Radiation Sensors

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1. Introduction

In Japan, the number of enterprises using radiation reached approximately 4,900 in March 1991.

In most of these enterprises, radiation sensors are used for some purpose or for radiation monitoring. The ptinciples and construction of many radiation sensors different with the type of radiation (nuclide). The principle of detection of the radiation sensors typically used and typical products are introduced here for each nuclide.

2. Types of Radiation Sensors

The types of radiation sensors have their origins in the atoms of the generation source or the nuclear process. For convenience, radiation sensors are grouped into the following four types:

(1) Charged particle radiation
 (a) Fast electron: Beta-ray (β)
 (b) Heavy charged particle: Alpha-ray (α)
(2) Uncharged particle radiation
 (a) Electromagnetic radiation: X-ray (X), Gamma-ray (γ)
 (b) Neutron radiation: Neutron-ray (n)

The energy range of each of these radiations differs considerably with the radiation handled or the nuclide.

The energy range of the radiation handled at nuclear power plants differs considerably from 2 to 8 or more digits for the nuclides:

β-ray: 10keV to 10MeV
X-ray: 10keV to 500keV
γ-ray: 10keV to 10MeV
n-ray: 0.025eV to 14MeV

The radiation sensor uses the features and properties of each of these nuclides, and their manufacture is based on the principles and specifications given below.

2.1 Geiger-Mueller counter tube

The Geiger-Mueller counter tube (GM counter) can directly obtain a large current pulse signal of about 50 to 500 μA by the amplification action of the gas sealed in it (when radiation is emitted in a high voltage field, ion pairs are generated by the ionization action of the radiation and 10^9 to 10^{10} ion pairs are produced by generating the electron flow phenomena).

At the present time, halogen gas is mainly used as the filling gas because of its reliability, life, etc.

An basic counting circuit using a GM counter is shown in **Fig. 1**. Here, resistor R and capacitor C are connected directly in front of an ordinary GM counter and have an external quenching role which bypasses the pulse signal at current pulse generation by C and assists quenching of the pulse current immediately following that by dropping the voltage with resistor R.

Fig. 1 Basic counting circuit using a Geiger-Mueller counter

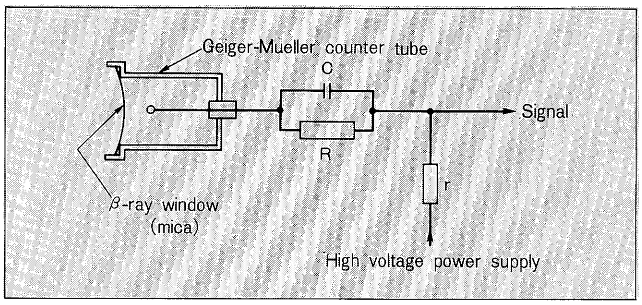


Table 1 Comparison of types and characteristics of Geiger-Mueller counter

Specification \ Model	NGMH9310-1	NGMH9212-4	NGMH8162-3
Type	End window type	End window type	Side window type
Application	β-ray, γ-ray	β-ray, γ-ray	γ-ray
Operating voltage (V)	700	700	700
Plateau range (V)	150	150	150
Plateau slope (%/100)	15	15	15
Natural background (cpm)	40*	60*	40*
Dimensions (mm)	ϕ63x101	ϕ26x158	ϕ24x158
Quenching gas	Halogen gas	Halogen gas	Halogen gas
Window thickness (mg/cm^2)	2 to 3	2 to 3	approx. 450

*: In a shield case with 50mm thick lead wall

A comparison of the types and characteristics of the GM counter is shown in **Table 1**.

2.2 Scintillator

When comparatively transparent matter was irradiated by radiation, the radiation can be detected by means of the scintillation light generated in the matter. The functions required as a scintillation material are:

(1) It must be possible to detect radiation at the highest scintillation efficiency.

(2) It must be possible to convert to pulse light as a strong/weak signal of light with as much proportionality as possible with the radiation irradiation energy.

(3) Since the emitted light is converted to an electric signal by a photoelectric sensor (photomultiplier, etc.), light transmittance must be good and the wavelength of the emitted light must be as close as possible to the sensing wavelength of the photoelectric sensor.

