CEBAF-PR-91-010

NEUTRON AND GAMMA BOUNDARY RADIATION MONITORING AT CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY

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A combined Neutron and Gamma Boundary Radiation Monitor installed at the Continuous Electron Beam Accelerator Facility (CEBAF) is described. CEBAF, located in Newport News, VA, is managed by Southern Universities Research Association.

The CEBAF accelerator is a high intensity (200 microamp), multi-GeV (4 GeV) continuous wave (CW) recirculating electron linac for research in particle and nuclear physics. The accelerating structure is based on a superconducting 1.5 GHz 5 cell cavity; each cavity is powered from individual klystron power supplies. The electron beams are fed to large shielded experimental halls containing targets and particle analysis equipment from thence to beam dumps.

The Boundary Radiation Monitors are required to measure the small increment to the natural background level that could be attributed to direct or scattered radiation from the accelerator, principally associated with beam handling and experimental equipment.

Present annual radiation limits for prolonged exposure of the population surrounding DOE facilities (excluding natural background and medical treatments) is set at 100 mRem per year for all pathways ("Radiation Standards for the Protection of the Public in the Vicinity of DOE Facilities". Memorandum & Attachments. Vaughan, W. A. Asst. Sec. Environment Safety and Health, U. S. Department of Energy, 5 August 1985). Reporting levels for DOE contractor facilities are established at 25 mRem per year. CEBAF has, therefore, adopted shielding design goals for the "fence post" of 10 mRem per year.

The predominant component of radiation outside shielding of high energy accelerators is from neutrons, normally a small part of natural background. The requirement, therefore, is for a sensitive neutron detection and counting system together with a separate gamma channel.

DESIGN APPROACH:

Traditionally, neutron detectors use a Boron Trifluoride (BF_3) Proportional Counter surrounded by a moderator, so as to permit the estimation of radiation dose equivalent from a neutron spectrum extending from thermal energies up to 20 MeV. The moderating shield is based on the design by Anderson and Braun.

The Gamma Detectors use an Ion Chamber or Geiger Mueller (GM) sensor.

DESIGN APPROACH: (Continued)

Several problems had to be addressed and resolved to satisfy the requirements at CEBAF. This included:

- o High neutron sensitivity
- o Wide dynamic range
- o Common operator controls
- o Adaptive display
- o Simplified calibration

A. NEUTRON DETECTOR SENSITIVITY.

The design goal for the CEBAF boundary was set at 10 mRem per year which is an average rate of approximately 1 uRem/hour. Improvement in the design of the neutron channel was considered to achieve the design goal. These improvements were:

1) Use of a low noise, high gain current amplifier providing better S/N ratio.

2) Operation of BF_3 proportional counter at sensitivity from 8000 counts/mRem to 10,000 counts/mRem.

3) Reduction in spurious noise counts from the chamber.

Tubes were pre-selected for low spurious noise counts. Tests conducted on the neutron detector indicated that total background counts were less than 100 counts over a 24 hour period.

Based on the definition of lower limit of detection (LLD) as given in HASL-300, Part D-08 and recommended by the USNRC and DOE

$$LLD = 1.96 \sqrt{N_B}$$

WHERE N_B is the background counts

$$= 1.96 \sqrt{100}$$

20 counts over 24 hours

A. NEUTRON DETECTOR SENSITIVITY. (Continued)

With a sensitivity of 10,000 counts/mRem for the improved BF_3 proportional counter

$$LLD = \frac{20 \text{ counts}}{10{,}000 \text{ counts/mRem}}$$

$$= 2 \text{ uRem over 24 hours}$$

that is, the minimum detectable rate will be

$$= \frac{2 \text{ uRem}}{24 \text{ hours}}$$

$$= 0.08 \text{ uRem/hr}$$

B. WIDE DYNAMIC RANGE.

To accommodate a wide dynamic range for the gamma measurement (10 uR/h to 50 R/h), a new patented method of operating Geiger-Mueller (G-M) tubes is used. The method, dubbed "Time-To-Count", measures the time elapsed from the instant that the G-M tube bias voltage is pulsed up into its plateau operating region until the first strike is detected by the G-M tube. When the strike occurs, the bias voltage is reduced to less than the minimum operating voltage and a wait period of approximately two milli-seconds is invoked. The tube is enabled again by pulsing the bias voltage high. This process is repeated indefinitely and an average "Time-To-Count" is computed. The radiation field strength is inversely proportional to the average "Time-To-Count".

