TECHNICAL MEMORANDUM

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ANL-CT-73-14

NEUTRON INDUCED CURRENT PULSES IN
FISSION CHAMBERS

by

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Components Technology Division

Base Technology

January 1973

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NOMENCLATURE

A, B, C	Dummy variables
C_1, C_2, C_3	Capacitance between SIG electrode and ground, between H.V. electrode and ground, and direct interelectrode capacitance, respectively
d	Distance between chamber electrodes
e	Base of natural logarithms
$e_1(t)$	Voltage developed across terminated end of the SIG cable as a function of time
$E_1(s)$	Laplace transform of $e_1(t)$
f_p	Fission products
F	Fission event
$F(t)$	Driving function dependent upon functional form of $i(t)$
$i(t)$	Chamber current as function of time
$i_e(t)$	Contribution to chamber current due to motion of negative ions
$i_p(t)$	Contribution to chamber current due to motion of positive ions
I	Maximum value of $i(t)$
$I(s)$	Laplace transform of $i(t)$
$J(t)$	Particular integral
K_1, K_2	Integration constants
N_{th}	Thermal neutron
p_1, p_2	Frequency poles
$q(t)$	Charge to be collected at time t
Q	Electron charge content in ionization track
R	Ionization track length
R_1, R_2	Characteristic impedance of SIG and HV cables, respectively
$\tau_1, \tau_2, \tau_3, \tau_4$	Time constants
t	Time
t_1	Time when first electron is collected
t_2	Time when last electron is collected
t_3	Time when last positive ion is collected
V_s	Potential difference between chamber electrodes

NOMENCLATURE (contd.)

W	Work performed in moving charge Q a specified distance
ω_e	Drift velocity of negative ions
ω_p	Drift velocity of positive ions
μ_e	Negative ion mobility
μ_p	Positive ion mobility
ϕ	Angle between ionization track and applied electric field
ρ	Positive or negative charge density in the ionization track; assumed to be constant along the length of the track

NEUTRON INDUCED CURRENT PULSES IN FISSION CHAMBERS

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ABSTRACT

The mechanism of neutron induced current pulse generation in fission chambers is discussed. By application of the calculated detector transfer function to proposed detector current pulse shapes, and by comparison with actually observed detector output voltage pulses, a credible, semi-empirical, trapezoidal pulse shape of chamber current is obtained.

1.0 INTRODUCTION

A neutron flux impinging on a fission chamber induces an energy dependent fission rate proportional to the flux density. Due to conservation of momentum during fission, and to the limited range of fission products, less than half of the primary fission fragments escape the fissile material coating and penetrate the gas filled sensitive volume. The fission fragments and secondary radiation from the ambient gamma field, alpha decay from impurities in the fissile coating, and from activation of the chamber structure, penetrate the gas and create tracks of electron-ion pairs. The collection of free electrons and ions results in a current pulse whose time integral (total charge) is proportional to the energy lost within the gas. The current pulse, or superposition of pulses, is transformed by the detector circuit into a voltage pulse of different shape at the preamplifier input.

A typical fission chamber, consisting of a pair of concentric cylindrical electrodes, a thin layer of fissile material coating the emitter electrode, a gas filled sensitive volume, and detachable signal (SIG) and high voltage (HV) cables will be considered. The intent of this report is to deduce the actual (but not directly observable) shape of the pulse of chamber current from the observed shape of the resulting voltage pulse at the terminated end of the SIG cable.

2.0 DETECTOR TRANSFER FUNCTION

For calculation of the detector transfer function, it is assumed that the fission chamber and cables can be represented by the equivalent circuit shown in Fig. 1. In order to avoid pulse reflections, the cables are assumed to be properly terminated with their respective characteristic impedances at the input to the amplifier. It is also assumed that the time delay occasioned by the finite signal propagation velocity in the cables is of no importance in the present analysis, that the distributed capacitance of the properly terminated cables can be disregarded, and that the cable impedances can be treated as pure resistances.