Sodium iodine [NaI (T1)] is generally used for γ-ray detection as an inorganic alkali crystal. Here, talium (T1) is doped as the wavelength shifter to match the sensing wavelength of the photomultiplier.

Generally, a scintillate with a fluorescent included in a plastic is used as an organic crystalline scintillator. This scintillator is mainly used for β-ray detection. Another special material is a transparent plate coated with a powder of zinc sulfide activated with silver [ZnS (Ag)]. However, since it cannot be procures as a transparent body, it is mainly used as a thin film sensor for α-ray and heavy ion detection.

A comparison of the types and characteristics of the scintillator is shown in **Table 2**.

2.3 Ionization chamber

An ionization chamber directly detects the ionization action of the gas atoms produced along the path of the radiation when radiation passes through the air or a gas. Its detection principle is the most basic, but since the sensor itself does not have any amplification action, the output signal (current) handled is a very small 10^{-15} to 10^{-8} A and as mentioned at the beginning, its measuring range is wide. Except for special ventilation type ionization chambers that measure the density in air, etc., the sensor is generally constructed by placing a collection electrode in a sealed cylinder and selecting the filling gas from inert gases to match the purpose. Generally, the gas is selected from argon (Ar), neon (Ne), xenon (Xe), etc. as a stable inert gas that generates many ion pairs in the same gas when irradiated by radiation. However, when irradiated by radiation that generates a charge of 2.58×10^{-4} C in 1kg of air, because the illumination amount in the old unit system can be converted to one roentgen, a sensor that uses air itself inside, such as a survey meter, may also be used.

Since the output current of an ionization chamber is very small, as mentioned earlier, the DC amplifier that amplifies this signal is a high impedance circuit. The basic circuit diagram of an ionization chamber type detector is shown in **Fig. 2**.

When the measuring range is about 2 to 3 digits, $R_1 = 10^{12}\ \Omega$, $R_2 = 10^{11}\ \Omega$, and $R_3 = 10^{10}\ \Omega$ are provided as the high resistances of **Fig. 2** and the objective output is found from the equation $E = IR$ by selecting the resistor with a high impedance switch. When a measuring range of 4 to 6 digits is necessary, or when the elimination of range switching is desired, the logarithmic chamber type

Table 2 Comparison of α-ray, β-ray and γ-ray scintillators

(a) α-ray scintillator and β-ray scintillator

Type	Crystal dimensions (mm)	Dimensions (mm)	Fluorescent matter	Application
NSB04AY0-6	ϕ45.0×7	ϕ54×9.5	Scintillate	β-ray
NSR04AY0-1	ϕ45.0	ϕ54×9.5	ZnS (Ag)	α-ray

(b) γ-ray NaI (Tl) scintillator

Type	JIS type	Dimensions (mm)		Energy resolution	Application
		Exterior	Height		
NSG04BY0-4B	4B4B	32.4	32.5	9% or less	General measurement
NSG07BY0-4B	7B7B	51.5	32.5		
NSG07BY0-4B	7B4A	51.5	32.5	6.5% or less	High resolution
NSG07BY0-8B	7B8B	51.5	57.9	9% or less	General measurement
NSG08BY0-8B	8B8B	57.8	57.9		
NSG12BY1-2B	12B12B	83.2	83.3		
NSG07WA0-8B	7WA8B	51.5	57.9	11% or less	Micro measurement (Well type)
NSG08WB0-8B	8WB8B	57.2	57.9		

