATORS AND THEIR APPLICATION
TO GAMMA AND FAST NEUTRON DOSE RATE MEASUREMENTS*

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INTRODUCTION

The measurement of gamma ray and fast neutron dose rates in a mixed radiation field poses some interesting problems. If the rates are to be measured by means of liquid scintillators, probably the most important of these is the fact that all of the common liquid scintillators are basically hydrocarbon in composition and consequently respond to both types of radiation.

A method has been described by Berlman and Marinelli (1) for the estimation of fast neutron rates in the presence of gamma rays. This system makes use of "twin" detectors having liquid scintillators of equal electron but dissimilar hydrogen content. The solvents used were xylene and 1,4-bis(trifluoromethyl)benzene. By suitable adjustment of solute concentrations, volumes of liquid scintillator and photomultiplier voltages, the Compton electron pulse-height spectra of the two solutions can be made to coincide satisfactorily under the action of gamma rays. In the presence of neutrons, the proton pulse-height spectra will differ in magnitude because of the different number of proton recoils produced in each liquid scintillator.

In the case of gamma radiation, scintillations are produced in the liquid scintillator by ionizing particles which arise as electrons from Compton scattering of gamma rays.

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When fast neutrons are involved, the ionizing particles arise as recoil protons from the collision of fast neutrons with hydrogen in the solvent. As a consequence, a solvent which contains no hydrogen should respond only to gamma radiation, and one which contains hydrogen should respond to both gamma rays and fast neutrons. In the method which is to be described, simultaneous gamma ray and fast neutron rate measurements are made by means of "paired" liquid scintillators, one of which is only gamma-sensitive and another which responds to both gamma rays and fast neutrons. With the two detectors in the same geometry with respect to the radiation source, the gamma rate is obtained from the hexafluorobenzene liquid scintillator. Based upon the calibrated ratio of gamma sensitivities, an equivalent gamma response is calculated for the hydrocarbon solution. Then, by difference, the net nongamma response of the latter scintillator represents the fast neutron component.

## PREPARATION OF HEXAFLUOROBENZENE SOLVENT

### Synthesis of Hexafluorobenzene

Of the organic compounds which do not contain hydrogen, perfluoro- compounds such as perfluorohexane, perfluorotoluene, and hexafluorobenzene ( $C_6F_6$ ) looked most promising as liquid scintillator solvents. Perfluorohexane was prepared but was an extremely poor chemical solvent for scintillator solutes. Perfluorotoluene has been obtained in small yield only as a by-product in various reactions. Hexafluorobenzene is not, at present, a commercially available chemical. In fact, specialty laboratories apparently were not interested in synthesizing this compound, probably because of the lengthy and inconvenient procedure, low yield, and high cost of catalytic materials. Consequently, the material used was prepared according to the procedure of Hellman et al. (2), which involves the pyrolysis of tribromofluoromethane in a platinum tube at 530 to 550° C under 4.5 atmospheres nitrogen pressure. Conditions (2) for optimum yields of product are given in Table 1. The contact time should be about 15 seconds with a nitrogen flow rate of about 100 cc per minute (3).

### Purification of Hexafluorobenzene

The crude product from the pyrolysis reaction contained

TABLE 1. PYROLYSIS OF TRIBROMOFLUOROMETHANE

| Temp.,<br>°C | Press.,<br>atm. | Feed<br>Rate,<br>g/min | Total<br>Recovery,<br>per cent | Bromine<br>Liberated,<br>per cent | Gross Yield<br>C <sub>6</sub> F <sub>6</sub> ,<br>per cent | Recovery<br>CFBr <sub>3</sub> ,<br>per cent | Net Yield<br>C <sub>6</sub> F <sub>6</sub> ,<br>per cent |
|--------------|-----------------|------------------------|--------------------------------|-----------------------------------|------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------|
| 530          | 4.5             | 5.1                    | 99                             | 50                                | 29                                                         | 43                                          | 50                                                       |
| 540          | 4.5             | 7.0                    | 95                             | 62                                | 38                                                         | 30                                          | 55                                                       |
| 550          | 4.5             | 3.5                    | 96                             | 67                                | 40                                                         | 25                                          | 52                                                       |

free bromine (~57 per cent by weight), unreacted tribromofluoromethane (~28 per cent by weight), and other bromofluoro- compounds. Bromine removal was effected by washing the crude product with bisulfite solution. Preliminary distillation of the product through a Snyder column gave two fractions: impure hexafluorobenzene (boiling range 60 to 92° at 585 mm) and recovered tribromofluoromethane. The product fraction was dissolved in ether, treated with 2N sodium hydroxide for 51 hours, washed with water, and dried over Drierite. This step was essential, since bromine was liberated in the subsequent fractionation from an unstable compound, probably symtetrabromodifluoroethane, and complete removal of this compound in the later gas chromatographic purification was difficult. The dry solution was then fractionated in a helices-packed column, and final purification of the hexafluorobenzene was accomplished by gas chromatographic resolution of 1- to 4-ml aliquots on a preparative-scale column.\* Purity of the finished product was checked by gas chromatography on two analytical columns with different packing materials. The analytical columns indicated a small amount of a second component, which was trapped from the gas stream and subjected to mass spectrometric analysis. Bromine was absent, but the -CF<sub>3</sub> group was present; hence, the contaminant was thought to be perfluorotoluene. The relative anode current measurement (4) obtained with 2,5-diphenyloxazole (PPO, 5 g/l) solute and a Cs-137 source was 23 per cent of that shown by a standard solution of PPO (5 g/l) in toluene.

