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DESIGN, CONSTRUCTION AND EVALUATION OF A SIMPLE RADIATION MONITOR FOR PROTECTION OF PATIENTS AGAINST DIAGNOSTIC AND THERAPEUTIC RADIATION HAZARDS

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ABSTRACT

A simple, low-cost, versatile and reliable electronic instrument capable of monitoring the intensities(in rads per minute) and exposure times of x-rays and gamma rays used for diagnosis of human ailments and in radiotherapy, and which can remotely shut down a.c. voltage supplies to x-ray and Cobalt-60 therapy machines in case of over-exposure and/or accidental exposure to high level radiation has been designed, fabricated and tested.

The monitor uses an off-the-shelf silicon diode as a direct-reading detector of the radiation because it generates an output current that is linearly proportional to the radiation intensity.

The monitor incorporates a voltmeter which displays voltage for direct reading of radiation intensity, a binary counter and a seven-segment red LED display unit to monitor the radiation exposure time. Also incorporated is an alarm system which sounds a pulsed tone for a fixed time say six seconds to the end of exposure time to warn radiologist(s) that the exposure time is almost over. It also sounds a continuous tone for a desired time say three seconds, if the patient is still exposed to radiation after the exposure time is over. The monitor switches off radiation machines automatically at the end of the continuous tone to avoid radiation hazards. Also, in case of a single accidental exposure to a high dose of radiation within a short time, the radiation machines are again remotely switched off .

The monitor can be used, in general, by a radiologist for any desired exposure time and dose limit that should not be exceeded for both diagnostic and therapeutic radiations, if appropriate circuit components are used
The detecting/monitoring electronic circuit fabricated is presented and described.

Keywords: radiation monitor, patients, radiation hazard, radiotherapy, radiologist.

INTRODUCTION

In hospitals, nuclear research centres and industries, ionizing radiations such as gamma rays and x-rays are often used for specific applications. Both radiations produce ionization in materials they interact with. This property of ionization provides a method for measuring the intensity of each radiation incident on a semiconductor detector (e.g. silicon diode) (Yeboah-Amankwah 1987; Prazak and Scott 1975;Fowler 1959; and Stanton and Lightfoot 1962).The two radiations have high penetrating properties.This fact forms the basis for modern clinical usage of the radiations in diagnosis and treatment of human ailments.

Generally, the use of these radiations can be either very beneficial or hazardous to both human beings and materials. In hospitals, intentional exposure of patients for diagnostic and therapeutic purposes by medical and paramedical personnel is done everyday through the use of x-rays and nuclear machines. For example, in radiotherapy, high voltage x-rays can be used for the treatment of deep-seated malignancies, while low voltage x-rays are useful in the treatment of skin lesions that require only surface penetration over a relatively large area. Certain ailments have been diagnosed using x-rays (National Research Council Committee 1990; Cember 1969; and Williams , Smith ,and Chalke 1962).

In radiological health physics, the two types of exposure attention is focused upon are (Attix et al 1966):

(i) a single accidental exposure to a high dose of radiation within a short time.This is referred to as acute exposure which depending on the magnitude of radiation dose could cause serious damages in human body like blood changes, sterility in human beings, severe nausea, vomiting, e.t.c. leading to sudden death within a few days.

(ii) long-term, low level overexposure, referred to as continuous or chronic exposure. This causes radiation induced cancer (radiocarcinogenesis), genetic effects, cataracts, etc which may not be apparent for years (i.e. delayed effects).

Exposure to radiation should therefore be avoided, and where it is unavoidable as in radiotherapy, the prescribed exposure time and the dose rate should not be exceeded for whatever reasons.

X-ray machines and Cobalt-60 radiotherapy machines are normally equipped with safety devices to protect patients against radiation hazards. To guard against unexpected malfunctioning of these safety devices, an additional protective device such as described in this work becomes necessary. The radiation monitor described in this paper is designed to fill in this gap to provide adequate protective measures against both acute over exposure and long-term low level overexposure to radiation and the associated disastrous biological effects.

The main objective of this design work is to construct an x-ray and gamma ray monitor that will detect if the prescribed exposure time is exceeded and/or the patient receives acute exposure and sound an alarm to enable preventive action to be taken by radiologist or shut down the radiation machines automatically. The radiation dose rate and exposure time

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that can be used for the treatment of a particular diseased tissue depend on the nature of the diseased tissue, the extent of ailment, its location, e.t.c. The monitor has been designed in such a way that the monitor components can be adjusted or substituted with appropriate ones to meet the radiologists prescribed dose rate that should not be exceeded and exposure time for both diagnostic and therapeutic radiations (i.e. a versatile monitor), without changing the principle of operation of the monitor.