Fig. 2 Basic circuit diagram of ionization chamber type detector

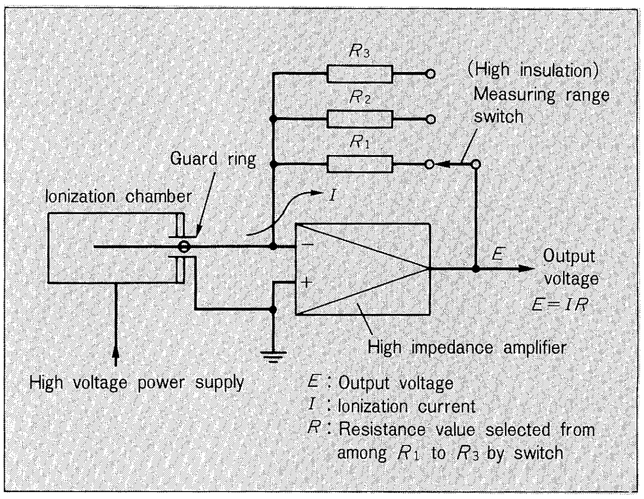


Table 3 Types and characteristics of logarithmic ionization chamber detector

Item \ Model	NDC22	NDC23	NDC24	NDC25	NDC26
Measuring range	0.1 to 10 μGy/h	1 to 10^2 μGy/h	10 to 10^3 μGy/h	0.1 to 10 mGy/h	1 to 10 mGy/h
Energy characteristic	±10% for 80keV to 1.3MeV γ-ray				
Output	0 to −1V at measuring range				

detector using a log diode or other logarithmic conversion elements instead of the high impedance amplifier above is often used.

The types and characteristics of the logarithmic chamber type detector are shown in **Table 3**.

2.4 Proportional counter

In principle, the construction of the proportional counter is the same as that of the GM counter. However, whereas the GM counter is used in the Geiger-Mueller range that is not affected by the energy of the irradiated radiation, the proportional counter is used in a proportional range that produces a number of ion pairs inside the counter directly proportional to the energy of the irradiated radiation.

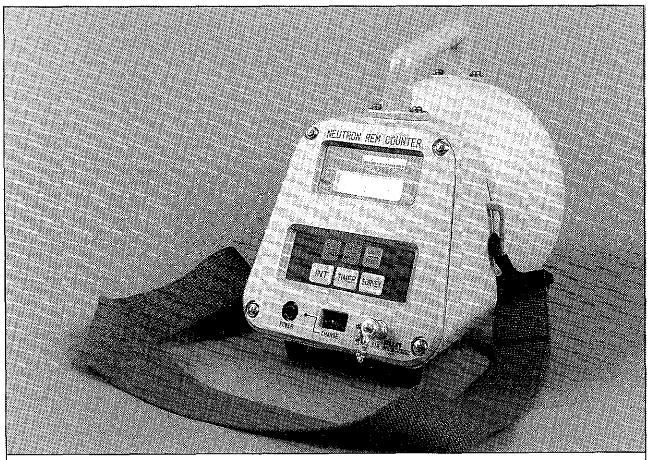
This type of detector consists of a cylindrical or spherical type neutron detector filled with ^3He, BF_3, etc. gas, a large area gas flow counter with a thin film window at the front to detect β-rays, etc. Currently, a neutron rem counter (**Fig. 3**) using a ^3He detector is mainly used in neutron survey meters.

A comparison of the types and characteristics of the BF_3 neutron counter is in **Table 4**.

2.5 Semiconductor detector

When desiring to detect radiation with a small volume, such as the pocket dosimeter, or when wanting to measure the concentration of the radioactivity in the dust in the air over a wide area and with a thin type instrument, etc., the use of a solid detector is often advantageous.

Fig. 3 Appearance and characteristics of neutron rem counter (NSNI)



Type NSN specifications

- Measured ray : Neutron rays
- Measurement sensitivity : Approx. 500cps/μSvh^{-1}
- Measurement dose rate range : 0.1 μSvh^{-1} to 9.999mV Svh^{-1}
- Measurement dose range : 0.001μSv to 9.999mSv
- Energy range : 0.025eV to 8MeV
- Natural background : 0.02cps max.
- Time constant : 1 to 60s, automatic switching
- γ-ray sensitivity : Not sensed up to 0.1 Svh^{-1}
- Dose rate linearity : Within $\pm$20%
- Directivity : Within $\pm$10%

With semiconductor detectors using silicon, a depletion layer that does not have electrons and holes is produced by providing a pn junction, or hetero-junction surface, on a high purity silicon substrate and applying a reverse voltage to both electrodes. Generally, a signal is obtained by generating an electron and hole pair charge by means of the energy of the radiation irradiated in this area.