The "Time-To-Count" technique removes most of the traditionally encountered deficiencies in the use of G-M tubes. Non-linearities due to dead time or recovery time are removed. The technique is inherently non-saturating and non-paralyzing since total recovery is accomplished after each count. Wide range operation (5½ decades) has been achieved in one instrument using a single G-M tube. Tube life is extended since it receives a maximum of 500 strikes per second, even in high fields. A brief description of the Time-To-Count and its advantages over the conventional G-M tube operation is provided in the Appendix.

OPERATION UNDER PULSED SOURCE CONDITIONS.

Many accelerators operate under pulsed conditions in which the pulse repetition frequency is sufficiently low as to give rise to erroneous output from pulse counting detectors such as geigers and to some extent proportional counters and even in extreme cases ion-chambers. In the case of CEBAF, which operates mainly in CW mode, this is no problem; and even in the test pulse mode, where chopped beams are used at say 100 Hz, the geiger will perform adequately at the low average dose rates. However, care should be taken at low pulse repetition frequencies, where all the dose occurs in short bursts of a few hundred microseconds at relatively long intervals.

OPERATION UNDER PULSED SOURCE CONDITIONS (Continued).

Under such conditions, a geiger tube can under-respond and, as the dose rate increases, will progressively under-respond up to the source pulse repetition frequency. This problem is not overcome by the Time-To-Count technique. Information on this aspect of accelerator operation may be found in such reference material as R. C. McCall et al.

Health Physics Manual of Good Practices for Accelerator Facilities, SLAC-Report-327 (April 1988), also from NTIS, U. S. Dep. Com. 5285 Port Royal Road, Springfield, VA 22161. Moderated neutron detectors perform rather better under pulsed source conditions due to the time delay engendered by thermal neutrons in the moderator; an excellent study of this phenomenon is given by H. Dinter and K. Tesch, Nucl Instrum and Methods 136 (1976) 389. At the low fence post dose rates, the neutron detectors would be expected to operate under most conditions but should the geigers give rise to concern, these may be replaced by ion chambers which are less subject to pulsed source radiation problems.

C. COMMON OPERATOR CONTROLS.

A single microprocessor based design was adopted to allow a common display and control module for both channels. The multifunction control module contains a CMOS microprocessor which makes possible the automatic, easy to use features. The processor controls both the detectors, interrogates the probes to identify their type and calibration factors. It also has a serial port for communicating with a PC style computer.

The gamma G-M tube is mounted internally, and provides gamma measurement independent of the attached neutron probe. Thus, gamma measurements are available, even when the attached neutron probe is disconnected or out of operation.

D. ADAPTIVE DISPLAY AND CONTROLS.

The operating controls of the unit consist of a membrane style keypad. The basic operation is the same for each probe, thus simplifying training. The display consists of two lines of sixteen alphanumeric characters. The display automatically shows the appropriate units and radiation type, corresponding to the neutron and gamma channels. The versatile display is used during test and calibration for message prompts. One line of the display is available for use as a bar graph of the radiation strength for rapid trend evaluation.

E. AUTOMATED DATA LOGGING.

Built-in RS-232 communication, real time clock, and non-volatile memory are incorporated to make possible automatic data logging of historical data. Historical data which includes radiation intensity, time, and date are stored automatically.

