NRL REPORT 4013

FR- 4013

# PULSED GEIGER TUBE OPERATION


S. W. Lichtman

Electron Optics Branch
Optics Division


July 25, 1952


**NAVAL RESEARCH LABORATORY**

**WASHINGTON, D.C.**

CONTENTS

# PULSED GEIGER TUBE OPERATION

## INTRODUCTION

It has been common practice since the inception of the Geiger tube radiation detector (1, 2) to energize it from a suitable source of constant potential. An inherent characteristic of the Geiger tube, when operated in this manner, in common with all gas discharge devices, is the intrinsic time for a discharge once initiated to become deionized following a counting event. This condition sets an upper limit to the count rate capacity for a given type of tube. Saturation effects occur when this state of operation is either approached or is exceeded. Extension of the radiation intensity measurement range therefore usually necessitates the use either of Geiger tubes with lowered sensitive volumes or their replacement with other detector devices more suitable for use in strong radiation fields.

An alternate means for increasing the range of response to radiation intensity of a Geiger tube of any sensitive volume lies in operating it from a recurrent pulse voltage rather than from a dc voltage source. This type of operation may also serve to raise the energy of each counting pulse, as was done by Rossi (3) to permit transmission over a long cable.

In the discussion that follows, two types of pulsed operation will be described. In one of these, the Geiger tube is made continuously sensitive to ionizing radiation by energizing it from a dc source within the Geiger plateau region. Upon this voltage there is then superimposed a narrow pulse voltage of uniform recurrence rate. In the second mode of operation, the tube is gated by means of a narrow periodic trigger pulse and it is thereby made responsive to radiation only during the brief interval defined by the pulse duration.

The principal purpose of this report is to illustrate by means of experimental curves some of the important performance characteristics of pulsed Geiger tube operation. Some of the phenomena to be disclosed are novel and potentially very useful. These are deserving of more rigorous interpretation which can only be accomplished by continued study of the detailed performance.

## CONTINUOUS SENSITIVITY (DC plus PRR) OPERATION

The simplest transition to pulse operation from conventional methods lies in the addition of a recurrent pulse voltage to the dc Geiger region voltage. By this means, the effective quenching action is improved and the useful response is extended to stronger fields of radiation.

With dc operation alone in strong radiation fields, the tube performance is typical of the form shown in the Stever diagram (4, 5) of Figure 1. Here the significance of the dead

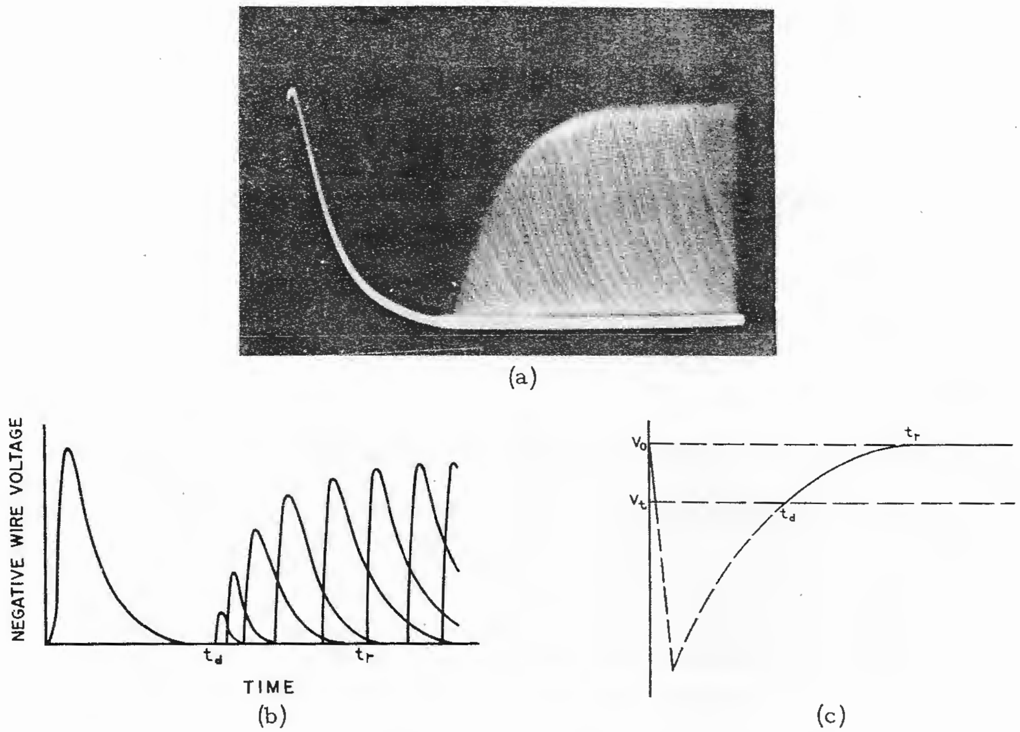


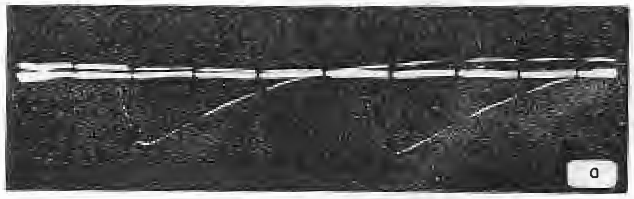

Figure 1 - Stever diagram: (a) Dead-time pattern photographed on triggered sweep; (b) Schematic representation of dead-time pattern indicating dead time, $t_d$, at foot of envelope of pulses triggered during recovery interval from $t_d$ to $t_r$; (c) Variation of electric field at the anode surface during period of ion sheath transport from anode to cathode

time and of the recovery time is clearly evident. During the dead-time interval following a count, the tube is paralyzed as a result of field reduction in the vicinity of the wire arising from the relative immobility of the positive ion sheath during the electron transit time, which condition renders the tube incapable of further response to ionizing radiation.

The effect upon the Geiger-tube pulse amplitude resulting from exposure to various levels of radiation is shown in Figures 2a, b, and c. Figure 2c shows the tube in a state of saturation and it is virtually blocked by the strong radiation exposure. Figure 2d illustrates the kind of recovery that takes place due to superimposing a narrow periodic pulse voltage upon the dc tube voltage.

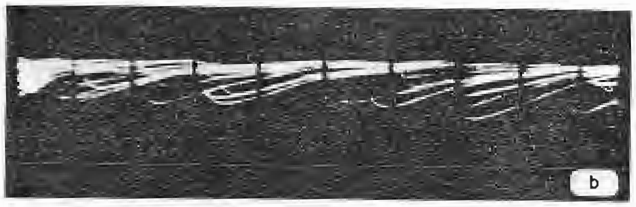
A similar set of characteristics showing Geiger tube current as a function of radiation intensity level appears in Figure 3. Adding a periodic pulse to the dc tube voltage extends the linear region without affecting the performance below saturation for the dc case alone. Combined pulse-plus-dc operation raises the radiation level at which saturation occurs. This, for convenience, is defined as the limiting radiation level beyond which the slope of th detector-current response characteristic changes sign.