The features of the semiconductor detector are long life, small size, high voltage unnecessary, etc. However, because the signal output does not have the same amplification action as the ionization chamber, a high gain pulse amplifier is necessary immediately following, or integrated with, the detector.

However, since the most important advantage of the semiconductor detector is that, compared to the ionization chamber and other detectors, the ionization energy is one or more digits smaller than detectors using air, liquid, scintillator, etc., the output signal for radiation of the same energy is at least 10 times larger and the signal/noise ratio is excellent.

The basic circuit diagram of the semiconductor detector is shown in **Fig. 4**. As shown in the figure, when reverse voltage V_0 (called the bias voltage) is applied between the

Table 4 Comparison of types and characteristics of BF_3 counter

Item \ Type	NDB52152	NDB52352	NDB54352
BF_3 gas pressure (cmHg)	15	35	35
Operating voltage (V)	1,400±200	2,000±200	2,000±200
Dimensions (mm)	ϕ25×266	ϕ25×266	ϕ25×446
Effective length (mm)	120	120	300
Effective volume (cm^3)	54	54	136
Sensitivity to thermal neutrons (cps/n/cm•s)	0.94	2.19	5.47
Application	General metering and monitoring		General metering and monitor (high sensitivity)

Table 5 Comparison of types and characteristics of pocket alarm dosimeter

Item \ Type	NRQ	NRP
Detector	Silicon semiconductor detector	Silicon semiconductor detector
Measured nuclide	x-ray and γ-ray (50keV to 6MeV)	x-ray and γ-ray (50keV to 6MeV)
Energy dependency	Within ±20% (70keV to 6MeV) However, reference point is 1cm dose equivalent energy characteristic.	Within ±20% (70keV to 6MeV) However, reference point is 1cm dose equivalent energy characteristic.
Calibration integration accuracy	Within ±10% (^{137}Cs, 1mSv/h)	Within ±10% (^{137}Cs, 1mSv/h)
Dose equivalent rate linearity	Within ±10% (^{137}Cs, 0.1mSv/h to 300mSv/h, reference dose equivalent rate 1mSv/h)	Within ±10% (^{137}Cs, 0.1mSv/h to 1Sv/h, reference dose equivalent rate 1mSv/h)

