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ABSTRACT

The fast-neutron detector described here is expected to be most useful for Health Physics purposes. The detector is a cobalt disc embedded in a cadmium-cased paraffin moderator. The Co^{60} produced in a disc during irradiation is measured subsequently with a γ-ray scintillation spectrometer to determine the integrated neutron exposure. The 5.3-year half-life of Co^{60} permits accurate flux integrals to be obtained from exposure times as long as one year. The detector-spectrometer system can measure integrated exposures of 1×10^{7} n/cm^2 or greater; the limit on the minimum detectable flux integral is imposed by spectrometer background count rate.

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DESCRIPTION OF DETECTOR

The fast-neutron detector described here is simple and economical to construct, convenient and unobtrusive to expose at irradiation sites, and yields to relatively straightforward data analysis. It consists of a cobalt disc surrounded by a cadmium-covered hydrogenous moderator. The disc measures 2 in. in diam by 1/8 in. thick and weighs about 57 g. Paraffin is generally used as the moderator material, and can be in the shape of a 6-in.-diam. sphere, a 6-in. cube, or a 6-in. -diam. by 6-in. -high cylinder. With such a moderator thickness, detector response is nearly uniform over a wide range of neutron energies, as shown by the work of Stephens and Smith.[1] The section view of a completely assembled detector appears in Fig. 1.

Assembled detectors are located in a radiation field at stations where information on fast-neutron flux is required. Fast neutrons are moderated as they penetrate the paraffin, and those degraded to thermal energy at the cobalt disc are captured by the disc in the reaction Co^{59} (n, γ)Co^{60}. The Co^{60} content of the disc increases as the irradiation proceeds:

In fact, the Co^{60} content is directly proportional to the time integral of the fast-neutron flux incident on the detector for exposure and decay times short compared with the 5.3-yr. half life of this radioisotope. For example, the amount of Co^{60} present immediately after a 1-yr. irradiation in an arbitrarily varying flux will be within ± 7% of the amount present from irradiation in a steady flux that delivered an equal integrated exposure.

Figure 2 illustrates graphically the relationship among three flux integrals for different time intervals. These curves show the quantity of Co^{60} present at the end of an integration period, compared with the Co^{60} quantity present from an equal integrated steady-flux irradiation. The upper curve is for 100% of the exposure occuring at the end of the irradiation time; the lower curve is for 100% of the exposure occuring at the start of the irradiation time. The horizontal line at 1.0 represents the steady-flux irradiation. Any knowledge of the time variation in neutron-flux intensity will, of course, permit calculation of a more accurate value for the true integrated exposure. Therefore, the upper and lower curves on Fig. 2 represent the maximum possible errors that can result from unknown changes in irradiation rate.

DESCRIPTION OF ANALYZING EQUIPMENT

Analysis of the Co^{60} activity is performed with a γ-ray scintillation spectrometer. A block diagram of the equipment setup appears in Fig. 3. The system shown here is that used for development and calibration of the detector, and is perhaps more complex than would be required for routine analysis.

Decay of Co^{60} is accompanied by the emission of two γ-rays in cascade, at 1.17-Mev and 1.33-Mev energy, respectively. These γ-rays are detected in a 3-in. by 3-in. NaI(Tl) crystal, coupled optically to a Dumont type-6364 5-in.-diam photomultiplier tube. Phototube output pulses are fed to a U.C.R.L. model-5 linear amplifier, which produces output pulses in the range 0 to 150 v

at an impedance level of ~100Ω. These pulses are coupled directly to the various analyzing units. The differential pulse-height spectrum is displayed on a 50-channel pulse-height analyzer, also of U.C.R.L. design.[2]

Only those pulses that fall within the 1.17-Mev and 1.33-Mev photopeaks are accepted as Co^{60} decay events; in this manner the background (BKG) count rate is greatly reduced for a relatively small sacrifice in detection efficiency. One integral scaler is set at the lower edge of the 1.17-Mev photopeak; a second integral scaler is set at the upper edge of the 1.33-Mev photopeak. The difference between these two scaler totals equals the summation of all channels in the differential spectrum within the accepted energy interval. The two-scaler set provides a check on internal consistency of data and offers a possible alternate counting method if no multichannel differential pulse-height analyzer is available.

A third integral scaler is set at a threshold of ~200 kev (lower edge of channel 5) to register a quantity that approximates the total scintillation events per run. A signal derived from the discriminator of this unit drives a binary-scaling count-rate meter, which in turn provides an input signal for the Leeds and Northrup chart recorder. Inspection of the chart record shows whether any significant change in count rate occurs during a measurement period.