ELECTRONIC CIRCUIT DESCRIPTION AND OPERATION OF RADIATION MONITOR

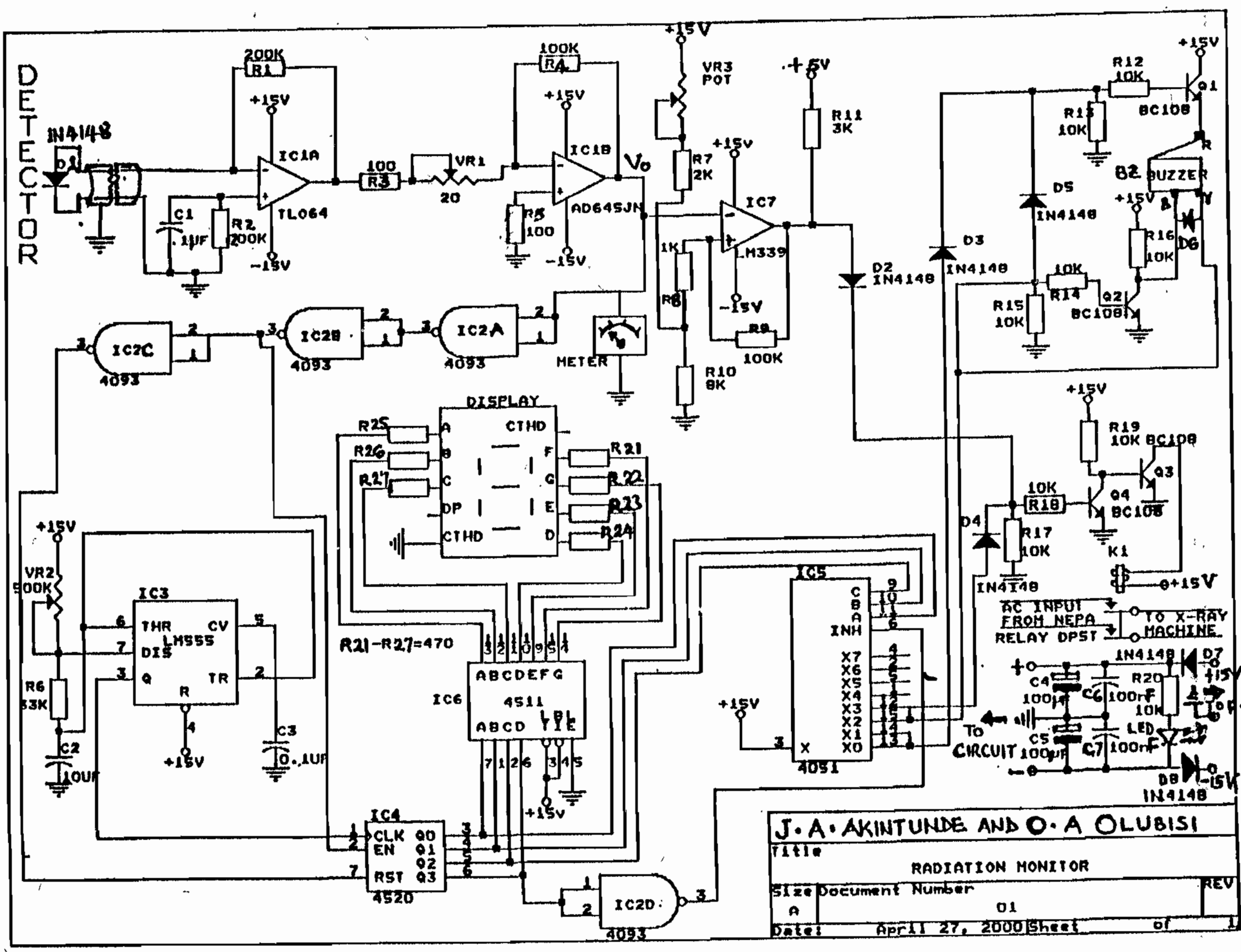
Figure 1 shows the circuit diagram of the radiation monitor. A well regulated power supply, external to the PCB, was used to provide the sta ble direct (d.c) voltages (+15V, − 15V, and +5V) required for the monitor operation. The main sections of the circuit are described below.