Fig. 4 Basic circuit of semiconductor detector

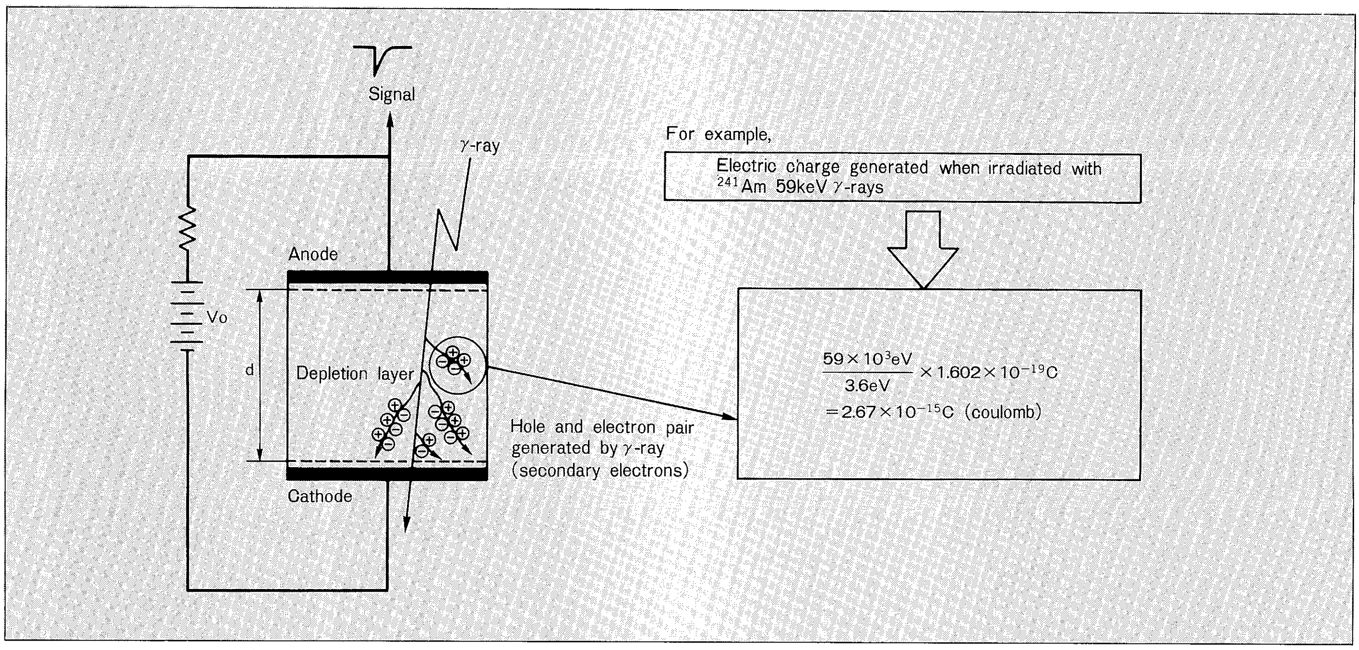


Fig. 5 Principle and characteristics of high-energy correct semiconductor detector

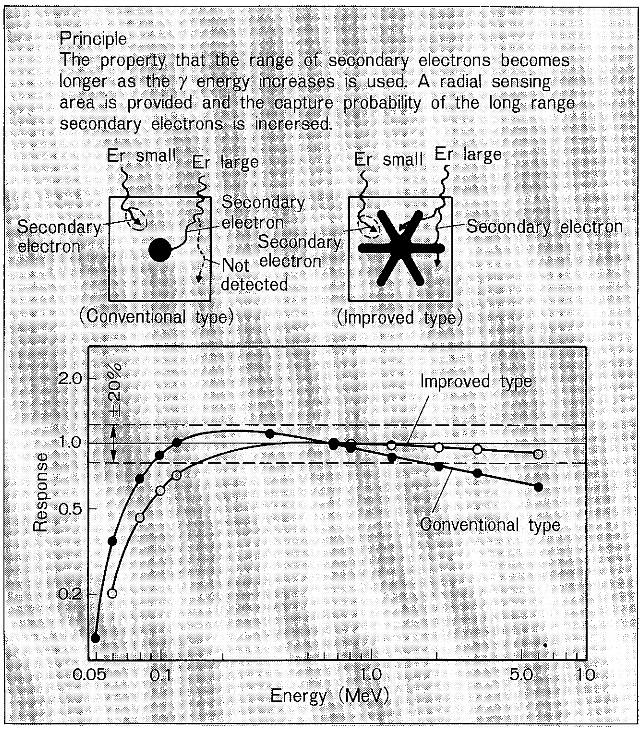
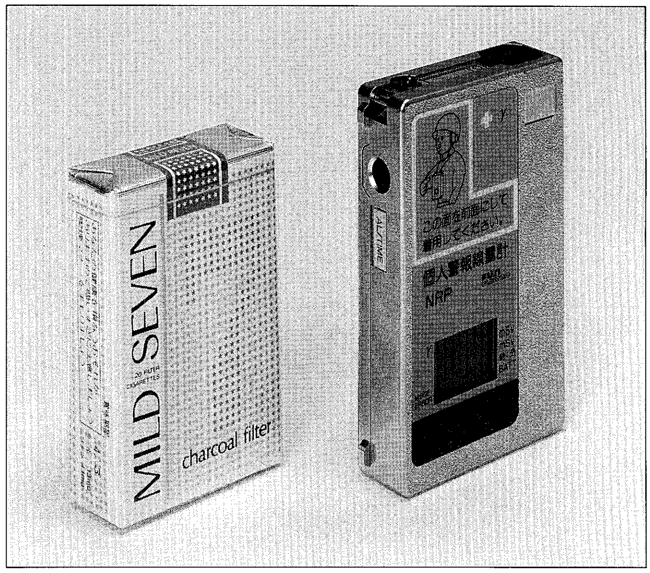