EVALUATION OF SOLUTES IN THE HEXAFLUOROBENZENE  
LIQUID SCINTILLATOR SYSTEM

Based upon light output, the radiation damage from a given total gamma dose to solutions of various solutes in hexafluorobenzene is considerably greater than to solutions

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\* The column, which was operated at a temperature of 80°C with a helium flow of 1400 cc per minute, was designed and constructed by R. N. Rogers of the Los Alamos Scientific Laboratory. This 10-ft column, 2 in. in diameter, was packed with Dow-Corning silicone high vacuum grease on C-22 fire brick support.

of the same solutes in hydrocarbon solvents such as toluene, xylene, and triethylbenzene. Since the damaged solutions are yellow in color, regardless of which solute is employed, transmittance of the solutions has been reduced. In addition, noncolored chemical substances which quench the scintillation process may also be present.

Although 2,5-diphenyloxazole (PPO) appeared to be the solute of choice for use with  $C_6F_6$  because of good solubility and scintillation characteristics, it was found experimentally (5) that exposure of  $C_6F_6$ -PPO (5 g/l) scintillator to a total gamma dose of  $3.2 \times 10^5$  roentgens,\* resulted in a 45 per cent reduction in scintillator response. Other solutes were then evaluated on the basis of the following criteria: solubility in  $C_6F_6$ ; relative anode current measurements; radiation damage to solutions in  $C_6F_6$ , as indicated by relative current measurements; and effect of oxygen on the rate of radiation damage. Results for a number of solutes are shown in Table 2.

Based upon the results obtained with the irradiations in vacuo, a solution of 9,10-diphenylanthracene (D7) in  $C_6F_6$ , free of oxygen and saturated with an inert gas, is considered to be the liquid scintillator of choice for monitoring high gamma dose rates; especially when the accumulated dose becomes large, i.e.,  $> 10^4$  r. In  $C_6F_6$ -D7 solutions, the average increase in sensitivity due to removal of the oxygen quenching factor (6), by saturating the solutions with argon, was 64 per cent. An oxygen-free solution of PPO offers greater sensitivity and would, therefore, be of interest for monitoring low gamma dose rates.

The deterioration process involved in radiation damage is probably one of free radical formation from molecules of the solvent with subsequent chemical reactions involving the solute. The result obtained when no solute was dissolved in the  $C_6F_6$  during irradiation suggests that substances were formed in the solvent which were either capable of quenching the scintillation process or of reacting with the added solute to form a scintillation-quenching or light-absorbing product.

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\* Gamma rays from a 25.5 kc barium-lanthanum source; average energy 1.1 Mev.

TABLE 2. RADIATION DAMAGE TO HEXAFLUOROBENZENE SOLUTIONS OF VARIOUS SOLUTES

| Accumulated<br>Dose, (a)<br>roentgens | Solute (b)   | Relative Currents (c) |                      | Ratio (d) |
|---------------------------------------|--------------|-----------------------|----------------------|-----------|
|                                       |              | Before<br>Irradiation | After<br>Irradiation |           |
| <u>In Air</u>                         |              |                       |                      |           |
| $1.46 \times 10^5$                    | D7 (3 g/l)   | 0.160                 | 0.014                | 0.088     |
| $1.6 \times 10^5$                     | PPO (5 g/l)  | 0.230                 | 0.190                | 0.825     |
| $1.46 \times 10^6$                    | PPO (5 g/l)  | 0.223                 | 0.091                | 0.408     |
| $1.46 \times 10^6$                    | G127 (2 g/l) | 0.124                 | 0.023                | 0.185     |
| <u>In Vacuo</u>                       |              |                       |                      |           |
| $1.24 \times 10^6$                    | PBD (3 g/l)  | 0.190                 | 0.124                | 0.654     |
| $1.24 \times 10^6$                    | D7 (3 g/l)   | 0.165                 | 0.128                | 0.776     |
| $1.24 \times 10^6$                    | PPO (3 g/l)  | 0.205                 | 0.092                | 0.448     |
| $1.24 \times 10^6$                    | None (e)     | 0.205                 | 0.188                | 0.917     |

(a) Cobalt<sup>60</sup> 1.3-Mev gamma rays.

(b) The solutes represented by these designations are: D7, 9,10-diphenyl-anthracene; PPO, 2,5-diphenyloxazole; G127, 3,3''-dimethyl-p-quaterphenyl; and PBD, 2-(4-biphenyl)-5-phenyl-1,3,4-oxadiazole.

(c) PPO in toluene (3 g/l) was used as the standard. Air-saturated solutions were used.

(d) This is the ratio of relative current after irradiation to that before irradiation.

(e) PPO (3 g/l) was added after irradiation of the solvent.

In this regard, it is of interest that hexafluorobenzene recovered, by high vacuum distillation, from a radiation-damaged solution gives the original relative current value when fresh solute is added.