The quality of performance obtainable from superimposed pulse operation is a function of the tube dead time, the operating voltage, pulse amplitude, pulse width, and repetition rate. The forms of these functions are illustrated in Figures 6 to 8, inclusive. In these figures, the range extension factor used as the ordinates is defined as the ratio of the saturation radiation fields for combined pulse and dc operation to dc operation alone.



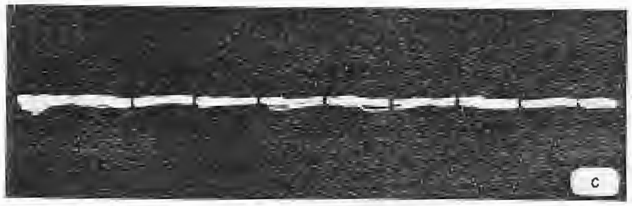
Excitation: 10 mr/hr

Two-inch mica window tube. 600 volts dc, 100-microsecond markers



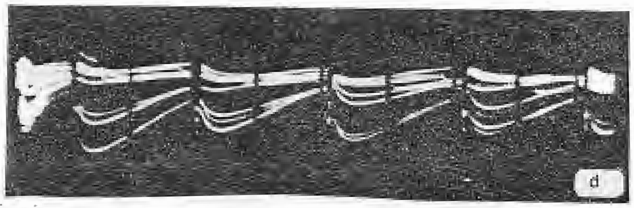
Excitation: 200 mr/hr

Two-inch mica window tube. 600 volts dc, 100-microsecond markers



Excitation: 100 r/hr

Two-inch mica window tube. 600 volts dc, 100-microsecond markers



Excitation: 100 r/hr

600 volts dc plus pulse voltage. (Pulse width, 5 microseconds; pulse rate, 5000 pps; pulse amplitude, approx. 800 volts) 100-microsecond markers

Figure 2 - Oscillograms of Geiger tube performance for dc and for dc-plus-recurrent-pulse operation

## COUNT RATE VERSUS DOSAGE

Referring again to Figure 2d, it becomes evident that the tube recovers in the period immediately following an injected pulse, so that quenching is effectively improved. In the presence of strong radiation fields, such performance would also indicate a convergence of the recovered Geiger-tube count rate towards the pulse repetition rate. This is further brought out in Figure 4 where count-rate saturation occurs at 12 mr/hr for the dc case alone (curve A). For combined pulse and dc operation and for the same pulse-amplitude detection-sensitivity condition as for curve A, curve B is obtained. The maxiumum count rate is seen to converge in a nonlinear manner towards the pulsing frequency. Such nonlinear performance is generally unsuitable for measurement purposes. By raising the amplitude discrimination level in the pulse-rate detecting system, curve C is obtained. This is seen to converge towards the pulse repetition frequency at 560 mr/hr in a manner more compatible with quantitative measurement requirements. The amplitude distribution of count pulses as a function of counting rate is illustrated in Figure 5.

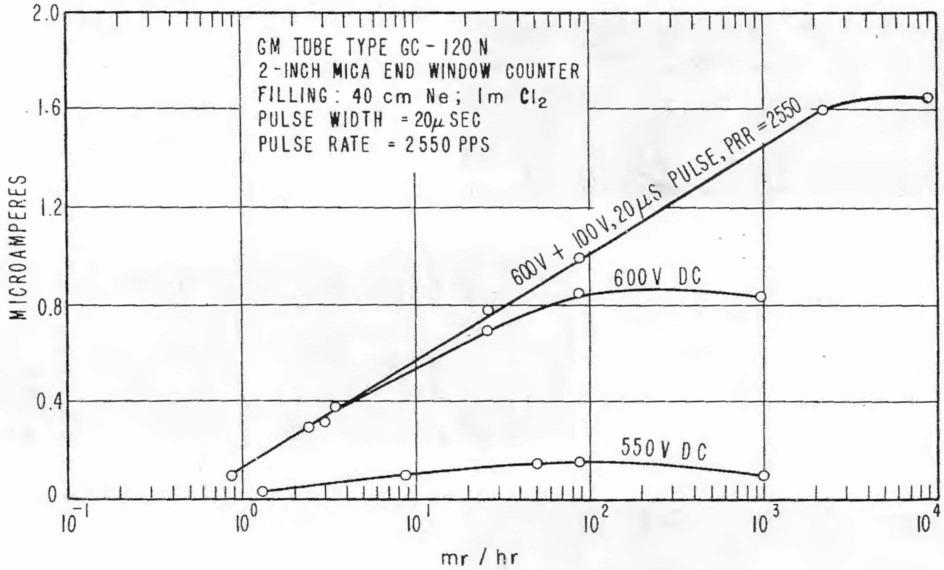



Figure 3 - Tube current vs. radiation intensity

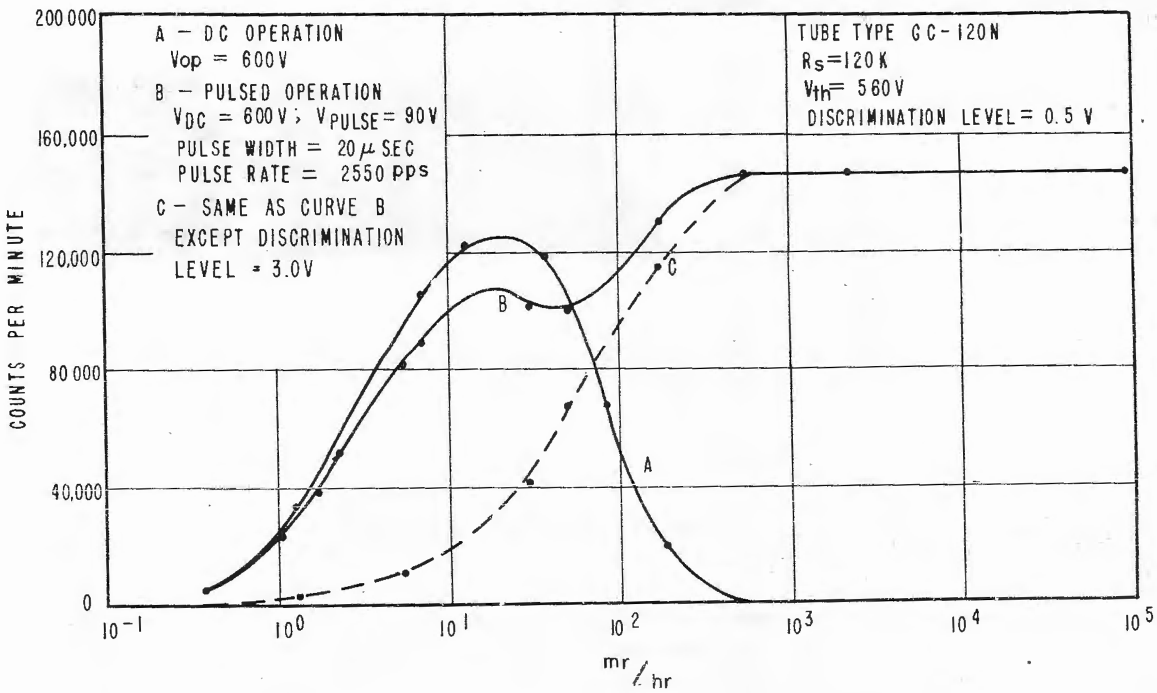



Figure 4 - Count rate vs. radiation intensity

In the example (Figure 4) of count rate detection, the radiation intensity range has been increased by a factor of approximately 46 by the introduction of a recurrent pulse voltage upon the dc Geiger region voltage. As will become apparent in the discussion that follows, the limiting PRR frequency, and therefore the highest linear count rate that may be extracte by this means, is related to the dead time of the particular tube used.