Fig. 6 Appearance of pocket alarm dosimeter (NRP)



anode and cathode, the depth d of the radiation sensing layer (called the depletion layer) corresponding to the solid ionization chamber of a silicon detector is

$$d\,(\mu\mathrm{m}) = 0.33\sqrt{\rho \cdot V_0} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where, ρ = specific resistance of silicon material (Ω cm). For example, when this depletion layer was irradiated with γ-rays, a charge (hole and electron pair) proportional to the energy of the γ-rays is generated. However, in many cases, the thickness d of the depletion area is insufficient to absorb all the radiation (for example, ^{137}Cs, ^{60}Co, and other high energy γ-rays). Therefore, a charge is generated by secondary electrons including some direct rays and Compton and other scattered rays. The affect of these scatter rays generally makes a larger contribution as the energy of the irradiated radiation becomes stronger.

A detector proposed as a method that does not reduce sensitivity even at high energy by using this phenomena is shown in **Fig. 5.** By making the electrodes a special

Fig. 7 Block diagram of pocket alarm dosimeter

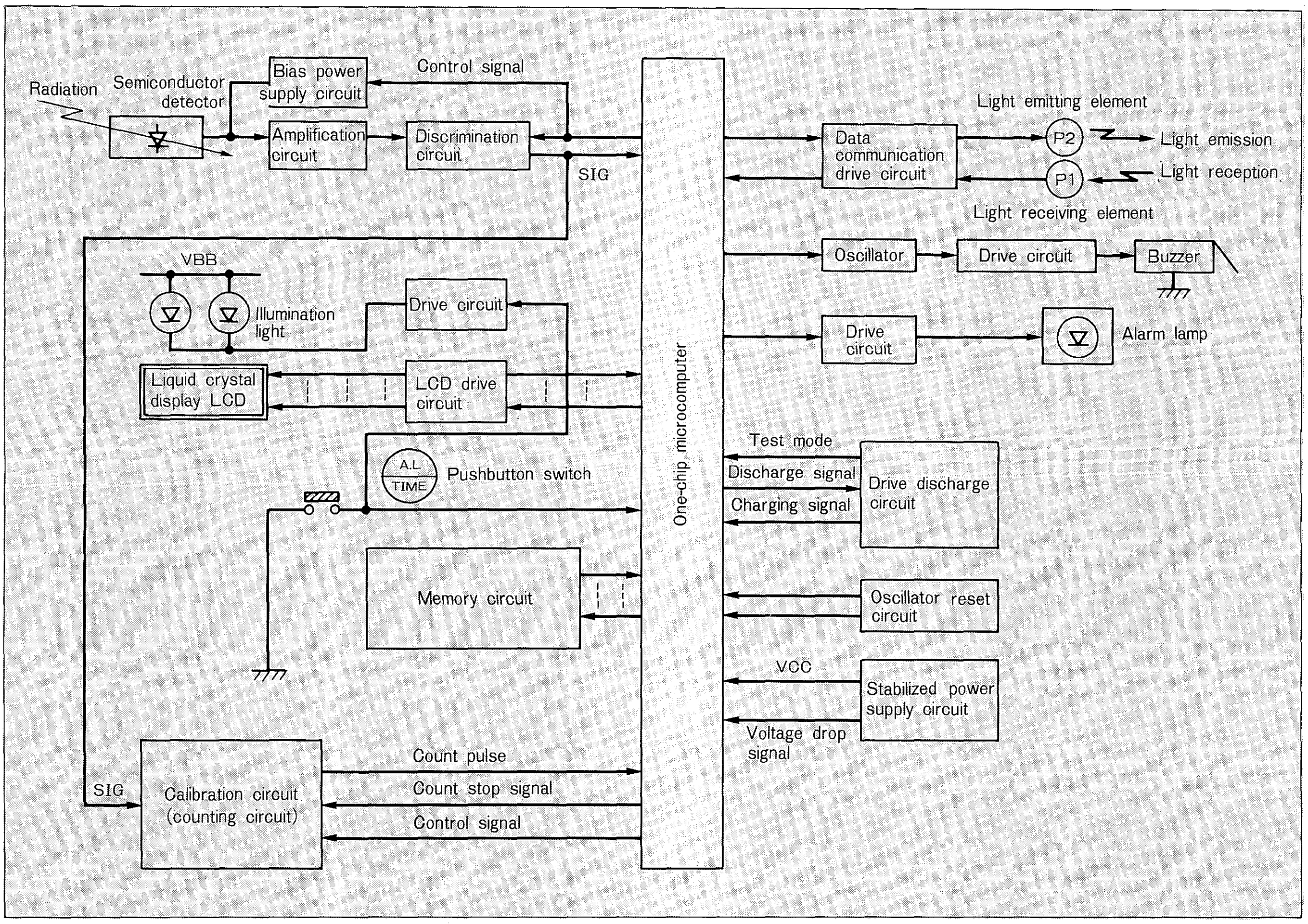
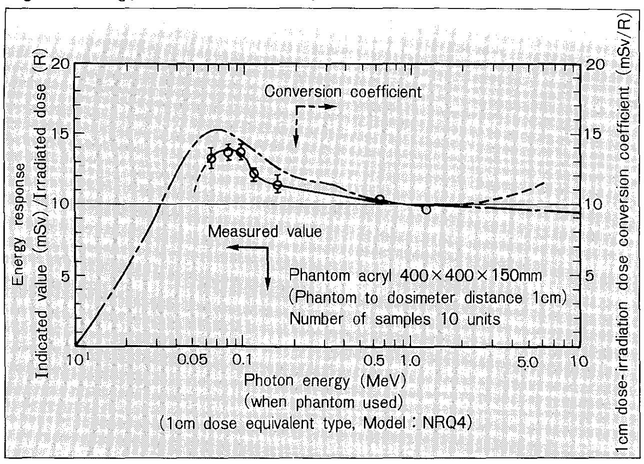