Radiation detection

A commercial silicon diode DI (IN4148) operated in a zero-bias short-circuit mode was used for direct detection of gamma rays and X-rays (Prazak and Scott 1975;Stanton and Lightfoot 1962; Jones 1963;and Attix et al 1966). The diode detector to be placed close to a patient was connected to the rest of the electronic circuit by a coaxial cable. Ionizing radiations incident on the diode junction deposit their energies to create electron-hole pairs, which are swept to the terminals by the depletion gradient to produce a low-level current (~nA) in the external circuit, that is linearly proportional to the intensities of the radiations. Thus the photocurrent is a funtion of the absorbed dose rate in the detector.The detector has a linear response.

Signal amplification and processing

The low-level current (~nA) induced in the silicon diode by the ionizing radiations was amplified to a useful level by using a low power BIFET-input operational amplifier IC1A (1/4 TL 064) having low offset voltage drift (±10μV/°C) and low bias current (30pA) (Texas Instruments 1995).The operational amplifier which was connected in a current-to-voltage configuration (Horowitz and Hill 1989) with the inverting input appearing as a virtual ground, delivered output voltages in the range μV and mV, which are well above the noise level. The 200KΩ resistor connected to the non-inverting input was used to balance the inputs to the amplifier, while the 0.1μF capacitor serves to stabilize the amplifier by shunting out noise and preventing



oscillations resulting from positive feedback. A second operational amplifier IC1B (AD645JN) (Texas Instruments,1995) having a lower offset voltage drift (± 1 μV/°C) was used to further amplify the signal to a few volts. The use of 100-ohm resistor was to balance the inputs to the amplifier. In order to calibrate an analogue voltmeter connected to the output of IC1B to indicate directly the radiation intensity in rads per minute, the gain of IC1B was adjusted to a suitable value using the 20Ω potentiometer, such that output voltage of IC1B (i.e V_0) is say 1% or 2% or 5% e.t.c of maximum incident radiation intensity, which is suitable for radiological operations, and to ensure that the output voltage lie within the range of the meter(e.g 0 to 10 Volts or 0 to 100 Volts). Since the diode response has been experimentally shown to be linear, voltage can be displayed on the meter for direct reading of the radiation intensity in rads per minutes. In this work a gain of about 1000 was used

The integrated circuit 4093 is a Quad 2-input NAND Schmitt trigger gate (Motorola, 1996) which converts the analogue signal at the output of IC1B to a digital form through IC2A and IC2B (i.e analogue-to-digital converter (ADC). This digital signal is then used to reset and enable or disable the 4-bit binary counter IC4 (4520) (Motorola, 1996).

Radiation exposure time monitoring

IC3 (LM 555) is a multivibrator (National semiconductor,1995) which gives out a pulse every 3 seconds. These pulses are counted in binary format by IC4 if it's enable input (pin 2) is high. For this design work, the maximum count used was 10 giving a time of 30 seconds. The choice of 30 seconds as the radiation exposure time is just to demonstrate that the monitor is sensitive and works accurately. A radiologist can chose his/her exposure time depending on the nature and extent of the ailment and fix in the appropriate timer and associated components. From Figure 1, the counter is enabled when radiations fall on diode D1 and counts up. If the counter is disabled it stops counting and a reset signal(high) immediately appears on it's reset input 7 to reset the counter. IC6 (4511) is a BCD-to-7 segment decoder, (Motorola,1996) which decodes the BCD code from IC4, to 7 segment code, which the 7 segment display shows. That is BCD data as input and 7-segment display as output. Thus the content of the binary counter is displayed by the 7 segment display.

Alarm and a.c. voltage supply shut down systems

The alarm and a.c. voltage supply shut down systems built into the radiation monitor consists of a buzzer (BZ) that can produce pulsed or continuous tone depending on connections (RS catalogue, 1994/95), a relay(K1) which is a general purpose 4-pole change–over relay (RS catalogue,1994/95),a voltage comparator (1/4339)(National,1995),a 8-input analogue multiplexer / demultiplexer (4051)(Motorola, 1996) connected as a demultiplexer, silicon npn transistors Q_1, and Q_2 (The world transistor cross-reference guide) around the buzzer, and silicon npn transistors Q_3 and Q_4 around the relay with associated diodes and resistors.

The buzzer has the following input terminals – Red(+V), Black(-V),and Yellow(sense lead). Yellow was connected to Black(-V) for continuous tone and Yellow was left unconnected for pulsed operation.