E. AUTOMATED DATA LOGGING (Continued).

The stored data is later retrieved through the RS-232 port by an IBM style personal computer. Microprocessor software provides step-by-step procedure on the display to allow ease of use with minimum training by both skilled and unskilled personnel.

F. SIMPLIFIED CALIBRATION.

An Am-Be (30 mCi) source was used for regular checking of both channels. Use of smart design allowed remote calibration of the unit. Procedures were incorporated in the software to initiate a calibration sequence. The normal counting is discontinued. The source is placed manually at a fixed position and then the calibration check is commenced for a given period or total count. At the end of the check period, the source is removed and the normal count re-established. A time stamp is put on the recorded data to show the time normal counting is discontinued and re-established, the calibration count and the time interval for the calibration count. The microprocessor compares the average readings with the expected true reading, and automatically adjusts the scale factor to maintain the required accuracy. This entire sequence is performed remotely without the need to open the unit, thereby reducing the risk of operator errors.

HARDWARE DESCRIPTION.

The Boundary Radiation Monitor (BRM) is a microprocessor controlled radiation detector for monitoring Neutron and Gamma radiation.

The BRM consists of two environmentally sealed, lockable NEMA-4 enclosures suitable for mounting on either a post or wall. The BRM also includes a sun shield for mounting above the control unit for shading the monitor from direct sunlight.

The BRM system is divided into two enclosures separating a high voltage transformer assembly from the detector electronics located in the main control unit. The main control unit consists of a 110 volt AC to DC power converter, battery charger, Neutron/Gamma Meter, Neutron Probe Assembly, and RS-422 communication port.

NEUTRON/GAMMA METER, NG-2.

The major assembly of the Boundary Radiation Monitor is the Neutron/Gamma meter. This microprocessor based unit was developed by Nuclear Research Corporation for this application. The Neutron/Gamma Meter, NRC Model NG-2 is located in the modified enclosure assembly. The NG-2 provides a local readout and keypad function at the BRM.

Gamma detection is achieved using a single halogen-quenched GM tube operated using the exclusive NRC "Time-To-Count" technique. The "Time-To-Count" technique allows the single detector to cover the specified dynamic range with accuracy within ± 10% of true values, while eliminating detector non-linearity, coincidence losses, and saturation or loss of signal in fields to 1000 R/h.

NEUTRON/GAMMA METER, NG-2 (Continued).

Neutron detection is achieved using an Anderson-Braun Moderator/Attenuator Assembly, and a BF_3 proportional detector. Neutron intensities from very low background levels of less than 0.8 microRem/h to 10 Rem/h are measured to within ± 10% of actual intensities for neutron energies from thermal to 15 MeV. BF_3 proportional counter selection provides sensitivities of between 8,000 to 10,000 counts per mRem, while preserving low background measurements.

POWER SUPPLY/BATTERY BACK-UP.

The BRM is designed to operate from 110 volt AC or from a 480 volt AC three phase system. The 480 volt AC input voltage is transformed to 110 volts and is then converted to DC levels to operate the NG-2.

Battery back-up is provided for the NG-2 in the event AC power fails and normal operating functions are required. Rechargeable ni-cad batteries located within the NG-2 provide a minimum of 24 hours of operation. The NG-2 battery back-up is continuously trickle charged when the BRM is operating off AC power. Battery back-up allows the BRM to maintain all its original functions except for remote RS-422 communication. When on battery power only, local (RS232) communication with the BRM is available.

Additional battery back-up for NG-2 memory is provided by a Lithium battery. Lithium back-up insures historical data is preserved in the event both AC power and normal battery back-up fails.

In the event of an AC power failure to the BRM, a contact pair is provided for signaling an alarm. The contact pair provides a current path under normal conditions, and an open circuit on power failure. The contact pair is automatically reset when power is returned.