Fig. 8 Energy characteristics of pocket alarm dosimeter (NRQ4)



shape, the probability of irradiation by scattered rays apart from the sensitive region of the depletion layer increases as the radiation energy is increases. As a result, a uniform energy characteristic within an error of about ±20% to low energy γ-rays is obtained without a significant drop of high energy γ-ray sensitivity.

Because of the recent demand for dose equivalent characteristics, a equal dose equivalent detector has also been practicalized by adding an energy filter at the same detector, in addition to the basic concept above. The pocket alarm dosimenter shown in **Fig. 6** is a practical example of this detector. This dosimeter can be realized together with advanced functions by taking advantage of the small size, high sensitivity, light weight, high voltage unnecessary, and other features of the semiconductor detector and using a microcomputer at the electronic caluculating section. (**Fig. 7**) The energy characteristic of this dosimeter (NRQ4) is shown in **Fig. 8**. A comparison of the types and characteristics of the pocket alarm dosimeter is shown in **Table 5**.

There are also area monitor detectors (**Fig. 9**) used in work environment measurement, etc. and dust monitor detectors (**Fig. 10**) to measure the radioactivity concentration in airborne dust, etc. realized by manufacturing semiconductor detectors whose dimensions and shape are matched to the objective.

Since the dust monitor detector measures the radiation of the airborne dust clinging to the surface of the filter paper inside the collector, a detector with a large area (50mmϕ equivalent) and a surface that passes β-rays easily is desired. Therefore, the window of the dust monitor detector of **Fig. 10** uses a special metal deposited thin film and is constructed so that it is not affected by light and

Fig. 9 Appearance of semiconductor type area monitor (NDM)

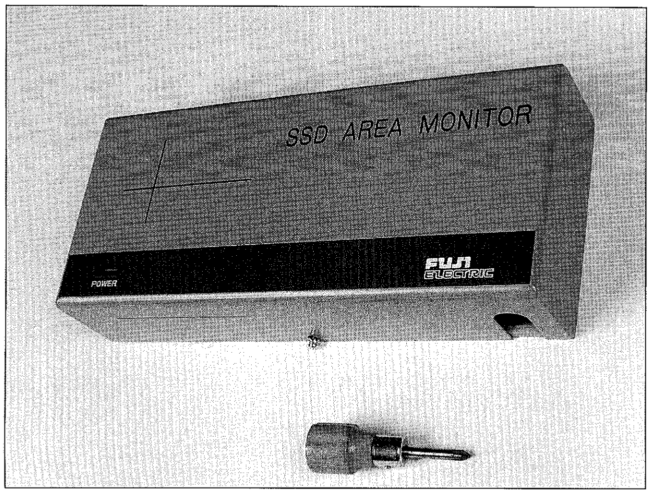


Fig. 10 Appearance of semiconductor type dust monitor detector (NDT)