The minimum integrated flux we can measure is limited by both the magnitude and constancy of BKG. Although considerable effort has been expended to reduce BKG to a constant low level, because of its present location the system is not useable during Bevatron operation and is noticeably affected by operation of the 184-in. cyclotron. Therefore we must know how BKG behaves during a low-activity determination. The scaler-chart recorder system detects primarily BKG when low-Co^{60}-activity runs are made. An average integral BKG count rate of ~300 counts per minute (cpm) and the smoothing effect of cascaded binary-scaler stages combine to produce a relatively smooth chart-recorder trace.

Thus, changes in BKG count rate of the order of 10% can be seen easily if the changes persist for several minutes, i.e., long enough to perturb a measurement. The chart record has been of great value as a criterion for determining acceptance or rejection of low-activity counting data.

CALIBRATION OF DETECTOR

The detector has been calibrated with PoBe neutrons. A source distance of 50 cm and 166-hr. irradiation time produced an integrated flux of 9.70×10^{8} neutrons per square centimeter (n/cm^{2}) at the detectors. Two cubical detectors were exposed--one with the plane of the cobalt disc perpendicular to rays drawn to the source, the other with the disc plane parallel to these rays--to test whether the detector showed any directional response characteristics, which are undesirable.

Results of the PoBe calibration are shown in Table I. No significant difference exists between the count rates observed from the two discs in different orientations; therefore this detector is nondirectional in its response characteristics. The third entry in Table I shows results obtained with disc 3 counted at a later date, and with a somewhat different BKG count rate. There is good agreement between these two disc 3 determinations. A typical Co^{60} spectrum and a BKG spectrum are plotted in Fig. 4. The Co^{60} spectrum is one of the calibration runs; the BKG spectrum is also from the calibration series. Both spectra are normalized to the same counting time. The counting-window limits are indicated by vertical bars on each spectra at the lower edge of channel 29 and the upper edge of channel 38. Note that in Fig. 4 the BKG count rate in the window is considerably above the normal value indicated below; 184-in. cyclotron operation produces this sort of effect.

The calibration constant of this detector for PoBe neutrons is 1.25 ± 0.03 cpm per 1.0×10^{7} n/cm^{2} integrated flux incident on the detector. The listed error

limits are those that derive from counting statistics alone, and are not meant to imply that our PoBe source strength is known so accurately. Source emission is probably known to within ± 5% absolute. The BKG count rate in the window is nominally 17 cpm. It is practical to measure 10^7 n/cm^2 with this system if the background can be kept constant throughout the counting time. For example, an integrated exposure of 10^7 n/cm^2 can be measured with a standard deviation of about 50% in a 100-min. count with the BKG at 17 cpm. Efforts are currently directed toward decreasing BKG and increasing detection efficiency.

Table I

Cobalt detector calibration, PoBe neutron data.

Disc number	Counts per minute per disc from 1.0×10^7 n/cm^2	
	September 25, 1959	October 2, 1959
3	1.25 ± 0.03	1.22 ± 0.04
4	1.21 ± 0.05	

An unexposed disc, cut from the same stock as the calibration discs, was counted at this time. No Co^{60} activity above the 17 cpm BKG was observed for a 10-min count. More information is needed about the Co^{60} activity in unexposed cobalt, particularly in view of the need to measure near-minimum flux integrals. We must not confuse any preexposure Co^{60} activity level with the activation produced during actual exposures. Work is in progress along this line.

Cobalt disc dimensions were chosen as a compromise among several factors. Both diameter and thickness should be large so that we can achieve a high count

rate per disc from a given flux integral. Disc diameter should be small, how-
ever, so that assembled detectors are of practical size and weight, and so a
reasonable-size NaI crystal can be used to count discs with good efficiency.
The 2-in.-diam is an effective compromise here. Disc thickness was originally
1/8-in. Experiments with discs 1/4-in. thick by 2-in diam showed that this
extra thickness yielded only a 20% greater count rate than 1/8-in.-thick discs
for equal flux integrals; self-absorption during activation had become the limit-
ing factor for the thicker disc. Thus the 1/8-in. value was accepted as the best
disc thickness.

Increased count rate can be achieved if several discs are exposed simultaneous-
ly in separate detectors, and are counted stacked together on the crystal. A disc
is found to give about 80% of the standard-position count rate when counted atop an
unexposed disc. Progressively smaller but worthwile increments are expected
from the addition of several more discs in this fashion. For certain situations
it may even be necessary to use larger-diameter discs (larger detectors) in
combination with "parallel" exposure and "series" analysis in order to make
successful measurements.

Increased counting efficiency can be attained if the cobalt disc is brought
closer to the crystal surface. The crystal in use has an irreducible 3/8-in. space
between the rear crystal face and the closest disc position. A decrease of this
space to about 1/8 in. will be realized in a new Harshaw "matched window" unit
which is on order; a detection-efficiency increase approaching a factor of two
may be achieved here.