## PHOTOVOLTAIC CELL AND PHOTOMULTIPLIER TUBE DETECTORS

### Photovoltaic Cell Detectors

A procedure has been described (7) for monitoring fairly high dose rates of pure gamma radiation. In this system, photons which are emitted from a liquid scintillator and impinge on a selenium photocell give rise to a measurable current by means of the photovoltaic effect. An adaptation of this method was used in designing our high dose rate detectors.

The design of the photovoltaic detector and especially the volume of the liquid scintillator chamber are directly related to the range of radiation dose rates to be monitored. The use of a glass container for the liquid scintillator is not satisfactory when high dose rates or large accumulated doses are to be encountered, because of browning of the transparent window facing the photovoltaic cell. Cerium-stabilized glass has been used satisfactorily, but it seemed preferable to have no glass at all. Consequently, detectors were made as shown in Fig. 1, in the form of a right cylinder with the photovoltaic cell cemented in place as one end of the container. Armstrong A-6 epoxy resin is a satisfactory adhesive and was found not to affect the liquid scintillator adversely. The detector barrel was made of steel and was coated on the inside with reflecting  $TiO_2$  epoxy resin paint (8). A step or shelf in the steel barrel and a spring contact make the necessary electrical connections to the collector ring and the back plate of the PV cell, respectively. Current from the PV cell is fed through a BNC connector and coaxial cable to the galvanometer system.

The size of the detector, i.e., the volume of liquid scintillator, is a function primarily of the dose rate range to be monitored and secondarily of the efficiency of the liquid scintillator in use. In order to preserve linearity of response of the PV cell with a safe margin, the maximum current from IRC-A5\* selenium PV cells should not exceed 300  $\mu a$

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\* International Rectifier Corporation, El Segundo, California.

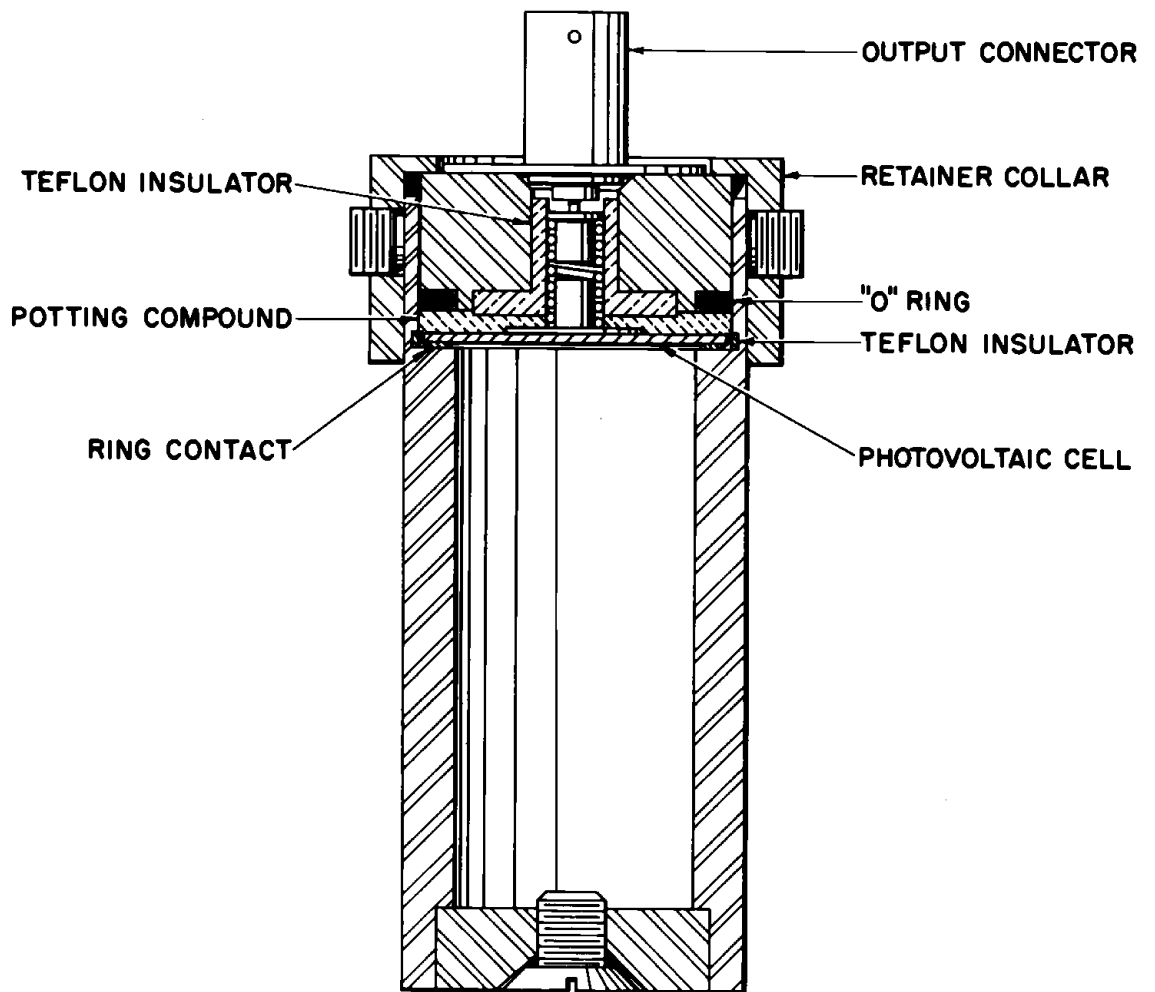


Fig. 1. Photovoltaic cell detector.