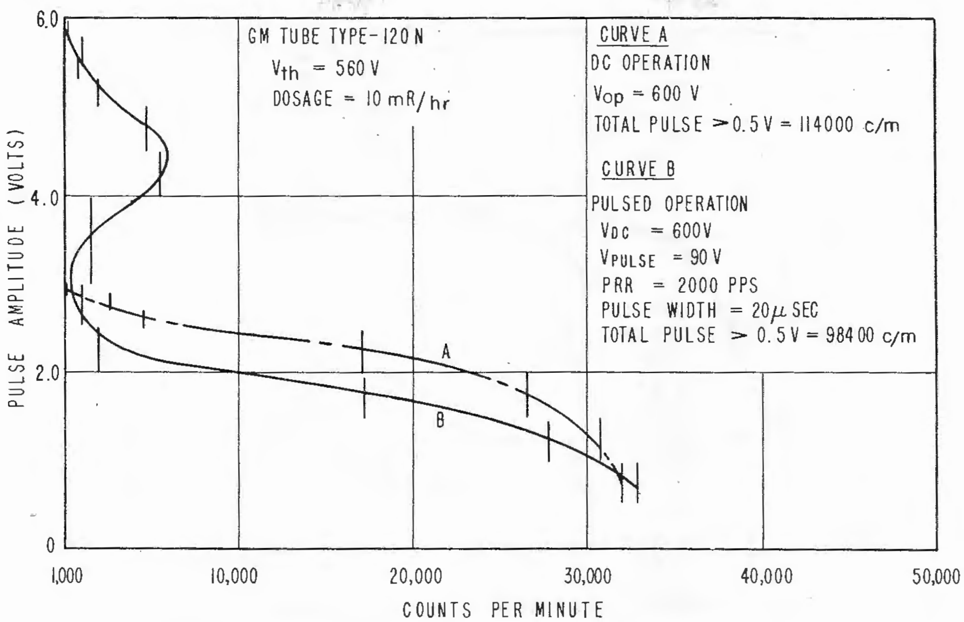



Figure 5 - Pulse amplitude distribution vs. count rate

## TUBE CURRENT VERSUS DOSAGE

An analogous set of curves representing tube current as a function of radiation intensity level is shown in Figure 3. For dc operation alone, the current curves corresponding to two levels of dc operation exhibit saturation at about 90 mr/hr. Above this level of exposure, the current decreases with further increases in the radiation intensity. When the dc voltage is supplemented with a recurrent pulse voltage, the tube current response becomes linear out to approximately 3000 mr/hr. Beyond this point saturation effects again become noticeable. The superimposed pulse will be observed to have straightened out the current-radiation field characteristic in the region wherein curvature would have otherwise occurred for dc operation alone. This was attained without altering the performance at lower intensity levels in the region within the normal measurement capabilities of the tube. For the example chosen, the use of combined pulsing and dc operation has extended the useful radiation-intensity capacity of the tube by a factor of 33.

## INFLUENCE OF PULSE PARAMETERS

The effect upon tube performance arising from the introduction of a recurrent voltage pulse into a conventional Geiger tube circuit is dependent upon all of the features that characterize the pulse. The repetition rate, pulse width, pulse amplitude, and pulse shape are each separate and controlling entities. Effects of these parameters upon the preformance are shown in Figures 6 to 8 inclusive. A rectangular voltage pulse was employed in all tests represented in these figures. Ordinates in these figures, as previously described, are the range extension factors due to combined recurrent pulse and dc operation. The effect of pulse shape upon performance has not been separately investigated as this, it was felt, may be largely inferred from the study of pulse width.

### Pulse Amplitude

Figure 6 shows the influence of pulse amplitude upon the radiation-intensity-versus-current characteristic of a Geiger tube for three levels of dc voltage. Each dc voltage level falls within the Geiger plateau region. The range extension factor from this figure

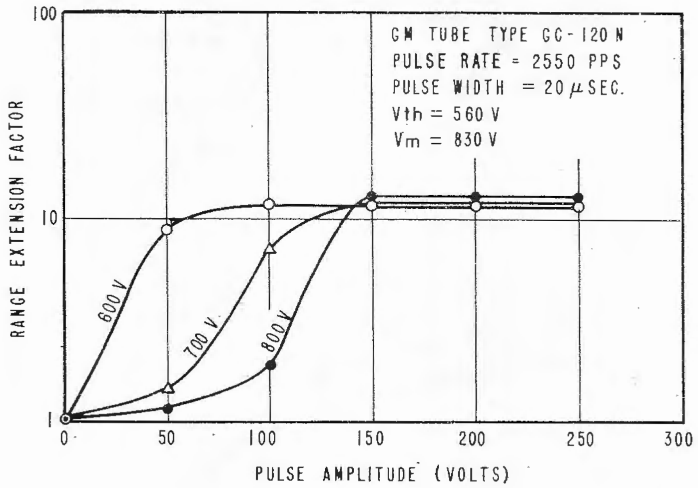



Figure 6 - Range extension factor vs. pulse amplitude

is seen to be independent of where on the plateau the dc operating point is chosen. Essentially identical performance is obtained from each of the three operating states shown, provided, however, that the pulse amplitude used is not less than 20% of the dc voltage employe The use of a larger pulse amplitude does not further extend the saturation capabilities as the curves simply level off. With narrow pulses, the combined pulse plus dc voltage may rise far beyond the Geiger plateau boundaries without adversely affecting the performance. Spurious counts are inhibited by the deliberate choice of a pulse width much less than the tube dead time and of periodicity approximating the reciprocal of the dead time.

## Pulse Width

To improve tube quenching, the pulse width chosen must be much less than the tube dead time. This fact is brought out in Figure 7 from which it may be seen that the range extension factor varies inversely as the pulse width. Continued improvement in operation down to the narrowest pulse employed, namely, about 1/2 microsecond duration, is evident from this figure. The ultimate extension in range, as will be brought out in the discussion on triggered Geiger tube operation, will be shown to reside in the extension factor $t_d/w$. Here $t_d$ is the Geiger-tube dead-time interval and $w$ is the width of the injected pulse.

For the above tests, the injected pulse duration was large by comparison with the elec tron transit time. As long as this condition is maintained the conclusion drawn therefrom, namely, improvement in range extension with reduction in pulse width, follows. If the puls were narrowed sufficiently so as to either approximate or become less than the electron transit time, the counter tube behavior would be altered markedly in accordance with transit time theory. One of the effects to be anticipated as such conditions of operation ar approached would be a reduction in influence of the pulse upon the tube performance. As the electron transit time is of the order of $10^{-8}$ seconds, this magnitude serves to establisl a possible lower limit to the pulse duration that may be beneficially employed. This entire matter, however, appears deserving of further investigation.