A more sophisticated and very attractive low-background detection system
is made possible by virtue of the Co^{60} γ-ray emission as a cascade process.
Thus, a pair of crystals can be used with coincidence counting techniques. One
proposed method is outlined briefly here. Scintillation events in the first crystal
are measured by a single-channel differential pulse-height analyzer set to accept

only the 1.17-Mev and 1.33-Mev photopeaks. Scintillation events from the second crystal are sent to the 50-channel pulse-height analyzer, which accepts for analysis only those pulses in time coincidence with first-crystal photopeak pulses. An entire spectrum is displayed on the multichannel analyzer. The BKG can be virtually eliminated by the coincidence arrangement, and it is possible that the entire spectrum of the multichannel display can be accepted as valid Co^{60} decay counts. Some of the inevitable efficiency loss inherent in coincidence analysis can be regained in this manner. Detectors to implement this approach are also on order.

The energy response of the cobalt detector has not been experimentally investigated in detail. However, since the only essential difference between this detector and the indium foil detector described by Stephens and Smith[1] is the substitution of cobalt for indium, the energy responses are expected to be very similar. Figure 5 shows the measured energy response of an indium detector. This detector employs a 6-in.-diam spherical paraffin moderator. The right-hand ordinate shows counts per minute per disc expected from cobalt for 10^7 n/cm^2 integrated flux of various-energy neutrons, normalized to the measured PoBe neutron point. Both energy response and calibration constant are expected to vary somewhat with detector shape. Thus the sphere will show enhanced response to less than 1-Mev neutrons compared with the cube, and the cube will show enhanced response to greater than 5-Mev neutrons compared with the sphere. The magnitude of change involved here, however, is small and can generally be neglected. The right circular cylinder was recently adopted as the standard detector shape at Berkeley. Additional calibrations at various neutron energies are scheduled, with emphasis placed on learning more completely the response characteristics of the cylindrical detector.

BACKGROUND-RADIATION PROBLEMS

Because of the great importance of the BKG count rate, short descriptions
of the crystal detector, its enclosure, and associated BKG problems are included
here. The NaI(Tl) crystal--a 3-in.-diam by 3-in-thick Harshaw unit--is cased in
electrolytic copper with a fused-quartz end window. The BKG observed with this
crystal is significantly lower than the BKG observed with a second crystal of
equal size but packaged in the conventional aluminum and glass container. Both
crystal and phototube are housed in a lighttight iron box, which is buried inside
a set of shields. A section view of the array appears in Fig. 6, with a cobalt disc
shown in standard counting position. The 4-in.-thick Pb shield is primarily a
gamma-ray absorber. A 0.030-in Cd sheet is provided to capture thermal neutrons;
the outer 3-in.-thick paraffin shield moderates fast neutrons so that capture can
occur in the Cd to prevent these thermal neutrons from reaching the crystal.
(Boron should perform better than Cd in this capacity.)

We can prevent the acceptance of all scintillation events that occur during
the actual acceleration cycles of such pulsed machines as the Bevatron and 184-in.
cyclotron: the data recording units are electronically gated OFF for these periods.
However, the residual BKG observed only during the "quiet" intervals is several
times larger than normal BKG. The excess count rate was thought to be caused
primarily by thermal-neutron activation of the crystal and nearby materials.
To suppress this mechanism, Cd and paraffin were added to the Pb shield. A
series of experiments was performed using the stray-neutron flux from the
Bevatron (the most troublesome accelerator in the present context), which showed
that crystal activation by thermal neutrons can account for essentially all the
excess BKG, and that the Cd - paraffin combination is quite effective. Measure-
ments with a Li^6I crystal show that the complete shield assembly provides an
attenuation factor of ×32 for the neutrons detected by this crystal. Unfortunately,

the count rate above 200-kev-energy threshold with complete shield and typical

Bevatron operation is about 450 cpm compared with the normal expected value of

about 300 cpm. The principal activity is definitely I^{128} with a 25-minute half life;

therefore, relatively short-term changes in Bevatron operation can drastically

change the BKG rate. In addition, sudden activation increases may accompany

sample changing, which requires that the shield be opened. These effects, noted

by observation of the integral BKG count rate, are reflected as equal or even

greater relative changes of BKG within the Co^{60}-photopeak counting window. It

has seemed too difficult to account accurately for such BKG fluctuations, and it

has not been possible to move farther from the Bevatron (575 ft at present

location). Thus the facility is used for low-level counting only when the Bevatron

is off--approximately 10 hr per 168-hr week.

It is important to note that these difficulties are encountered in neutron

fluxes at the shield exterior which are measured to be only:

(a) 4.8 n/cm^2-sec slow-neutron flux (measured with a bare BF_3

proportional counter.)

(b) 2.1 n/cm^2-sec fast-neutron flux (measured with a BF_3 proportional

counter encased in a paraffin moderator of such thickness as to exhibit nearly

uniform response in the neutron energy interval 0.1 Mev to 14.0 Mev).

In particular, we note that the thermal-neutron flux at the crystal is only about

0.15 n/cm^2-sec, and that this small flux induces a measured equilibrium I^{128}

decay rate of about 150 cpm in the 3-by 3-in. crystal.