with an external resistance of 10 to 100 ohms and 10  $\mu$ a with an external resistance of 1000 to 1100 ohms. The acceptable minimum current from the PV cell is considered to be  $10^{-2}$   $\mu$ a, since noise pick-up may occur below this level. The gamma dose rate range of a 20-ml detector, having a typical sensitivity of  $1.3 \times 10^{-3}$   $\mu$ a/r/min, would, therefore, be 7.7 r/min to  $2.6 \times 10^5$  r/min. It also follows that for a detector with a 10 fold increase in volume, the sensitivity is increased by a factor of 10, and both the minimum and maximum measurable dose rates are decreased by the same factor. Since maximum current limits apply as described above, the high dose rate range of a detector can be extended somewhat by reducing its gamma sensitivity. This may be accomplished in a number of ways, which include: reduction in the volume of scintillator solution; reduction in the concentration of solute; and selection of the solvent and/or the solute, on the basis of relative pulse height or relative anode current measurements.

### Gamma Calibrations

In our work, gamma sensitivity, in  $\mu$ a/r/min, of the PV gamma detectors, was determined with a Co-60 source. As already mentioned, a typical sensitivity for the  $C_6F_6$ -D7 liquid scintillator is  $1.3 \times 10^{-3}$   $\mu$ a/r/min. When these detectors are to be used in mixed radiation gamma-neutron fields, calibrations are made in double-walled aluminum cans with 0.04 in. of Li-6 shielding against thermal neutrons. Gamma sensitivity of the PV gamma-neutron detectors was determined in a similar manner, also with Li-6 shielding. A typical sensitivity is  $1.32 \times 10^{-3}$   $\mu$ a/r/min, when the liquid scintillator is mineral oil/D7 (2 g/l).

In a mixed gamma-neutron field, the fast neutron contribution to the response of hexafluorobenzene solutions, due to hydrogen in the solute, is considered to be negligible. For example, in a solution of hexafluorobenzene-D7 at a concentration of 2.25 g/l, the weight of hydrogen per liter is 0.124 g. This weight of hydrogen is 0.15 per cent of that in 1 liter of xylene-D7 (3 g/l), or 0.1 per cent of that in 1 liter of mineral oil/D7 (2 g/l). Since the gamma sensitivities of hexafluorobenzene and mineral oil solutions of D7 are approximately equal, i.e.,  $1.3 \times 10^{-3}$   $\mu$ a/r/min, and the ratio of neutron to gamma sensitivity of the latter solution is 0.22, the fast neutron response due to hydrogen in the  $C_6F_6$  solution should not exceed 0.02 per cent of the gamma response.

## Fast Neutron Calibrations

Fast neutron sensitivity, in  $\mu\text{a}/\text{rad}/\text{min}$ , was determined at the Los Alamos Godiva II reactor. Paired detectors, shielded with Li-6, were placed at identical distances from the reactor. At a given power level, the gamma response of the gamma detector and the gamma plus neutron response of the gamma-neutron detector were read simultaneously. The integrated fast neutron dose for each run, from which a dose rate was calculated, was determined with sulfur monitors. From the gamma dose rate obtained, with the gamma detector and the previously calibrated gamma sensitivity ratio of the two detectors, an equivalent gamma response was calculated for the gamma-neutron detector. Then, by difference, the neutron response in microamperes was equal to the total response of the gamma-neutron detector minus its calculated gamma response. The neutron sensitivity of the detector was then obtained by dividing the net neutron response by the neutron dose rate. The ratio of gamma sensitivity to neutron sensitivity thus obtained for the PV gamma-neutron detectors was 4.6.

When a gamma-neutron detector is employed in a mixed radiation field, dose rate limits are dependent upon the composition of the radiation since the sensitivity of the detector toward gamma rays and fast neutrons, respectively, differs by the factor 4.6. For example, in a pure neutron field, using a typical fast neutron sensitivity of  $2.87 \times 10^{-4} \mu\text{a}/\text{rad}/\text{min}$ , the rate range would be from 35 to  $10^6$  rads/min. Applying the above-mentioned gamma sensitivity, the range of the same detector for gamma rays only would be 7.6 to  $2.3 \times 10^5$  r/min.

## Photomultiplier Tube Detectors

A more sensitive system for low radiation rates was devised by cementing the cathode of a 1 in. diameter DuMont No. 6467 photomultiplier tube into a standard 20-ml steel chamber,\* with reflecting inner surface. A variable high voltage supply is used with this type detector. By adjustment of the total resistance in the photomultiplier tube

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\* Chambers made for photovoltaic detectors may be used with slight alteration.

bleeder network, the currents developed in this detector are made compatible with the limits imposed by the galvanometer assembly.\* The resistance was set at 3.4 megohms.