Referring again to Figures 2, 3, and 6, the injected periodic pulse voltage may be seer to assume the role of a catalyst by speeding recovery from each discharge without materially affecting the count pulse energy.

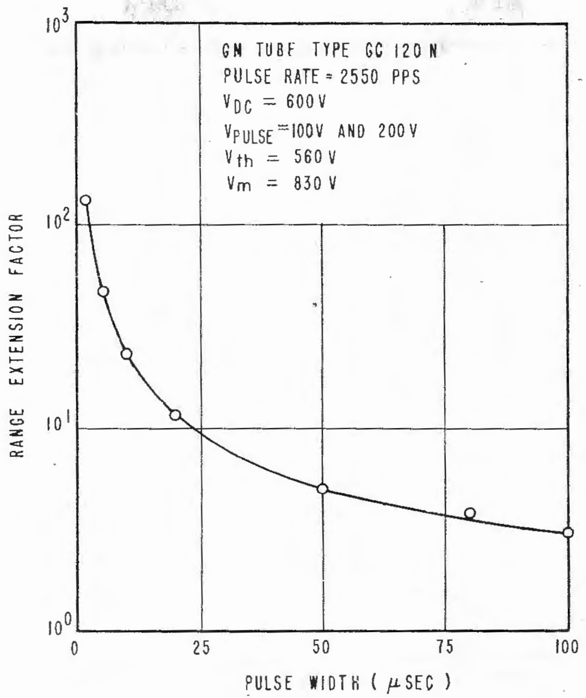



Figure 7 - Range extension factor vs. pulse width

Pulse Repetition Rate

The influence of repetition rate upon range extension is illustrated in Figure 8. An optimum well-defined rate occurs, for the tube illustrated, at a repetition rate of 2500 cps. This period agrees identically with the tube dead-time interval, namely, 400 microseconds, which was verified by means of a Stever oscilloscope pattern.

This behavior is understandable when it is observed that a PRR period longer than the dead time will result in the tube saturating and blocking up between pulse intervals. Also, when the PRR period is shorter than the dead-time interval, complete recovery between pulsing events will not occur with a consequent lowering in range and in the maximum Geiger tube current. Maximum circuit current conditions and a capacity for covering the greatest range of radiation intensity are both therefore satisfied by a PRR period equal to the Geiger-tube dead time. For direct counting applications, as previously described, these criteria also fix the maximum count rate as the reciprocal of the dead-time interval.

SUMMARY OF CONTINUOUS SENSITIVITY OPERATION

In summary, the addition of a narrow, recurrent, pulse voltage to the normal dc Geiger region voltage will extend the useful radiation intensity measurement capabilities for a tube of any sensitive volume. For greatest range extension, the pulse chosen must have an amplitude of not less than 20% of the dc voltage value, its duration should be as brief as can be managed in any case, but much less than the tube dead time, and the repetition rate period should be equal to the counter-tube dead time.

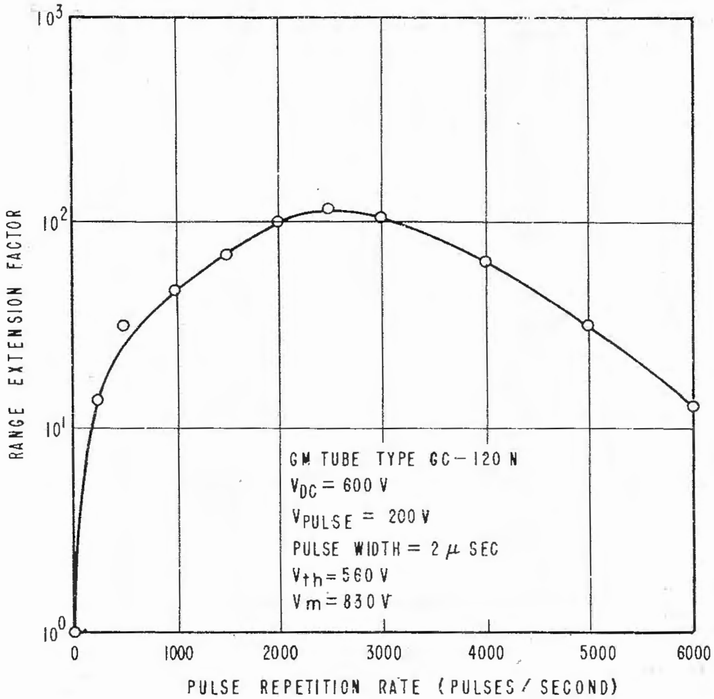



Figure 8 - Range extension factor vs. pulse repetition rate

INTERMITTENT SENSITIVITY (Pulse Trigger) OPERATION

If the high voltage furnished to a Geiger tube is applied for brief intervals at a periodic rate, the tube is rendered sensitive to radiation only while the voltage is impressed upon it. The measured count rate when triggered in this manner will be a fraction of the count that would have been measured had the voltage been constantly applied to the tube. The ratio between both count rates may for convenience be called the scale factor, SF, or

$$SF = \frac{\text{Count rate for continuous (dc) operation}}{\text{Count rate for intermittent (triggered) operation}} \qquad (1)$$

SF according to this definition will always be greater than unity.

The relationship between trigger pulse parameters, detectable count rate, and the scale factor SF is illustrated in the experimental curves of Figures 9 and 10. These show that the measurement rate varies directly with the pulse width, the repetition rate, and the intensity level of the radiation field. For pulse widths considerably less than the tube dead time, SF is equal to the reciprocal of the duty factor

$$SF = \frac{1}{wf} \qquad (2)$$

where w is the pulse width and f is the repetition frequency.

Equation (1) may now be represented as

$$\Delta f = F(R)wf, \qquad (3)$$

where $\Delta f$ is the measured count rate and where F(R) is the maximum count rate (corresponding to continuous sensitivity) and is represented as a linear function of the radiation intensity level, R.