As a matter of further interest, the cosmic-ray neutron flux at sea level

reported by Hess, Moyer, Patterson, and Wallace[3] can be described in the

following manner:

(a) Total neutron flux intensity, including all energies: 0.04 n/cm^2sec

(b) Slow-neutron flux intensity, including energies from thermal to 30 ev,

detected by bare BF_3 counter: 0.004 n/cm^2-sec

(c) Fast-neutron flux intensity, including energies from 0.1 Mev to 14.0

Mev, detected by moderated BF_3 counter: 0.03 n/cm^2-sec.

If all item-3 neutrons were thermalized at our crystal, an elevation in the

integral BKG rate of about 30 cpm would be expected from I^{128} decay alone. In

addition approximately 30 cpm would arise from the activation process itself by

detection of the capture γ-rays produced in the I^{127} (n, γ) I^{128} reaction. Although

this example represents the limiting case, it is possible that a significant fraction

of the fast flux will be thermalized through an unfortunate combination of moderat-

ing and non capturing materials, to become a potential crystal-activation threat.

These remarks obviously apply to any other neutrons with similar energy character-

istics. The results should be borne in mind when one attempts to perform care-

ful low-level NaI(Tl) counting in the presence of any neutron flux appreciably

greater than the natural BKG (cosmic-ray) flux.

APPLICATIONS FOR THE DETECTOR

For integrated fast-neutron irradiation the practical detectable minimum is

defined here to be 10^7 n/cm^2; there is no practical maximum detectable exposure.

Accurate ($\pm 7\%$) flux integrals are obtained from 1-yr exposure times. Therefore,

the cobalt detector is potentially useful at any location where the flux integral is

$\geq 10^7$ n/cm^2-yr. Several combinations of exposure time and neutron flux to

produce the 10^7 n/cm^2 minimum are listed in Table II and are plotted in Fig. 7.

It is clear that the cobalt detector can provide neutron-exposure information

for the low flux intensities of great interest to the health physicist. An important

use for this detector can be to supply a record of the integrated flux at selected

locations in the vicinity of neutron-producing particle accelerators and nuclear

reactors. This record can be re-examined at leisure, and if properly stored in

a low-neutron flux area, is a semi-permanent record (5.3-yr half life). In fact

Table II.

Combinations of flux and time to produce minimum detectable integral.

Exposure time		Steady flux
	(sec)	(n/cm^2-sec)
1 hr	3.60×10^3	2800
8 hrs	2.88×10^4	350
24 hrs	8.64×10^4	120
40 Hrs	1.44×10^5	70
168 hrs	6.05×10^6	17
30 days	2.59×10^6	4.0
90 days	7.77×10^6	1.33
365 days	3.15×10^7	0.33

any detector exposed to $\geq$ 10 rem of 1-Mev neutrons can be considered a permanent record, since the activity will be $\geq$ 1.5 cpm after 25 yr decay time.

Such a network of detectors is now in operation at L.R.L., Berkeley. The period of exposure is 30 days, chosen to coincide with the regular monthly exposures of both location films and personnel film badges. Detector stations have been selected on the basis that previous data showed these stations likely to be within the 10^7 n/cm^2 minimum per 30 days. Parts of many permanently occupied Laboratory buildings are suitable from this standpoint. Virtually all Laboratory buildings are suitable for the 90-day period; a schedule for certain stations in this category is being determined.

The integral flux value obtained from cobalt data can be converted to a biological-dose value (rem value) if the neutron spectrum is sufficiently well-known. The experience gained at this Laboratory indicates that the neutron spectrum outside a well-shielded accelerator is relatively independent of both beam-target conditions and beam energy. Therefore, if special external beam situations are excluded, only the flux intensity and not the energy spectrum is expected to vary with accelerator parameters. A relatively few spectral measurements can then be used to provide factors for conversion of cobalt integral flux to rem values. A method used extensively at Berkeley for this purpose employs two counters exposed simultaneously to the neutron flux:

(a) Polyethylene-lined proportional counter with response proportional to the product of energy and flux density over the neutron energy range 0.1 to 14 Mev.

(b) Moderated BF$_3$ proportional counter with response independent of neutron energy over the range 0.1 to 14 Mev.

The ratio of counts from these two counters is used to determine the mean neutron energy. This mean neutron-energy value is then used to determine the rem value appropriate to the flux integral obtained at that location.

Another application is in conjunction with, or in some cases as a substitution for, the "Oak Ridge type" threshold detector system recently adopted for potential criticality accident situations. The low cost of the cobalt detector, the ease of fabrication and exposure, the straightforward and unhurried analysis, and the permanence of record are advantages to be considered here.

The detector could also be used as a dosimeter for experiments in which integrated exposures of $>10^7$ n/cm^2 are delivered. The permanence of this detector record may be an advantage here; it may also be useful as a comparison against other dosimetry methods.