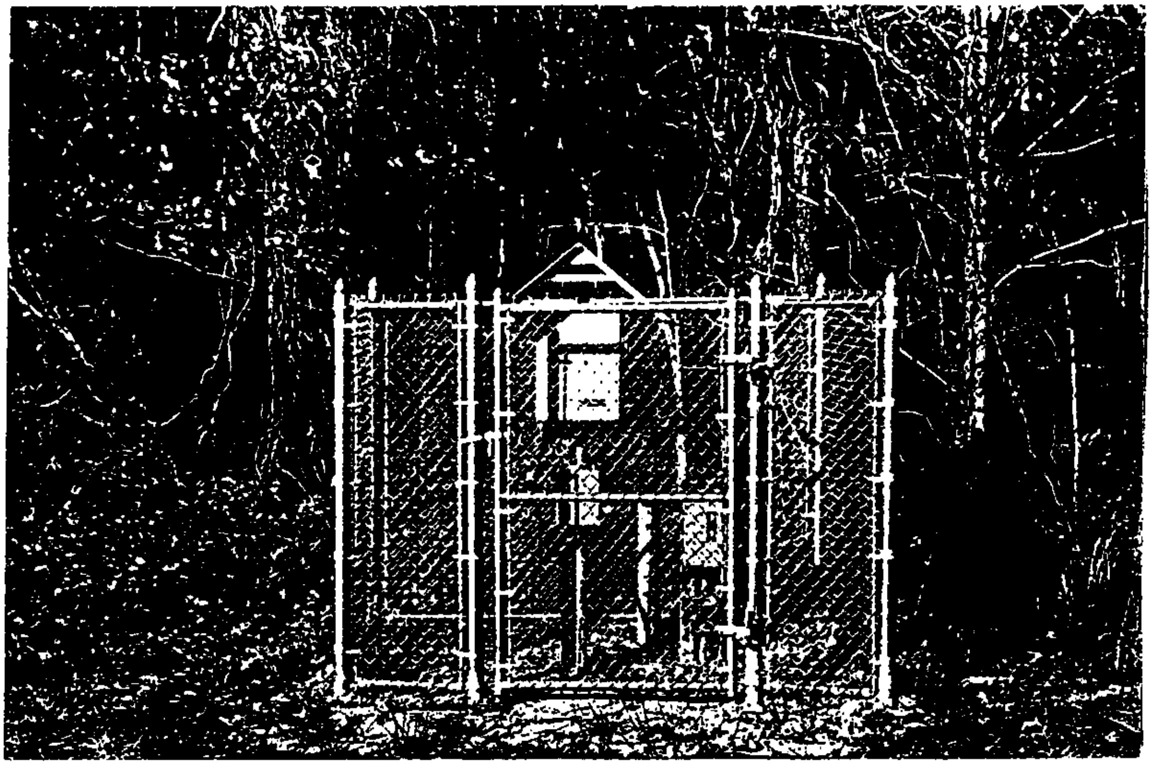
COMMUNICATION.