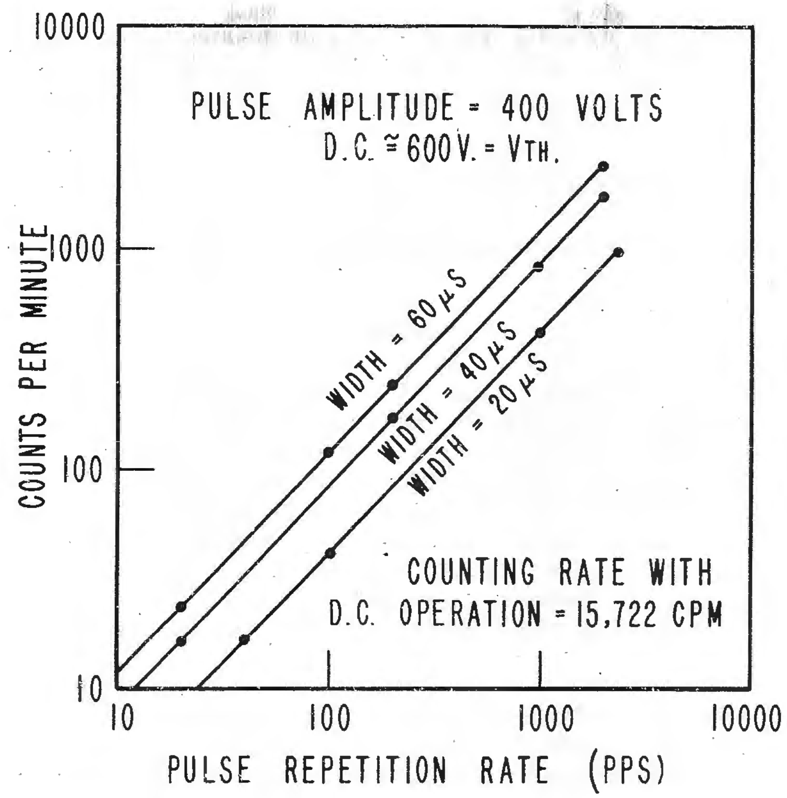



Figure 9 - Pulsed GM tube counting characteristic

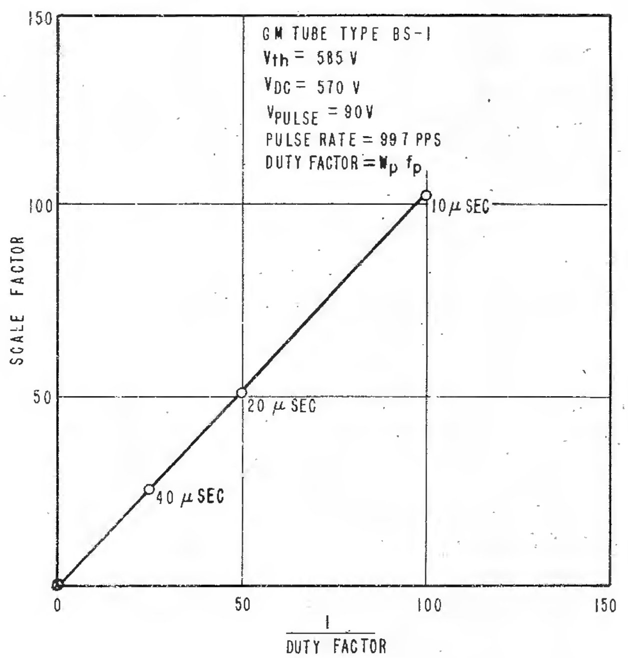



Figure 10 - Scale factor vs. reciprocal duty factor

From the foregoing, it is clear that by pulse trigger operation, the total potential count rate is lowered at the tube by the duty factor $wf$. This feature, for all practical purposes, removes the saturation limitations in high-radiation fields from the Geiger tube.

## CHOICE OF TRIGGER PULSE REPETITION RATE

If the PRR frequency, f, is held constant for a given sensitivity scale range, Equation (3) may be rewritten in the form

$$\frac{\Delta f}{f} = F(R)w . \qquad (3a)$$

From this expression it it apparent that $\Delta f$ will approach f as a limit. The left-hand member will, therefore, approach unity, regardless of the choice made in f. The range extension capabilities under these circumstances are then seen to reside entirely in the choice made for pulse width, w. The PRR value, f, therefore becomes a matter to be determined by the statistical accuracy requirements of the measurement data, rather than one of range extension. Furthermore, to provide for complete recovery of the counter tube discharge between successive counts, the PRR frequency, f, must not exceed the rate prescribed by the reciprocal of the deionization or recovery time. Otherwise, the discharge will be reignited by the triggering pulse and it will be self-sustained at the trigger pulse rate.

Recent experiments with halogen-filled tubes, of the type BS-1 variety, have shown that normal counting operation occurs for triggering intervals reduced to less than 10% of the Geiger-tube dead time. This very interesting phenomenon is worthy of further investigation.

## CHOICE OF TRIGGER PULSE WIDTH

To examine further the influence of trigger pulse width, w, upon the range extension capabilities, it is necessary to rewrite the count rate function F(R) in Equation (3a). F(R) is the count rate which the tube is capable of if operated normally so as to be continuously sensitive to radiation. In the limit, the count rate capability would then be determined by the reciprocal of the tube dead-time period, or

$$F\left(R_{Max}\right) = \frac{1}{t_d} . \qquad (4)$$

Inserting this limiting value in Equation (3a), this becomes

$$\frac{\Delta f}{f} = \frac{w}{t_d} . \qquad (5)$$

By choosing $w/t_d$ less than unity and observing that this quantity represents the fraction of maximum count rate output available from triggered operation, which corresponds to a radiation field $R_{Max}$, then the system is capable of normal performance up to a factor $t_d/w$ of this amount before saturation will occur. This will be marked by the left-hand term of the equation becoming unity.

If $R_{Max}$ is then the strongest radiation field that a counter tube is capable of being used in with dc operation, due to dead time, $t_d$, limitations, and if $R_p$ is the strongest radiation field which this same tube is capable of being used in under triggered conditions of operation using a pulse of width w, it follows that

$$R_p = R_{Max} \frac{t_d}{w} . \qquad (6)$$

The range extension factor is clearly seen to be the ratio of the tube dead time to the triggering pulse width. Equation (6) may also be seen to generally describe the behavior of the experimental curve of Figure 7 for the case of combined dc and PRR operation.

## OPERATION WITH LARGE OVERVOLTAGES

The use of a narrow trigger pulse for energizing a Geiger tube precludes gaseous discharge except by pulse coincidence with an external ionizing agency. This feature extends counter operation far beyond the usual limitations imposed by the Geiger plateau region, to very high overvoltages. The ultimate useful limitation of the impressed voltage under these circumstances is determined by the insulation capabilities of the tube terminals rather by restrictions imposed by properties of the gaseous vehicle itself. Such counter operation projected into the realm of strong transient voltage fields introduces a number of potentially useful performance phenomena.

Typical performance curves obtained for a type BS-1, halogen filled Geiger tube (Figures 11 and 12) disclose several items of interest:

(a) Normal count-detection operation was limited by the voltage range of the available pulsing source rather than by the tube characteristics.

(b) The counting threshold for triggered operation is several hundred volts higher than for the corresponding dc case. This condition may be brought about by a reduction in energy per count pulse resulting from an acute reduction of the spread of discharge — the latter being restrained by the brief duration of the impressed voltage.

(c) The charge per count pulse increases at first linearly with overvoltage. But for operating voltages approximating three times the normal dc Geiger threshold value and beyond, the charge per pulse levels off and becomes virtually independent of the tube voltage. This operation is best realized with the narrowest pulse used (1.5 microseconds). The pulse charge is seen to grow in size at first. It finally levels off after reaching a magnitude approximately $10^4$ times greater than is obtainable from conventional dc operation in the Geiger region.

A closer examination of the character of the discharge in the region where leveling off of the pulse size occurs, has shown the light output of the tube to increase proportionately with voltage while the ionization current remains substantially constant in value. Over this realm of operation, increases in tube voltage seem to favor the excitation of light radiation without influencing the total ionization. Fluctuations in tube overvoltage are thereby converted to corresponding changes in light energy with little or no influence upon the ionization current. Although the curves (Figures 11 and 12) are shown as taken out to 2200 volts, additional tests have shown that the tube current was still independent of impressed voltage at 5300 volts.