Problems such as standardization of counting techniques, calibration of detection systems, and intercomparison of results are expected to present only minor difficulties. In the first place, standard Co^{60} sources are readily available from the commercial market. Secondly, activated cobalt discs identical to those used in the detector can be produced easily by short irradiations in neutron beams of accelerators or reactors. And finally, particular activated discs can be sent around to all interested laboratories so that direct intercomparisons can be performed. The long half life is advantageous for all these purposes.

PRECAUTIONS

Several notes of caution deserve mention in connection with the detector and its use. At least 1 hr. should come between the end of a detector irradiation and the start of a cobalt-disc activity measurement. This period will allow for essentially complete decay of 10.5-min metastable Co^{60} (mainly into 5.3-yr Co^{60}) and will also eliminate the presence of an unwanted 1.33-Mev γ-ray which accompanies the other branch (0.3% probability) of 10.5-min Co^{60} decay.

If near-minimum flux integrals are expected, it is important to know the pre-exposure Co^{60} count rate of the discs. As a corollary, it may be important to

store unexposed cobalt in a low-flux area; this should not be a difficult require-
ment. Storage of exposed discs may require a similar low-flux area if long-
term data preservation is desired.

A potential difficulty with all activation detectors is the possibility that
competing reactions will produce radioisotopes which decay in a manner that
interferes with correct evaluation of the desired activity. The use here of a
thermal-neutron reaction of relatively large cross section (36 barns) tends to
minimize the difficulty because all competing reactions are high-energy reactions
with much smaller activation cross sections. However, a low cross-section
reaction that produces a short-lived activity can cause trouble. Therefore it is
necessary to be particularly careful when analyzing discs that have been exposed in
situations likely to produce such activities. The competing reactions generally
have thresholds of 8 to 10 Mev per nucleon or higher and are not expected to be
troublesome outside well-shielded accelerators or reactors. However, exposure
to the unmoderated fission spectrum or to the energetic particles in unshielded
locations at high-energy accelerators are potentially troublesome situations.
For such cases it is important to examine the shape of the entire differential
spectrum carefully, especially with regard to unwanted photopeaks at or above the
Co^{60} peak positions. It may be possible to correct for the competing activities by a
process of channel-by-channel subtraction of appropriate amounts of the pure γ-ray
spectra from these isotopes. This technique is most successful when the unwanted
isotopes are few, have simple spectra, and are available in reasonable purity
as separate sources from which can be obtained the "master spectra" shapes required
for the empirical subtraction process. However, the competing reaction products
may be numerous, with resulting complex spectra. Then the most promising
approaches would seem either to await sufficient decay of these products so that
they can be ignored, or to make a detailed study of changes in the spectrum as
decay proceeds. In general, discs that require the complex-analysis techniques

will also show relatively high count rates, by virtue of the large exposures typically delivered in this sort of situation. Such discs will therefore make it possible to achieve the good statistical accuracy required for successful analysis by these methods.

DETECTOR FOR THERMAL NEUTRONS

The bare cobalt disc, without moderator or cadmium cover, can be used to integrate the thermal component of a neutron flux. The methods of analysis and precautions to be observed are identical to those which apply in the case of a fast-neutron detector. The activation produced by a thermal-flux integral is expected to be nearly the same as that produced from an equal fast-flux integral incident upon an assembled detector. The bare disc is therefore a very sensitive thermal-neutron detector from the standpoint of minimum detectable biological dose.

FUTURE PLANS

The direction of future effort has been indicated at appropriate places in the previous pages. In brief summary of the main items: efforts will be directed to increase counter efficiency, decrease counter BKG, and obtain good calibrations at several neutron energies. Particular importance is also placed on the coincidence-analysis technique. Progress along these lines, as well as representative data obtained from actual exposure periods, will be reported when such information is available.

CONCLUSIONS

The cobalt fast-neutron integrator is a simple and inexpensive detector which can perform accurate long-term flux integration. The detector sensitivity and the time-scale of activation or decay are such that accurate data can be obtained in the low fluxes of interest to the health physicist, and in practical time intervals. Furthermore, the data are faithfully retained, with a 5.3-yr half life, when proper storage precautions are taken. The detector could come into widespread use as the nuclear-energy field continues to expand and as greater importance is attached to the sort of information this device can provide.