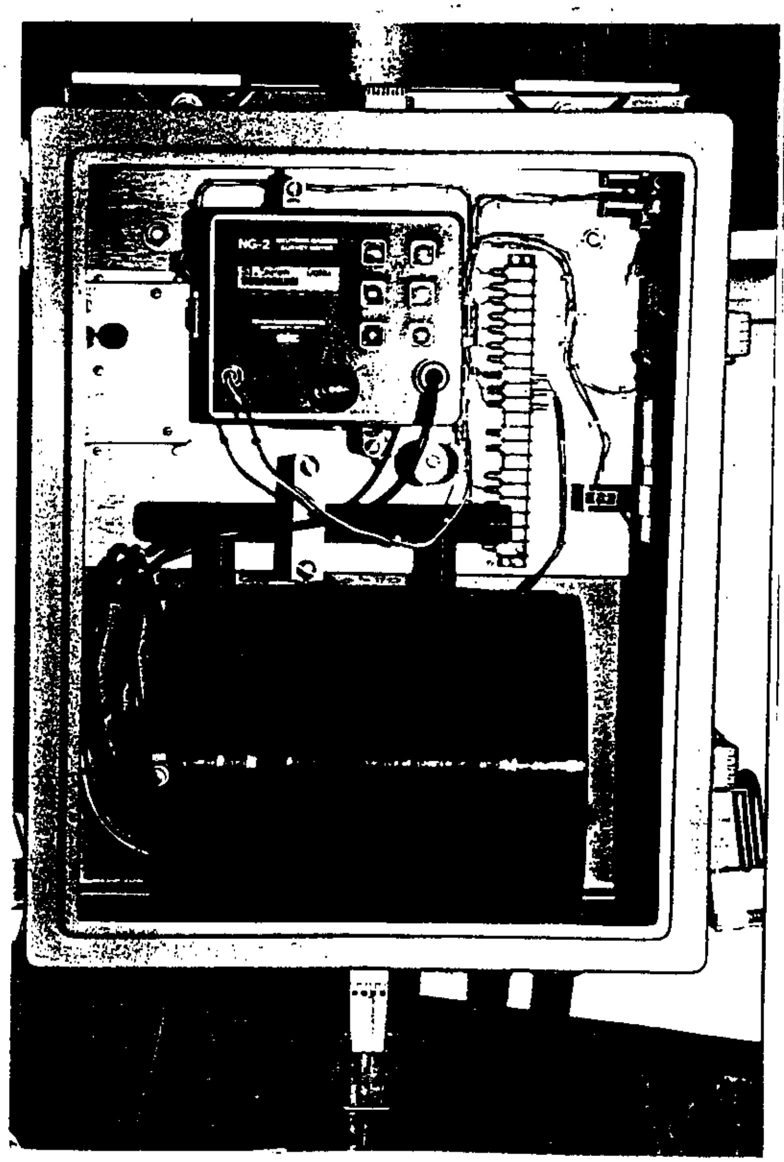
A serial communication link allows computer control over many of the BRM functions. User selectable, an RS-232C communication port provides local control of the monitor, or a four wire RS-422 port provides remote communication with the BRM to distances of 5000 ft. A switch located in the control unit selects either RS-232 or RS-422 communication.

HOST PROGRAM/HISTORY.

Historical data for both Neutron and Gamma Detectors is stored within the NG-2 for later archival and analysis. Each history point contains the data collection period, the date and time of the history, accumulated gamma dose, accumulated neutron dose, and accumulated neutron detector counts.

A host program provides computer interface to the NG-2 using an IBM-PC or equivalent. With a local or remote communication link established, host program allows control of functions such as historical data collection, timekeeping, and data analysis.