The growth of light emission from a Geiger tube, operating within the constant ionization current region, is illustrated in the oscillogram of Figure 13. This photographic record represents the voltage obtained from a photomultiplier tube arranged so as to view the light output of a type BS-1 Geiger tube immediately following a counting event.

The removal of an upper voltage limit in the useful employment of counter tubes, aside from insulation requirements, permits high voltages to be utilized with the accompanying benefit of dealing with stronger charges from each counter pulse. If the triggering pulse is narrowed sufficiently, the tube voltage may be raised so that operation may be confined to the region wherein the tube current becomes largely independent of the amplitude of the impressed voltage. This characteristic may prove useful in radiac designs by either

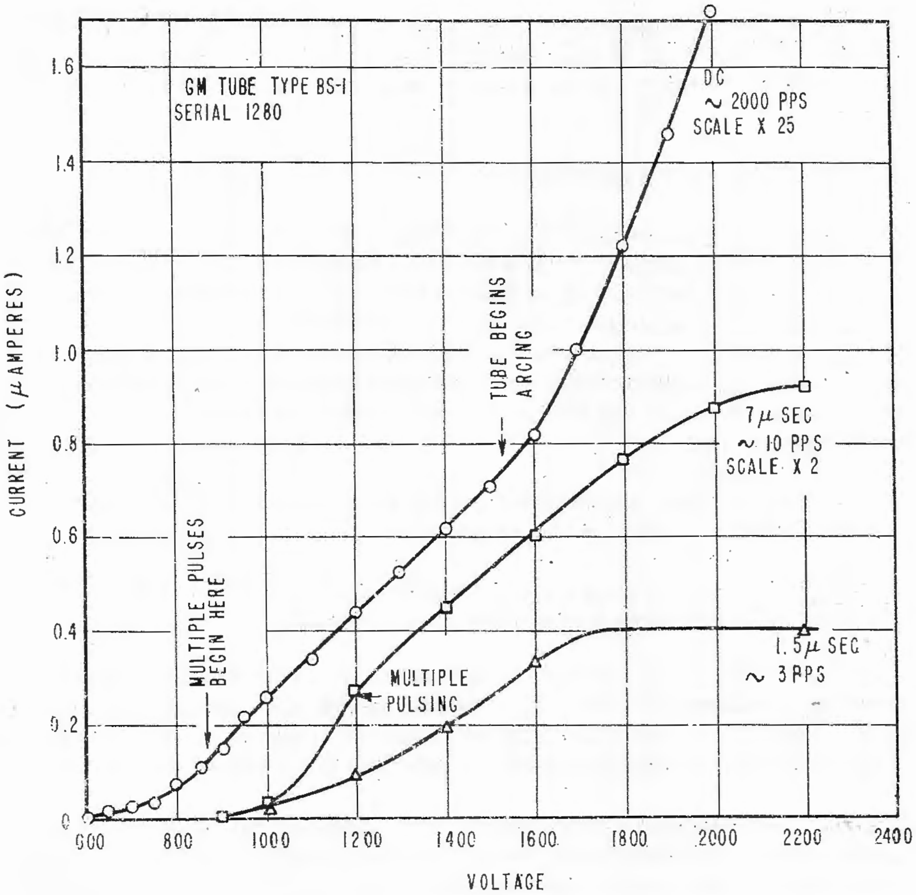



Figure 11 - Tube current vs. voltage for high overvoltages

reducing or completely eliminating dependence of instrument calibration upon tube overvoltage. It also furnishes a basis for dispensing with the need for high voltage stabilizers for counter tubes.

Since triggered operation enables only one measurement count to occur for each triggering pulse, it becomes obvious that spurious counts are inhibited from developing.

## CHOICE OF GAS FILLING

The trigger pulsing technique is not critical with regard to the choice of filling gas used. Any pure gas whether used alone or in combination with other gases and whether of monatomic or of polyatomic structure will be found capable of performing as a radiation counter. This latitude in the selection of gas fillings further enhances the desirability and potential usefulness of triggered operation.

Counter tubes of self-quench or nonself-quench characteristics may be used. Self-quench tubes offer the advantage of fast operation combined with minimum circuit complications arising from their inherently rapid deionization properties. The choice of a filling medium that does not deteriorate with use, such as is obtainable from the use of halogen gases in combination with neon or argon (6), removes any upper limiting restriction on the overvoltage that may be beneficially employed. Operation may be thereby extended into