ACKNOWLEDGMENTS

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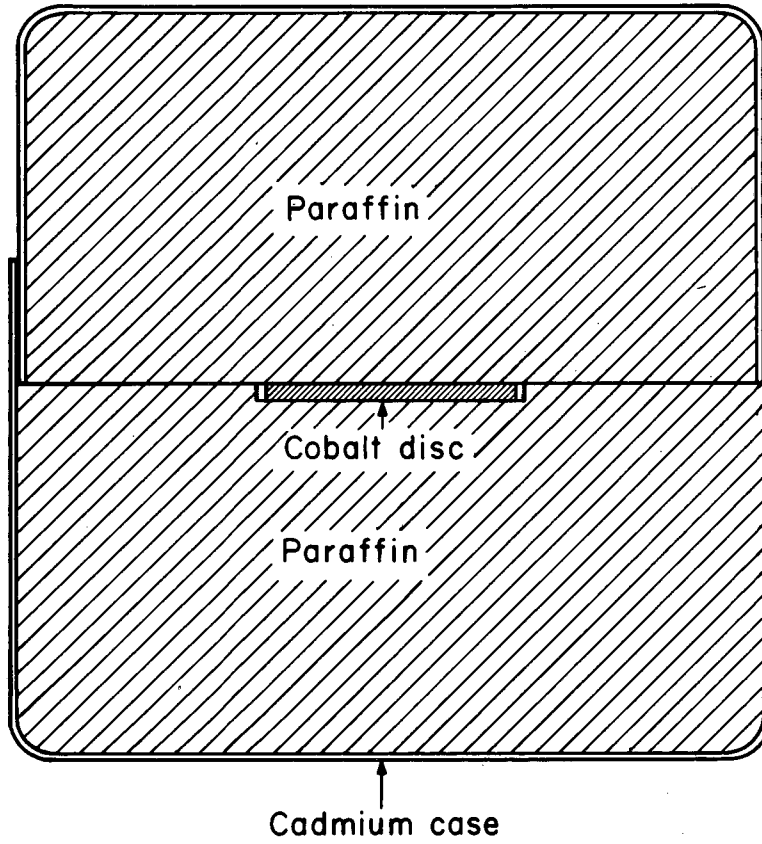
MU – 20803

Fig. 1   Cut-away view of assembled detector.
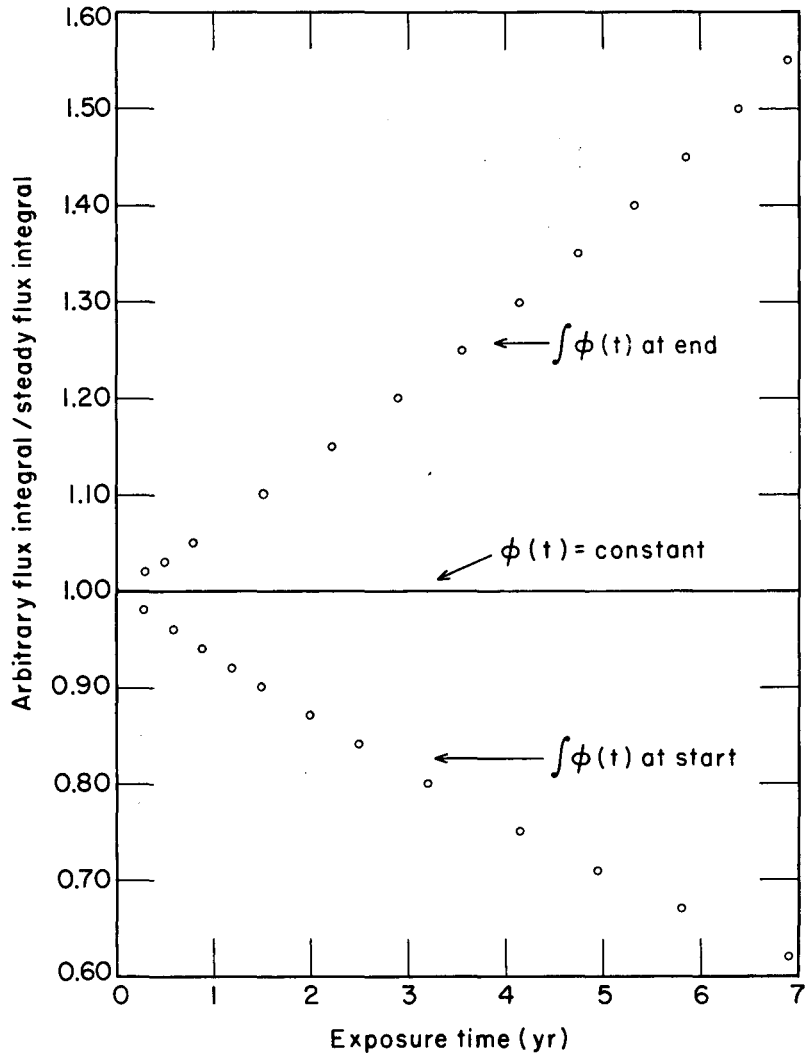
Fig. 2. Relationship among different time-dependent
         flux integrals.
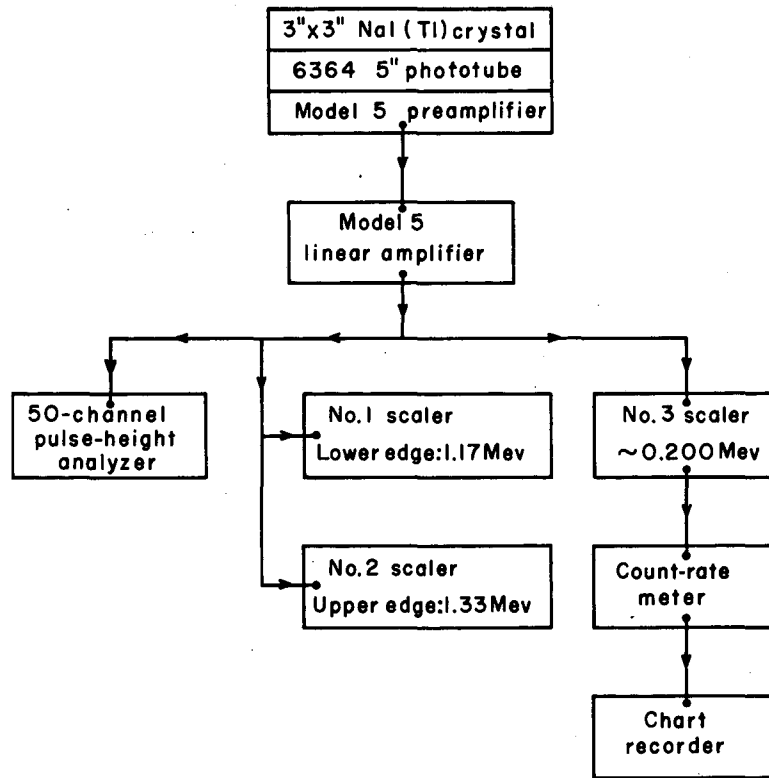
MU — 20805