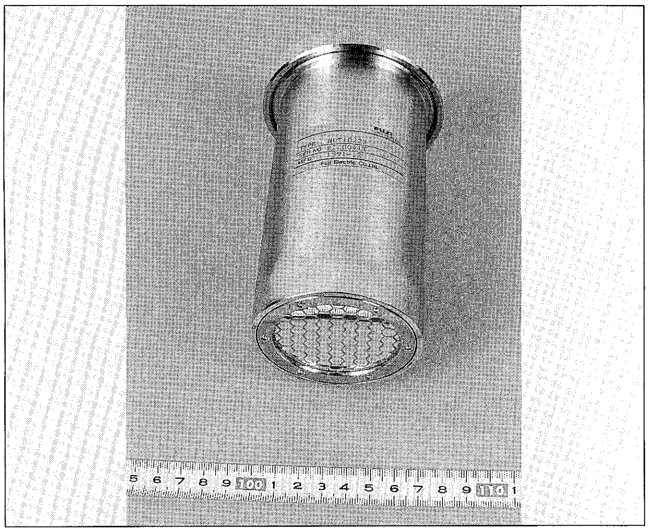


Table 6 Comparison of types and characteristics of semiconductor type area monitor

Item \ Type	NDM1□□□ 1	NDM2 □□□ 1	Dependence
Dosage rate dependence	10^{-4} mSv/h to 10mSv/h (10^{-2} mR/h to 10^{-3} mR/h)	10^{-2} mSv/h to 10^{3} mSv/h (1mR/h to 10^{5} mR/h)	±10%
Measured ray	x-ray and γ-ray		
Directivity	Within ±10% at 0 to 45° Within ±20% at ±(45° to 60°)		
Power requirement	+12V (150 mA), −12V (50 mA)		
Operating humidity range	98%RH or less (no condensation)		
Output pulse width	2 μs ± 20%		
Output pulse peak	+1.0V or more (75Ω termination)		
Dimensions	330×140×68 (mm) (including cover)		
Mass	Approx. 2.5 kg		

Table 7 Comparison of types and characteristics of semiconductor type dust monitor detector

Item \ Type	NDT101□□	NDT102□□
Measured ray	β-ray and γ-ray	
Effective diameter	ϕ50 mm	
Detection efficiency (cpm/dpm)	U_3O_8 20% or more (radiation source distance 3 mm)	
Natural background	30 cpm max. (in 50mm thick lead shield case)	
Operating temperature range	−5 to +45°C	
Operating humidity range	30 to 90%RH	
Operating lighting range	500 lx max.	
Power requirement	±12V (150 mA), −12V (50 mA) Each ripple 10 mV or less	
Dimensions	ϕ70×185 (mm)	ϕ70×140 (mm)
Mass	Approx. 1.3 kg	Approx. 1.2 kg

electrical noise.

A comparison of the types and characteristics of the semiconductor type area monitor is shown in **Table 6**. A comparison of the types and characteristics of the dust monitor detector is shown in **Table 7**.

3. Future Trend of Radiation Detector

Of the variety of radiation detectors, the one being researched most today is the semiconductor detector. This trend is expected to continue in the future. In particular, α-ray and β-ray surface pollution measurement, with which it is difficult to increase the area, and micro radioactivity measurement in the air are expected to capable of covering a wider area and become more sensitive with improvement of semiconductor manufacturing technology and the demand for improvement of social performance in this field.

4. Conclusion

The radiation sensors introduced this time are typical. Various products matched to the objective, application, and usage environment are manufactured. We will make efforts in the future to practicalize products matched to the demands of the market.