NG-2

APPENDIX

TIME-TO-COUNT TECHNIQUE

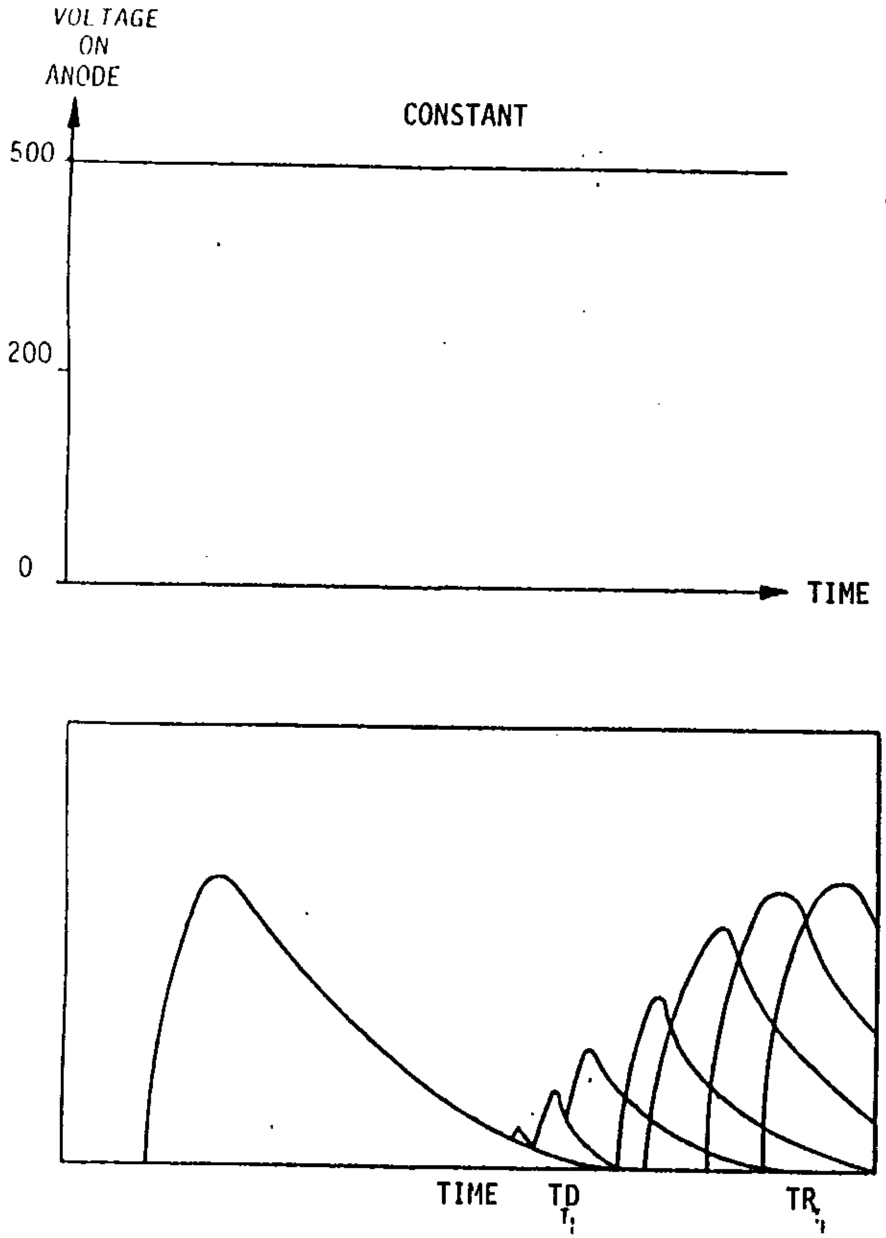
Conventionally, a GM tube is operated with a fixed dc voltage continuously applied. Readings of rate are a function of the number of pulses (counts) produced by the tube per unit time. This type of operation is characterized by increasing non-linearity as the field intensity increases. This effect, due to the inherent "dead time" of the tube, limits its range of usefulness. The problems associated with the conventional dc mode of operation are best understood by examining the "Stever Pattern" (Figure 1) produced by the tube in response to a radiation field.

Assume the GM tube is energized and the first pulse is produced by the tube in response to an ionizing event. This initial pulse will be full-sized and will typically follow the pattern shown. Following the initiation of this pulse is an insensitive period during which the discharge mechanism is operating within the tube. During the insensitive time, if another ionizing event occurs in the tube, it cannot be detected. This time is defined as the dead time (TD). If an ionizing event occurs immediately following the dead time, a small pulse, barely detectable, could be observed.

Dead time vary with the dimensions of the tube, the operating impedance, the mobility of its gases, and, to a lesser extent, the operating voltage. The dead time of the low range tube used in the NG-2 is about 150 microseconds.