Fig. 3. Block diagram of Co^{60} analysis equipment.
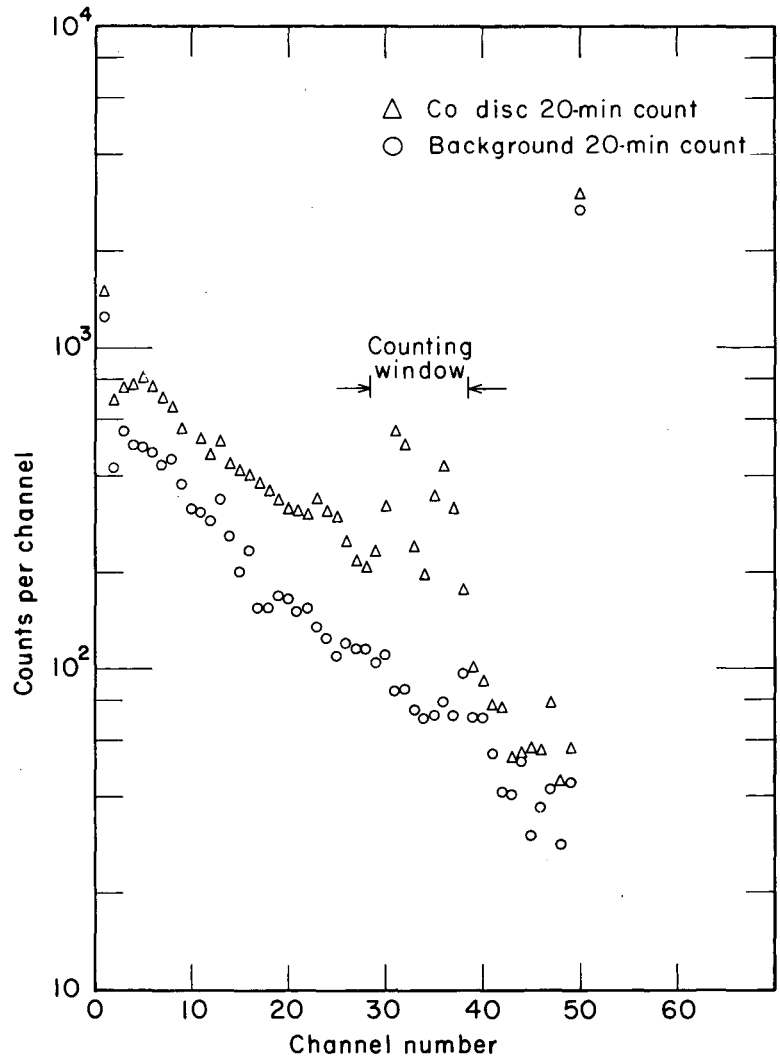
Fig. 4. Typical differential spectra for BKG and
activated disc.
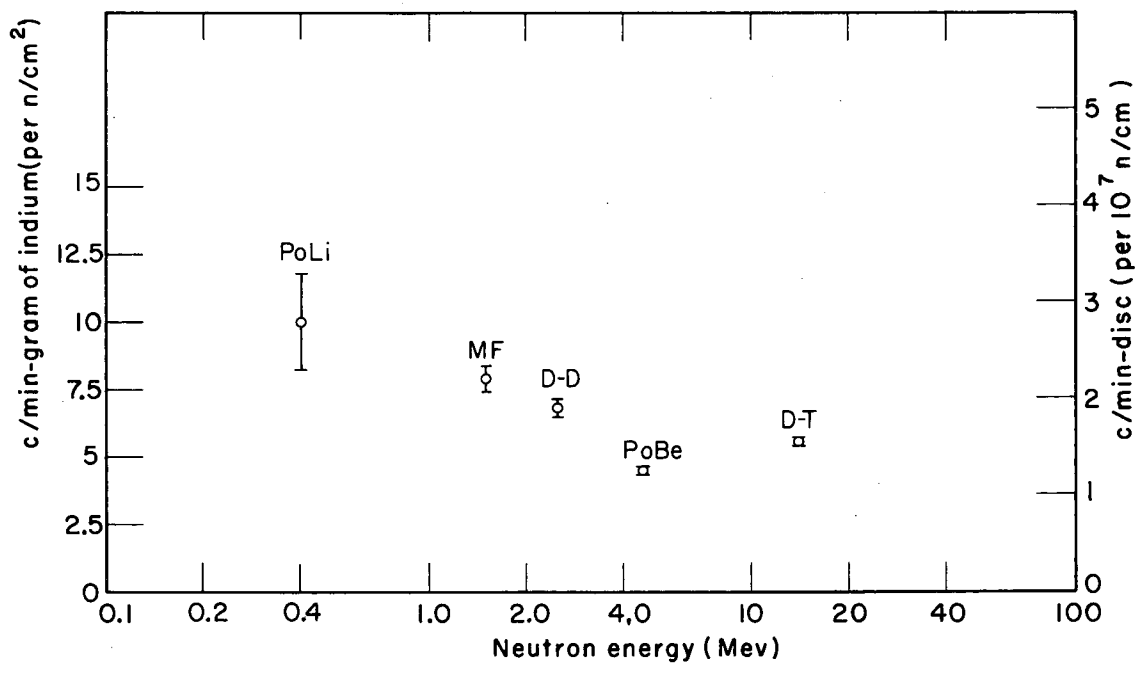
Fig. 5.   Energy response of detector.