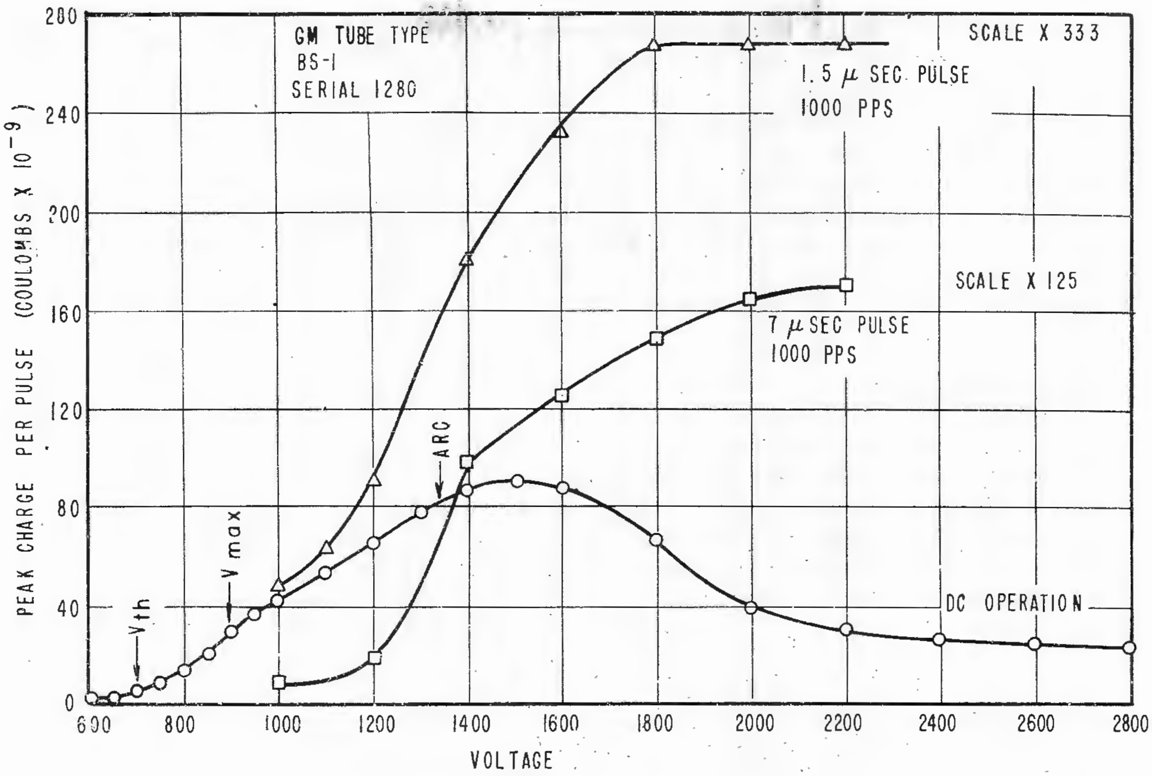



Figure 12 - Charge per pulse vs. voltage for high overvoltages

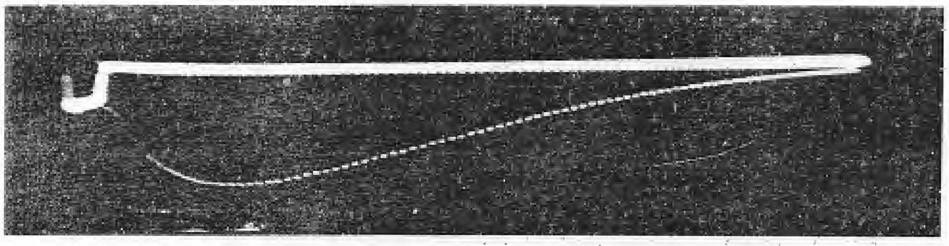


Figure 13 - Growth of Geiger tube light output in constant ionization current region. Type BS-1 Geiger tube; pulse amplitude, 4000 volts; pulse width, ≈ 4 microseconds; PRR, 1000; base line, ≈ 100 microseconds; type 1P22 photomultiplier tube.

the realm of constant ionization currents, with ensuing advantages of maximum energy per tube count and greatest operational immunity from tube-voltage amplitude variations.

The use of an organic or polyatomic vapor for the filling medium, imposes a practical upper limit upon the overvoltage that may be used, as determined by reasonable tube life expectations. This limitation arises by virtue of the dissociation that occurs in such a gas, which varies directly with the intensity of the discharge current.

Counters filled with a pure gas such as neon or argon are of the nonself-quench variety but may also be made to serve as satisfactory triggered counters. Tubes of this type are desirable in view of the filling-gas simplicity and the high order of stability that may be readily obtained therefrom. The trigger pulse must not be reapplied, however, until complete deionization has taken place from the previous count. Otherwise the discharge will be sustained at the pulsing rate and the usefulness of the tube as a radiation counter will be destroyed. As this process is slow in such a tube, the triggering rate must also be kept proportionately low. In a typical counter tube filled with either argon or neon gas, for example, it was found necessary for the triggering rate to be kept below 15 pulses per second for normal counter operation to exist. Faster operation may be acquired and the deionization time may be hastened, however, by the use of a suitable dc collecting field in combination with the triggering pulse, such as was done by Rossi (3).

## RADIAC CONSIDERATIONS

Equation (3) is in a form that is useful for radiac design applications. As stated therein the total available count rate, F(R), expressed here as a function of the radiation intensity level, is scaled down by factors w(pulse width) and f(pulse repetition rate)to a detectable rate, $\Delta f$. Consequently either or both of these parameters may be controlled so as to provide the desired amount of scaling. The pulse width, w, is usually most readily kept constant, thus enabling an instrument's scale range to be calibrated by adjustment of the pulse repetition rate, f.

## RANGE LINEARITY

The Geiger tube when operated from a pulse triggering source may be made to perform either as a linear or as a nonlinear radiation detector. Pulse counting operation, as typified by Equation (3), yields linear performance (Figure 14).

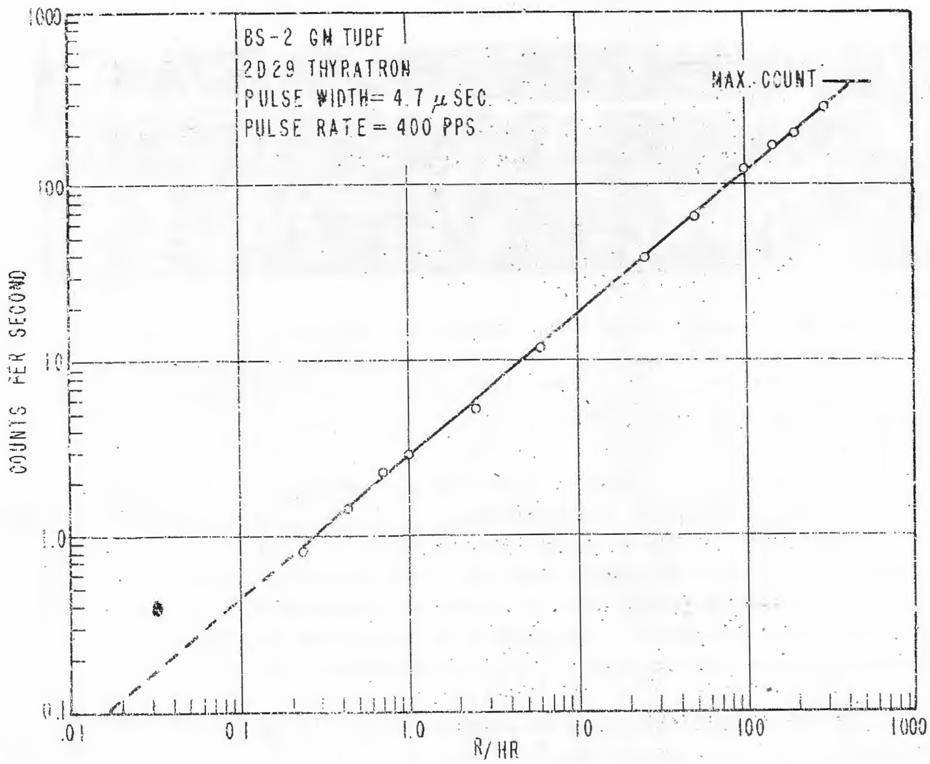



Figure 14 - Count rate vs. radiation intensity

Where several decade levels of radiation intensity are required to be covered on one scale range, nonlinear performance and scale compression become essential. This may be achieved in a radiac device utilizing either tube current or count-pulse amplitude as the measuring quantity. In both instances nonlinearity arises by virtue of the interruption of the discharge before it has had sufficient time to spread fully. The spread velocity of the discharge is of the order of $10^6$ to $10^7$ centimeters per second (5). This phenomenon yields an accumulation of progressively smaller count pulses in unit time as the quantity $\Delta f/f$ in Equation (3) approaches unity and as the saturation capabilities of this sort of device are approached. Discharges occurring near the leading edge of the trigger pulse will have the greatest time to spread and will thereby contribute a larger amplitude than those that are formed near the trailing edge. The gradation in pulse sizes that occur over the triggering pulse pedestal may be seen in the oscillograms of Figure 15.

Control of the trigger pulse shape furnishes a means for attaining a desired amount of compression. A trigger pulse of long rise and rapid decay times will tend towards equalization of the amplitude distribution of count pulses that occur over the triggering interval, with a consequent trend towards linear performance. Conversely, a triggering pulse of rapid rise and long decay characteristics may be used to provide scale compression in the vicinity of strong field operation. Figure 16 illustrates a compression characteristic obtained for a triggered Geiger tube radiac by utilizing tube current measurement. Several decades of intensity levels are readily covered in this device.