The current produced may become significantly nonlinear if it exceeds 0.1 of the current flowing in the bleeder network. Hence, the maximum usable current at any given high voltage is:

$$I_{\max} (\mu\text{a}) = \frac{\text{voltage (volts)}}{\text{resistance (megohms)}} \times 0.1$$

Since the measurable radiation rates are limited by the maximum and minimum allowable currents, as well as the sensitivity of the detector, there is a maximum and minimum value of dose rate measurement at each high voltage available. Using typical sensitivity values, the range of the PM-type detector for gamma radiation is from  $1.87 \times 10^{-4}$  r/min to 295 r/min, when the liquid scintillator is hexafluorobenzene-D7 (2.25 g/l). The PM-type gamma-neutron detector, filled with hydrocarbon liquid scintillator, may also be used to measure gamma dose rate in a pure gamma field and has a typical range of  $6.4 \times 10^{-5}$  r/min to 129 r/min, when the scintillator is p-xylene-D7 (3 g/l).

### Gamma Calibrations

Gamma sensitivities, in  $\mu\text{a/r/min}$ , of the PM gamma and gamma-neutron detectors was determined with a Co-60 source over a wide range of high voltages applied to the tube. These calibrations were also made with Li-6 thermal neutron shielding. The calculated values of maximum and minimum measurable dose rates cover more than a thousand fold range of dose rate at a given high voltage. Since it is often necessary to pre-set the high voltage, a suitable range can be selected to cover the estimated dose rate with considerable room for error in the estimation.

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\*The recording galvanometer assembly may be used interchangeably with either the PV- or the PM-type of detector.

## Fast Neutron Calibrations

Fast neutron sensitivity of the PM gamma-neutron detectors was determined at the Godiva II reactor essentially as described for PV detectors. The ratio of gamma sensitivity to neutron sensitivity for the PM detectors filled with mineral oil/D7 (2 g/l) was 4.2. Using this ratio of response, fast neutron sensitivity for each high voltage setting may be calculated as a function of the gamma sensitivity calibration.

## INSTRUMENTATION

The currents generated by either the PV- or PM-type detector are measured by means of a transistorized galvanometer\* (Fig. 2). This instrument is equipped with a choice of external resistance parallel to the input such that voltages are developed across a net input resistance of either 10 or 1000 ohms. By this means, that resistance which both develops the voltages to be measured in the galvanometer and is part of the load across the PV cell is altered to coincide with the range of current to be measured and still preserve linearity of response of the PV cell. Low-impedance coaxial cable carries current from either type detector to the galvanometer.\*\* The output from the galvanometer is fed through a voltage divider into a strip chart recorder,\*\*\* with 100 mv full-span. A voltage regulator is used to supply power at constant voltage to the galvanometer. Since this is a low current device in which the output from the detector is not amplified before transmission, it has been found advantageous to operate the detector-galvanometer circuit as a full floating ground system.

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\* Kintel Model 204A electronic galvanometer and amplifier.

\*\* RG58/U coaxial cable, impedance 0.014 ohm/ft, has been used to transmit signal over distances up to 2 miles.

\*\*\* Model G-11A, Varian Recorder.



Fig. 2. Photovoltaic cell detector and galvanometer.

## DOSE RATE INDEPENDENCE

Linearity of response over the entire dose rate range of a detector is considered to be a primary requisite of these devices. Thus, a calibration at a given dose rate is effective over the entire rate range.

Linearity of response of the PV gamma and gamma-neutron detectors was demonstrated, with a 25.5 kilocurie barium-lanthanum source, to be very good over a dose rate range from about  $10^2$  to  $10^4$  r/min. Similar good linearity was shown by: a PV gamma-neutron detector to fast neutrons in a mixed radiation field from the Godiva II reactor, over a range from 28 to 74 rads/min; a PM gamma-neutron detector to Co-60 gamma rays over a range from  $10^{-1}$  to  $10^2$  r/min; and a PM gamma-neutron detector to 3 Mev neutrons over a range from  $2.5 \times 10^{-1}$  to  $7.4 \times 10^{-1}$  rad/min.

## FACTORS AFFECTING DETECTOR RESPONSE

### Photomultiplier Tube Fatigue

In the case of photomultiplier-type detectors, one limitation must be observed in adjusting the sensitivity of the detector for the probable dose rate range which is to be monitored. When relatively large anode currents, those greater than  $1 \mu\text{a}$ , are delivered for more than a few minutes, a change in the response of the photomultiplier tube is observed. Different brands of tubes behave differently under these circumstances. For example, DuMont No. 6467 tubes show an increase in sensitivity, whereas RCA No. 6199 tubes decrease in sensitivity. From a study of this feature with PM detectors under gamma ray excitation, the following generalizations may be made for DuMont No. 6467 tubes. At  $2 \mu\text{a}$  anode current, the tubes are stable for about 15 minutes; near  $1 \mu\text{a}$ , the response is constant for at least 30 minutes; and below  $0.5 \mu\text{a}$ , stability is good over several hours. Tubes which have had a change in response recover over a period of time, which is roughly proportional to the magnitude of the change.