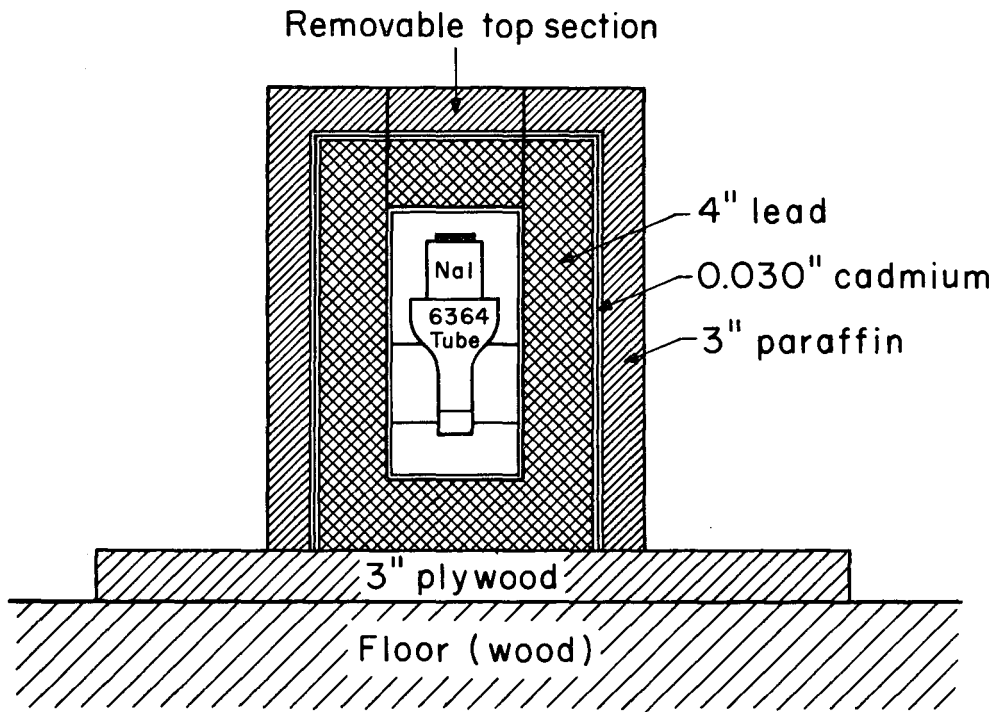
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Fig. 6. Cut-away view of the crystal shield.

Fig. 7. Combinations of exposure time and neutron flux
to produce the 10^7 n/cm^2 minimun detectable integral.