Table 1: Function table for the binary counter (4520)

Count	Outputs			
Clk	Q_3	Q_2	Q_1	Q_0
0	L	L	L	L
1	L	L	L	H
2	L	L	H	L
3	L	L	H	H
4	L	H	L	L
5	L	H	L	H
6	L	H	H	L
7	L	H	H	H
8	H	L	L	L
9	H	L	L	H
10	H	L	H	L
11	H	L	H	H
12	H	H	L	L
13	H	H	L	H
14	H	H	H	L
15	H	H	H	H

When the counter IC4 counts 8, corresponding to a time of 24 seconds(see table 1), Q_3 = H; Q_2 = Q_1 = Q_0 = L and the inputs of IC5 – ABC(figure 1) are C = B = A = L and EN (INH) input = L, which enables IC5. From the function table 2 for IC5, pin 3(i.e X) at +15V is connected to pin 13 (i.e X – X_0), which in turn is connected through diode D3 to the base of transistor Q_1 which becomes conducting. The buzzer input red terminal R is therefore connected to +15Volts. Q_2 is not conducting and –15Volts is connected to the buzzer's input black terminal B. The buzzer starts to sound pulsed tone to warn that the prescribed exposure time is almost over. The buzzer remains in this mode of operation when the counter counts 9 (i.e X – X_1) and 10 (table 2), on the count of which correspond to a time of 30 seconds (table1), and Q_3 = Q_1 = H; Q_2 = Q_0 = L; and the inputs of IC5 ABC(fig. 1) are C = A = L; B = H; and INH input = L.. Pin 3 at +15Volts is connected to pin 15 (i.e X – X2), which in turn is connected to the bases of Q1 and Q2 and the anode of diode D6 which becomes conducting.

Thus the buzzer input yellow terminal Y is connected to the black input terminal B, and +15Volts and -15Volts are connected to R and B/Y buzzer terminals respectively. The buzzer starts to give continuous tone which lasts for 3 seconds i.e until counter counts 11 (X – X3). At count 11, +15Volts on pin 3 is connected to pin 12 which in turn is connected to the base of transistor Q_4. The relay K1,is energized through Q_3 and Q_4 to open a normally closed switch

Table 2: Function table for the 8-channel multiplexer/demultiplexer (4051)

Inputs				Conn.
C	B	A	INH	
X	X	X	H	----
L	L	L	L	X - X_0
L	L	H	L	X - X_1
L	H	L	L	X - X_2
L	H	H	L	X - X_3
H	L	L	L	X - X_4
H	L	H	L	X - X_5
H	H	L	L	X - X_6
H	H	H	L	X - X_7

through which the a.c mains supply is connected to the radiation machines. Thus the radiation machine is remotely switched off to avoid diagnostic and therapeutic radiation hazards.

A reference voltage (Vref) of 10 volts to the comparator (1/4 LM339N) was obtained using two resistors R_7 (2KΩ) and R_{10} (8KΩ), across which a voltage of 12.5 volts was maintained by adjusting POT VR3. In this work, a maximum amplified voltage of 10 Volts at the output of IC1B (i.e V_0)was assumed for a maximum radiation dose rate on a patient(i.e on the detector).Therefore any induced voltages higher than 10 volts indicate that the patient is exposed to injurious high level radiation.The reference voltage (Vref) and the amplified induced voltages (V_i) were fed into the comparator and the output was either high (~5 volts) or low (~0.8 volts) (see figure1). A Pull-up resistor R_{11} (3kΩ) was used at the comparator's open collector output to obtain a non-zero voltage. Resistors 1kΩ and 100kΩ were used to build a small amount of hysteresis for comparator to ensure that the output voltage occurred at a precise value of input voltage. When V_i > Vref, the comparator output is high, Q3 and Q4 are conducting and the relay K1 is energized to open a normally closed swich (DPST) to shut down the a.c. voltage supply to the machine producing the radiation.

METHOD OF MANUFACTURING PRINTED CIRCUIT BOARD

The steps used to manufacture a printed circuit board were choice of PCB material, preparation of positive master transparency, plate sensitization, exposure and processing, etching, drilling and mounting of components by soldering. (RS, 1995;and Jawitz, 1997).

A piece of single sided, photo-sensitized copper clad board measuring 160mm long and 100mm wide was used in this design project.

A computer software called ORCAD was used to prepare circuit diagram. A positive master transparency was produced from the circuit diagram using a photocopier.