## Radiation Damage to Liquid Scintillators

Radiation damage to liquid scintillators becomes a serious factor when high dose rates are encountered, especially if monitoring is on a continuous basis. As illustrated in Fig. 3, the damage resulting from a given integrated gamma dose from Co-60 is greater to a hexafluorobenzene solution of D7 (2.25 g/l) than to a solution of the same solute in p-xylene (3 g/l). These results were obtained in each case with PV detectors filled with oxygen-free argon-saturated solutions.

An effect which has been noted in instances of alpha and beta particle damage to polystyrene scintillator (9) and with cathode rays (10) was observed in the case of damaged hexafluorobenzene scintillator. When irradiation was interrupted, partial recovery of sensitivity took place, reaching a maximum in about 24 hours. The maximum recovery amounted to about 14 per cent, based on the sensitivity of the damaged solution. When irradiation was resumed, however, the damage rate was much faster than at the time of interruption but soon dropped to the former rate.

### Temperature Effect

The effect of temperature on the sensitivity of photovoltaic- and photomultiplier-type detectors was determined over the range of most probable practical application, 22 to 32° C. The results for both hexafluorobenzene-D7 and p-xylene-D7 solutions are shown in Fig. 4. These data were obtained with oxygen-free argon-saturated solutions and include the effect of temperature on response of the photomultiplier tube or the photovoltaic cell.

It has been demonstrated by Seliger and Ziegler (11) that the temperature effect is linear and inverse with changes in temperature. Response curves were obtained, in their case, for solutions of several solutes in the same solvent; the slopes of the curves differed considerably. The effect of temperature on photomultiplier tube response was of about the same magnitude and opposite in sign to the effect on the scintillator solution. In the present work, the decrease in sensitivity with temperature was considerably larger in hexafluorobenzene than in p-xylene solutions of D7 solute. The lesser effect in the photomultiplier-type detector, for both