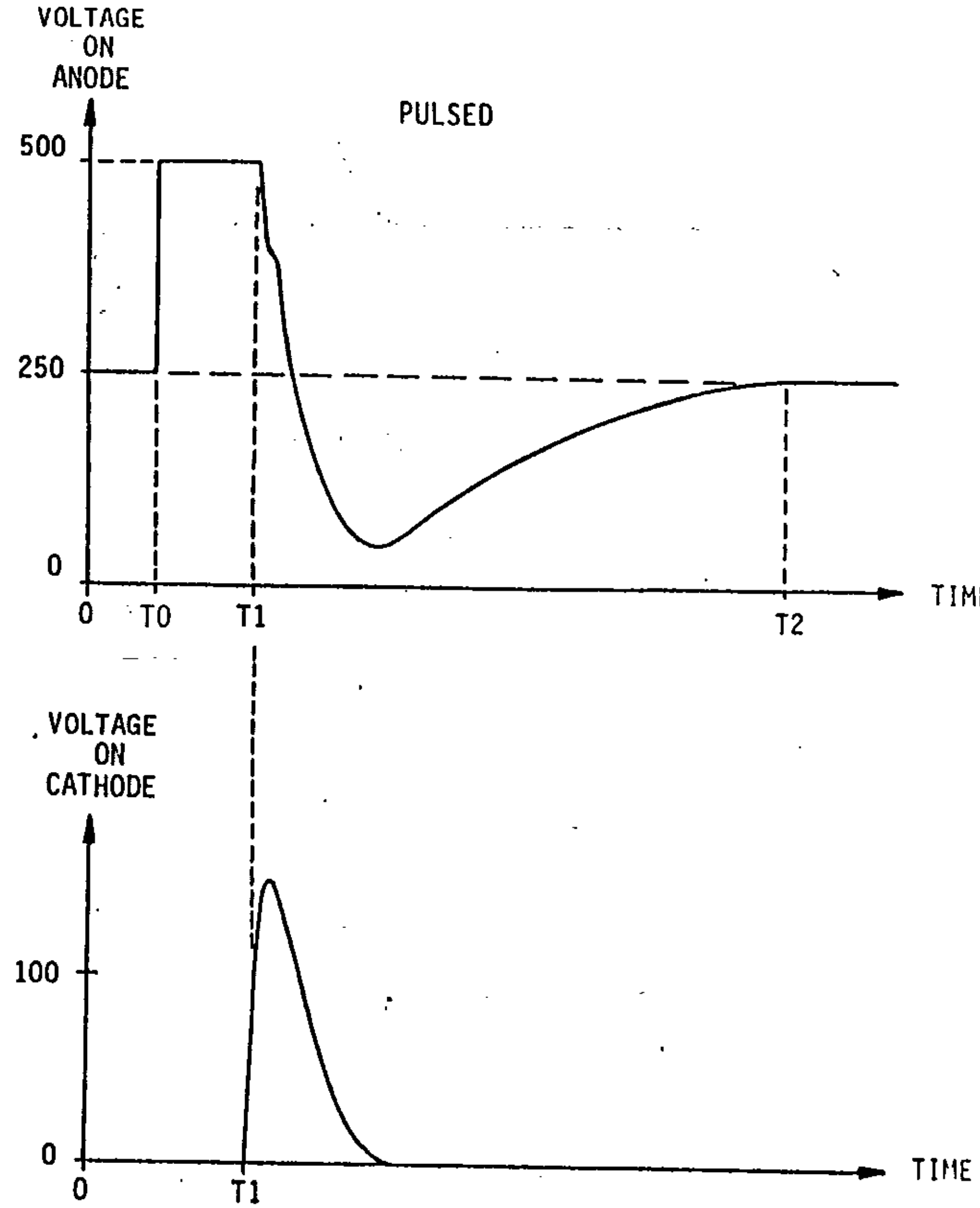
If an ionizing event takes place a trifle later than the dead time, the pulse produced would be larger and finally a time will occur when the pulse formed is of full height; i.e., equal to the amplitude and shape of the initial pulse observed. This time is called the recovery time, and corresponds to the time when the positive ion sheath (formed during the discharge mechanism) is neutralized at the outer wall of the GM tube. The dead time, which characterizes all GM tubes, produces the non-linearity at higher field and severely limits the range over which the tube is usable.