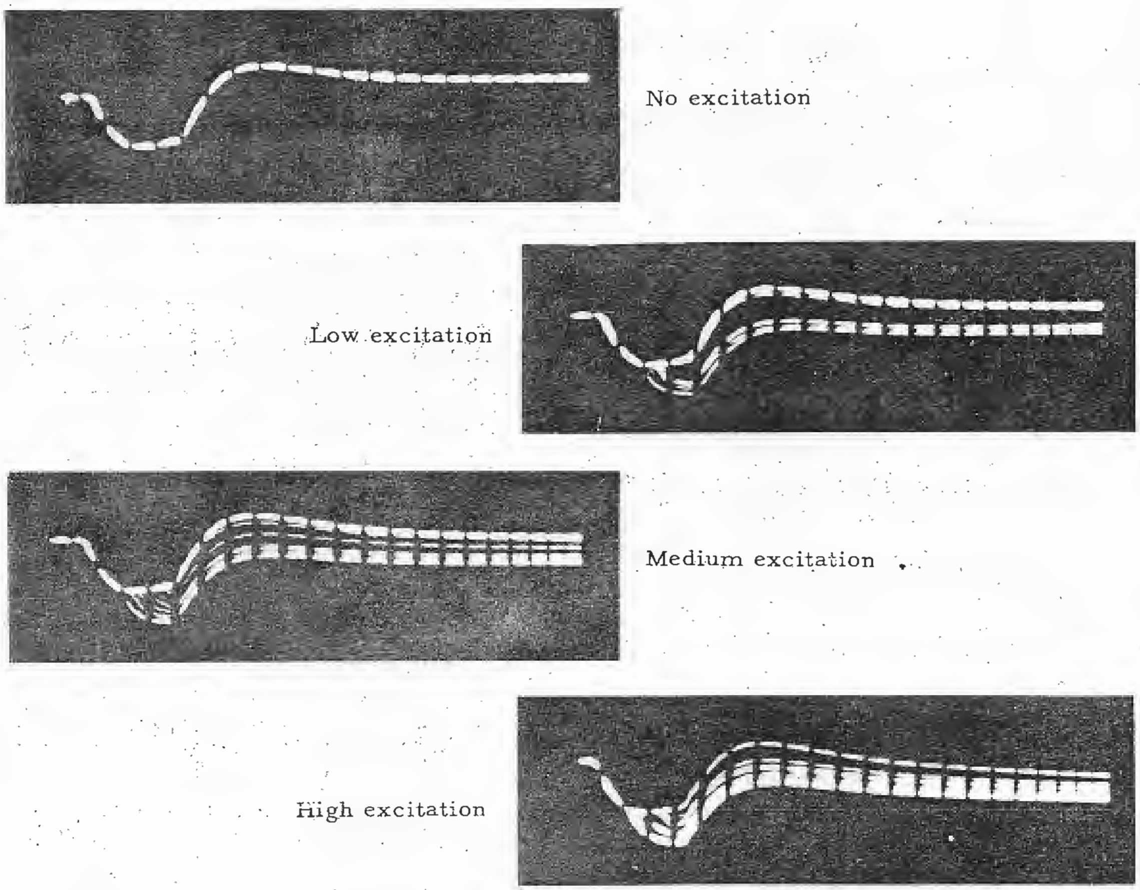



Figure 15 - Trigger pulse operation of Geiger tube, oscillograms: Type BS-1 mica window tube, pulsed operation, no dc. (Pulse rate, 500 pps; pulse width, 5 microseconds; pulse amplitude, approx. 800 volts.) 1 microsecond markers

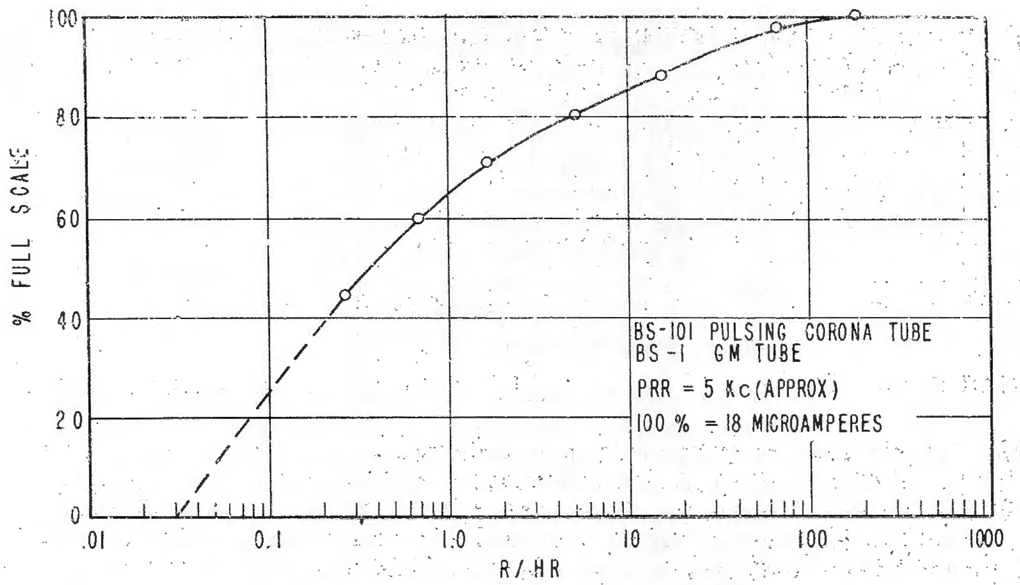



Figure 16 - Tube current vs. radiation intensity

## SUMMARY OF INTERMITTENT SENSITIVITY OPERATION

Pulse triggering operation of a Geiger tube of dead time, $t_d$, extends the usefulness of the tube for the measurement of strong radiation fields by the factor $t_d/w$, where $w$ is the trigger pulse width. The triggering rate $f$ may be chosen to comply with the statistical accuracy requirements of the measurement problem and for convenience in adjustment of the scale range calibration. In addition, $f$ must be chosen to provide for complete deionization and recovery of the counter to avert self-sustained discharges from occurring at the pulse triggering rate.

Operation with strong pulse overvoltages in the realm of constant ionization currents furnishes a means for obtaining counter operation with minimum dependence upon voltage stability. This may serve to simplify radiac designs and to improve counter tube performance.

A linear detector response function is obtainable by measurement of the counting rate. For nonlinear performance either the tube current or the count pulse amplitude may be measured. The degree of nonlinearity obtainable by these means is related to the shape of the triggering pulse employed.

* * *

## REFERENCES

1. Rutherford, E., and Geiger, H., Proc. Roy. Soc. A81:141 (1908)

2. Geiger, H., and Muller, W., Phys. Zeits 29:839 (1928); 30:489 (1929)

3. Rossi, B. B., and Staub, H. H., Ionization Chambers and Counters, McGraw-Hill, New York, (1949) pp. 117-122

4. Stever, H. G., Phys. Rev. 61:38 (1942)

5. Friedman, H., Proc. I.R.E. 37:791-808 (July 1949)

6. Liebson, S. H., and Friedman, H., Rev. Sci. Instr. 19:303-307 (May 1948)

* * *