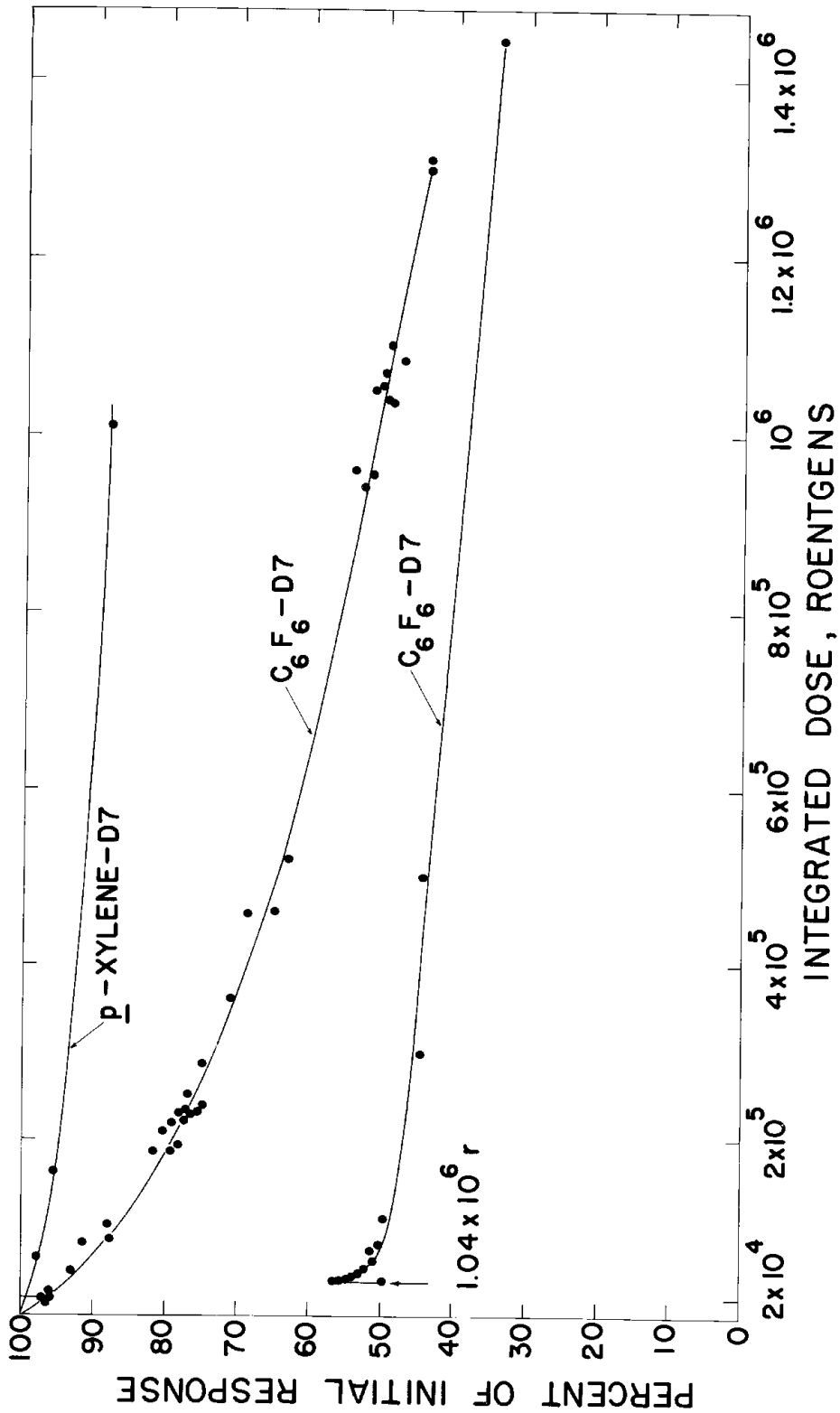


Fig. 3. Effect of large doses of gamma radiation on PV gamma detector response (dose rate  $\sim 10^3$  r/min). The lower C<sub>6</sub>F<sub>6</sub>-D7 curve is a continuation of the upper curve from the 50 per cent response point after time was allowed for recovery; add  $1.04 \times 10^6$  r to the abscissa units for the lower curve.

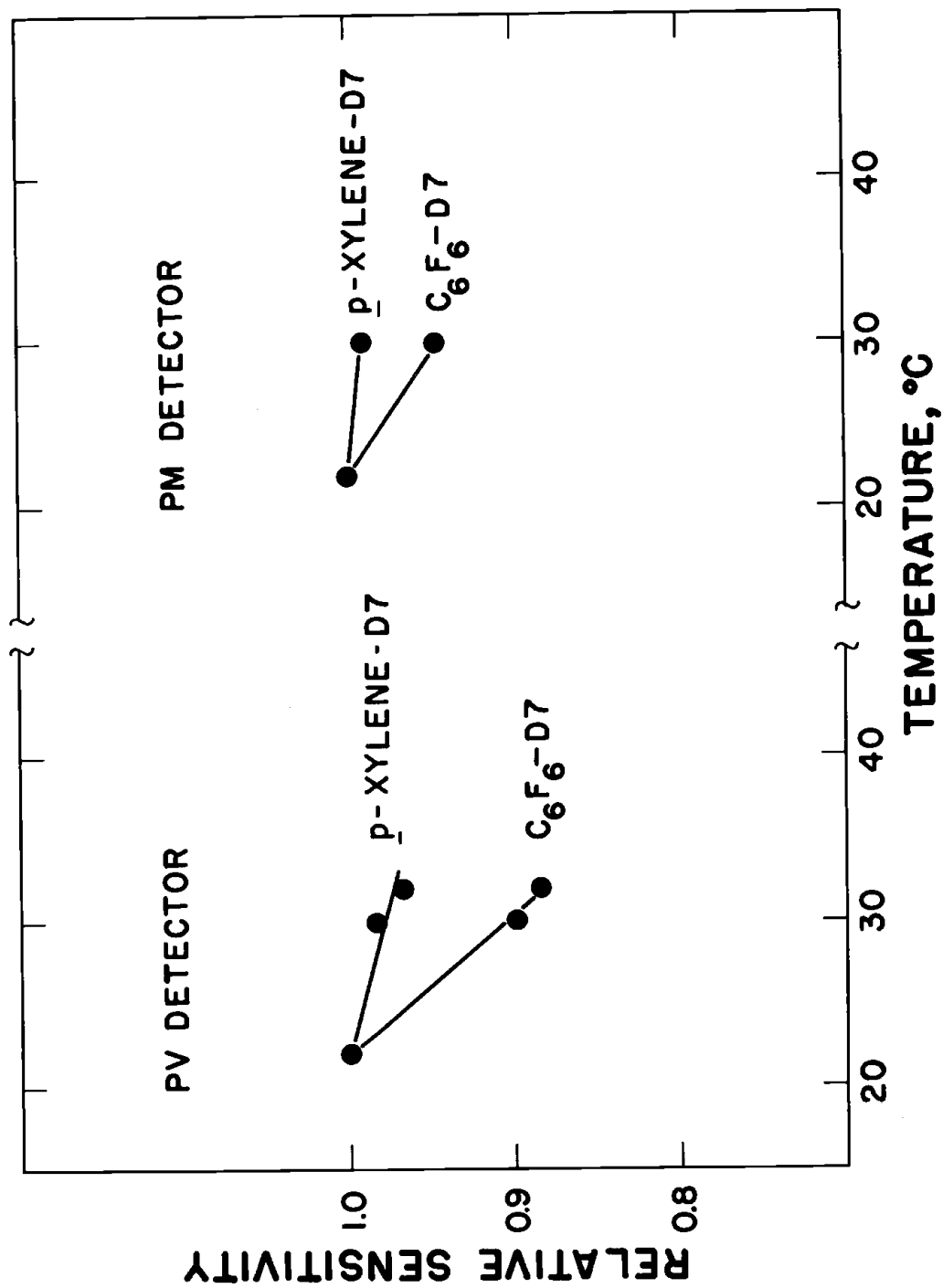


Fig. 4. Effect of temperature on detector response to gamma radiation.

solvents, probably reflects the positive effect of temperature on the tube response.