A second undesirable characteristic of GM tube operated in the conventional mode is saturation. It can be seen that as the field intensity is increased (Figure 1), more and more ionizing events will arrive in close proximity to the dead time. The pulses produced by the tube will become smaller and smaller and eventually will no loner trigger the input circuit of the instrument in which it is being used, causing the reading to drop to very low values or zero. Most GM tube instruments currently produced will display this hazardous condition.



CONVENTIONAL GM TUBE OPERATION

FIGURE 1



TIME-TO-COUNT GM TUBE OPERATION

FIGURE 2

APPENDIX

TIME-TO-COUNT TECHNIQUE

In the "TIME-TO-COUNT" technique, the dead time, and saturation effects are eliminated. Figure 2 demonstrates the technique.

The upper chart depicts the application of voltage on the anode of the GM tube. The lower chart depicts the GM pulse produced at the cathode. Referring to the upper chart, a low dc bias voltage is applied to the anode at all times. This bias is well below the starting voltage of the tube. At time "TO", this voltage is abruptly raised to 500 volts dc carrying the tube into its operating region. The rise time of this voltage is less than 0.2 microseconds. At the same time this rapid increase in voltage is applied, a crystal controlled, 1 megacycle oscillator (clock) is gated on and time, in the form of 1 microsecond cycles start being counted. Time counting continues until a GM tube pulse is obtained; at which point, time counting is stopped and the accumulated time is recorded. At the same time, the anode voltage is reduced to the low bias level. The GM pulse produced at the cathode is shown on the lower chart. The voltage on the anode is maintained at the low bias level for 1.5 to 2 milliseconds, a time period which is long compared to the dead time and recovery time of the tube.

After 2 milliseconds, when the GM tube is fully recovered, the voltage is again applied to the anode. Only one GM tube pulse can occur in any one on-time; and since the tube is fully recovered between on-times, the pulses produced by the tube are full size. The process is repeated many times a second to obtain a statistically reliable average time to count. In this fashion, dead time losses are eliminated and saturation cannot occur.

APPENDIX

TIME-TO-COUNT TECHNIQUE

It can be shown that the radiation field intensity is proportional to the reciprocal of the average time to count. Consider the probability equation:

EQUATION 1 - $P = 1 - e^{-nRt}$

WHERE P = Probability of a GM count
n = GM Tube sensitivity (c/s/mR/hr)
R = Field intensity (mR/hr)
t = Observation time seconds

Since we are allowing detector sufficient time to produce a GM count, we can assign a constant value to the probability term, independent of the radiation field intensity, the equation reduces to:

EQUATION 2 - $K_1 = 1 - e^{nRt}$

Since n is a constant:

EQUATION 3 - $K_1 = 1 - e^{K_2 Rt}$

Since 2 of the 3 terms in Equation 3 are constants, the third term must also be a constant:

EQUATION 4 - $e^{-K_2 Rt} = K_3$ = a constant

From Equation 4, it can be seen that if $e^{-K_2 Rt}$ is a constant, the exponent of e must also be a constant and we may write:

$-K_2 Rt = K_4$

OR, by defining a new constant

$K_5 = \frac{K_4}{-K_2}$ = we may state:

$Rt = K_5$ OR

EQUATION 5 - $R = K_5 / t$

Thus, the radiation field intensity is proportional to the reciprocal of the time required to obtain a GM count. Looking at a single event of a random nature would, of course, be statistically unreliable. However, if this measurement is repetitively made over a defined period of time; for example, 2 seconds, and the average time to obtain a GM pulse is determined, we now have a statistically reliable measure of field strength. This precise microprocessor controlled relationship forms the design basis for the TIME-TO-COUUNT technique and enables many decades of linear performance.