The protective coating of the photo-sensitized copper clad board was removed . The board was overlaid with the positive master transparency.

The board was exposed to ultra-violet (UV) light in a Mega LV204 UV exposure unit for about five minutes.

The board was removed from the UV unit, the overlay removed, and quickly placed in the developer, which is sodium hydroxide solution contained in a photographic developing tray. Disposable gloves were used to avoid contact with the developer. The concentration of the developer used was about seven grams of sodium hydroxide crystals in one liter of water at 20°C. The processing time was about two minutes at room temperature. The tray was gently agitated, until the copper track pattern clearly appeared on the surface of the board. The developed board was rinsed under a running water tap.

The board was placed in warm (40°C) ferric chloride solution (i.e.etching solution close to saturation) contained in a PCB etching tray. The etching process was completed in about 25 minutes.

The board was removed immediately from the etching solution and rinsed the second time with water. A high speed drilling machine was used for drilling holes in the PCB, with a 0.6 or 0.8 or 1mm drill bits depending on the size of the leads of the electronic components to be mounted on the board.

All the circuit components were soldered to the PCB using the drilled holes and jumpers, after which the circuit was tested.

PERFORMANCE TESTS

Performance test was carried out on the radiation monitor by simulating the low - level currents (~ nanoamperes) normally induced in the silicon diode (detector) following irradiation of the diode junction by gamma- and x-rays (Prazak and Scott, 1975; Stanton and Lightfoot 1962;andJones,1963) because x-rays machines and Cobalt-60 radiotherapy machines capable of producing variable radiation dose rates used for therapeutic purposes in hospitals were not available. Keithley 263(calibrator/ source) was the current source used, and it was connected to the input of IC1A. The current was varied from 1nA to 60nA in steps of 10nA,and the voltages at the output of IC1B were indicated fairly accurately by the voltmeter. This output voltages varied linearly from ~0.19V to 11.95Volts as the simulated diode current (i.e radiation dose rates if radiation machines were used) was increased (Figure 2). The level of resolution of the meter was better than ± 10mV.

A reference voltage of 10 Volts assumed for the purpose of this test to be the maximum voltage at the output of IC1B, that correspond to the maximum radiation dose needed by a patient, was fixed at the input of the comparator (LM 339 in Figure 1). A voltage of 11.95 Volts at the second input of the comparator obtained by increasing the simulated diode current above the present value of

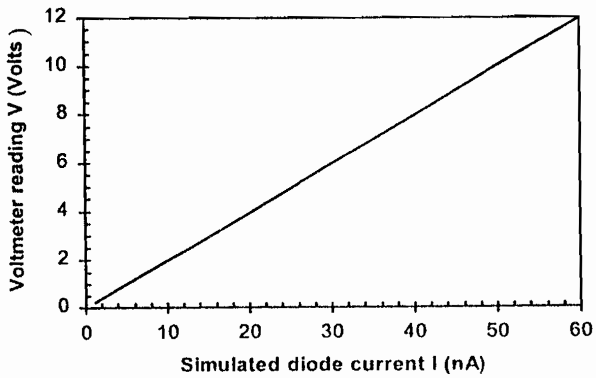


Figure 2

50nA(corresponding to 10 Volts), represents an overdose of radiation, and made relay K1 to be energized leading to the shut– down of a.c voltage supply to the radiation machine to avoid any radiation hazards.

The monitor also showed continuously the radiation exposure time and six seconds to the preset (i.e prescribed) exposure time of 30 seconds(fixed for performance test purposes), the monitor gave pulsed tone to warn that the exposure time was almost over. When the preset exposure time was exceeded, the monitor gave an audio alarm (i.e continuous tone) and the relay K1 was again energized to disconnect the mains voltage supply (240 Va.c) to the machine producing the ionizing radiation

CONCLUSION

It has been demonstrated that low-cost, compact, versatile and reliable radiation monitor can be fabricated locally using an off-the-shelf silicon diode as a direct-reading detector of gamma-and x-rays, commonly available integrated circuits and other discrete components. Cost of components needed to construct the monitor is about twelve thousand naira.The monitor indicates continuous reading of the radiation exposure time, could sound an alarm and remotely shutdown automatically ac voltage supply to external machines producing the radiations when the prescribed radiation dose or exposure time is exceeded to avoid radiation hazards.

The monitor can be used, in general, by a radiologist for any desired exposure time or maximum permissible radiation dose, if appropriate circuit components are selected.

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