### Response to Thermal Neutrons

Thermal neutron response of a photovoltaic cell gamma-neutron detector, liquid scintillator triethylbenzene-terphenyl-POPOP,\* was observed in the north thermal column of the Los Alamos Homogeneous Reactor. The lithium extrapolation method (12) was used to determine the thermal neutron sensitivity of the PV-type detector. In terms of gamma-equivalent r per tissue rad of thermal neutrons, the sensitivity was 6.9. In actual practice, this factor is virtually eliminated by shielding with Li-6.

### Energy Dependence to Fast Neutrons

Energy dependence of the photomultiplier gamma-neutron detector was studied with monoenergetic fast neutrons from the Los Alamos Van de Graaff accelerator. Two detectors with different wall materials, iron and beryllium, in the liquid scintillator chambers were used. The liquid scintillator in each case was p-xylene-D7 (3 g/l).

As illustrated in Fig. 5, with beryllium wall material the response per tissue rad of fast neutrons steadily increases with energy in the region from 1 to 8 Mev. The difference in response of the two detectors may be due, in part, to neutron-induced activity in the iron chamber. Since equal volumes of the same liquid scintillator were used in the two detectors, the other factors affecting sensitivity were light-gathering efficiency and the sensitivity of the photomultiplier tube.

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\* 2,2'-p-Phenylenebis 5-phenyloxazole .

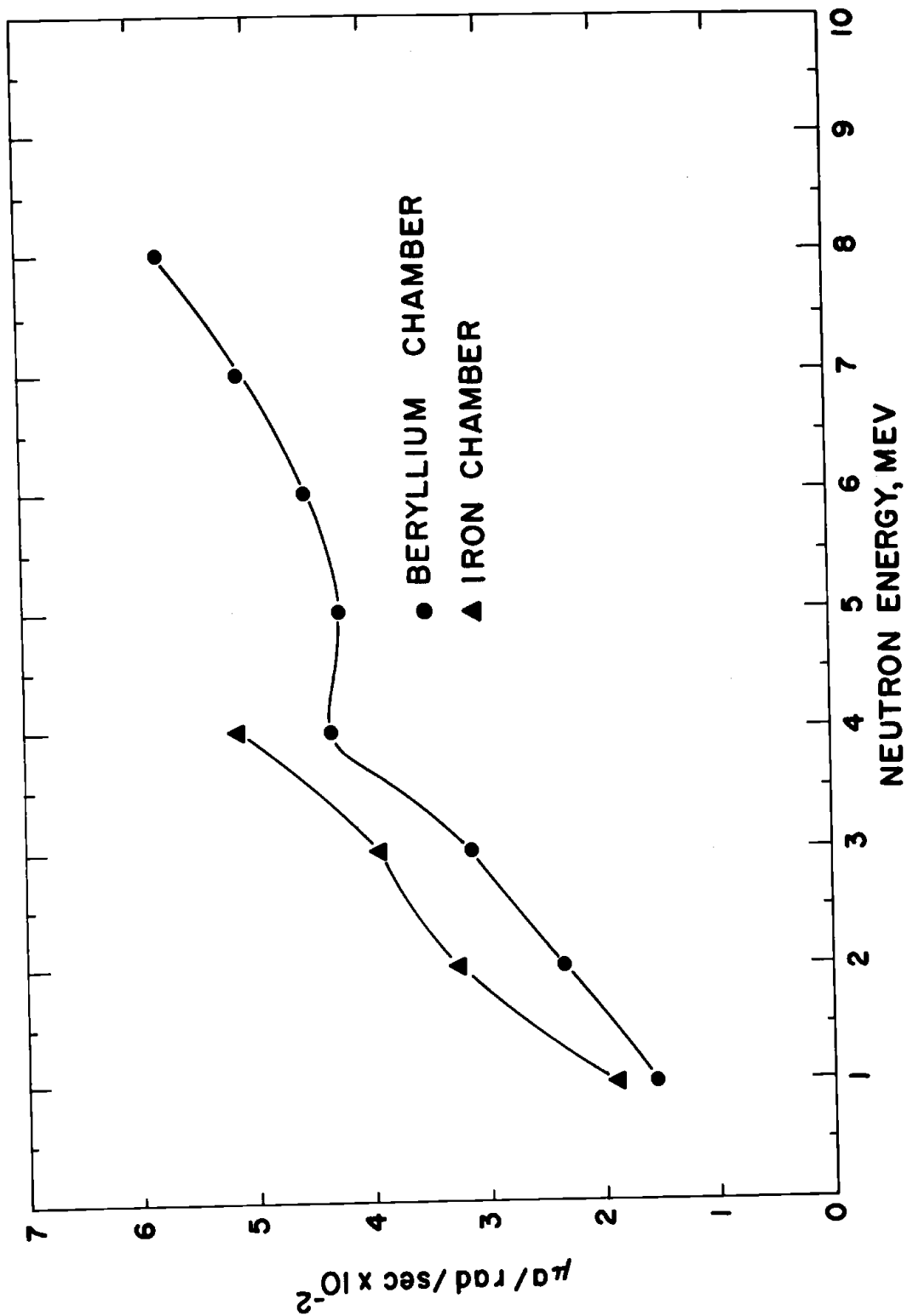


Fig. 5. Effect of neutron energy on PM gamma-neutron detector response to fast neutrons (p-xylene-D7 scintillator).

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