If we define the following time constants associated with the circuit parameters:

$$\begin{aligned}\tau_1 &= R_1 C_1 & \tau_3 &= R_1 C_3 \\ \tau_2 &= R_2 C_2 & \tau_4 &= R_2 C_3\end{aligned}\quad (1)$$

then the transfer function from the signal current source to the output end of the SIG cable can be obtained from

$$A e_1''(t) + B e_1'(t) + C e_1(t) = F(t) \quad (2)$$

where

$$\begin{aligned}A &= \tau_1 \tau_2 + \tau_1 \tau_4 + \tau_2 \tau_3 \\ B &= \tau_1 + \tau_2 + \tau_3 + \tau_4 \\ C &= 1\end{aligned}\quad (3)$$

$$F(t) = \tau_2 R_1 i'(t) + R_1 i(t).$$

The complete solution of Eq. (2) has the form:

$$e_1(t) = K_1 e^{-P_1 t} + K_2 e^{-P_2 t} + J(t) \quad (4)$$

where K_1 and K_2 are constants determined by the initial conditions, $J(t)$ is a particular integral whose form depends on $F(t)$, and

$$P_1 = \frac{(\tau_1 + \tau_2 + \tau_3 + \tau_4) - [(\tau_1 - \tau_2 + \tau_3 - \tau_4)^2 + 4\tau_3\tau_4]^{\frac{1}{2}}}{2(\tau_1\tau_2 + \tau_1\tau_4 + \tau_2\tau_3)} \quad (5)$$

$$P_2 = \frac{(\tau_1 + \tau_2 + \tau_3 + \tau_4) + [(\tau_1 - \tau_2 + \tau_3 - \tau_4)^2 + 4\tau_3\tau_4]^{\frac{1}{2}}}{2(\tau_1\tau_2 + \tau_1\tau_4 + \tau_2\tau_3)}$$

WHERE:

- $i(t)$ = the current flowing between the two electrodes. It may also be called "chamber current" or "source current".
- C_1 = capacitance between SIG. electrode and ground (case).
- C_2 = capacitance between H.V. electrode and ground (case).
- C_3 = direct capacitance between SIG and H.V. electrodes.
- R_1 = characteristic impedance of the SIG cable. Assumed to be pure resistance.
- R_2 = characteristic impedance of the H.V. cable. Assumed to be pure resistance.
- $e_1(t)$ = voltage developed across the termination at the end of the SIG. cable.
- $e_2(t)$ = voltage developed across the termination at the end of the H.V. cable.

Fig. 1 Equivalent Circuit of Fission Chamber with Separate Signal and High Voltage Cables

Using the Laplace Transform of Eq. (2), and requiring that $\lim_{t \rightarrow 0} i(t) = 0$, the transfer function in the frequency domain can be shown to be:

$$\frac{E_1(s)}{I(s)} = \frac{(\tau_2 R_1)(s + 1/\tau_2)}{(s + P_1)(s + P_2)} \quad (6)$$

3.0 CALCULATED OUTPUT VOLTAGE PULSE SHAPE

Various arbitrary current pulse shapes for a parallel plate fission chamber are assumed, and the corresponding output voltage pulses are calculated by application of the detector transfer function. For each given chamber current pulse shape, the calculated output voltage pulse shape is compared with the output of an actual fission chamber. A theoretical shape of chamber current can be obtained for which the predicted output voltage pulse closely matches the shape of the observed pulse.

For comparison purposes, the output voltage pulse shape of the Reuter-Stokes fission counter, Model RSN-314, S/N M1060 was used. A schematic of the electronics used, and the observed output voltage pulse shape is shown in Fig. 2. The internal capacitances of the detector were measured to be: $C_1 = 42.3$ pF, $C_2 = 129$ pF, and $C_3 = 112$ pF. The detector was used with detachable RG-62 cables terminated in 93Ω .

3.1 Rectangular Pulse of Chamber Current

A rectangular current pulse shape of the type shown in Fig. 3A has been proposed as the current pulse shape from an ideal parallel plate ionization chamber.^{1,2,9} A rectangular current pulse assumes that all the free electrons between the chamber electrodes are collected at a particular instant T . This pulse shape can be considered as a superposition of two step functions, one having amplitude I , beginning at $t = 0$, and the other having amplitude $-I$, beginning at $t = T = 40$ ns.

(A) Schematic of electronic system used for observation of neutron induced output voltage pulse shape

(B) Observed neutron induced voltage pulse shape (average from several photographs of oscilloscope screen traces).

Fig. 2 Electronics System Used and Observed Output Voltage Pulse Shape

(A)
RECTANGULAR PULSE OF
CHAMBER CURRENT, $i(t)$

(B)
CALCULATED OUTPUT VOLTAGE PULSE SHAPE FOR
RECTANGULAR PULSE OF CHAMBER CURRENT.

Fig. 3 Response to Rectangular Pulse of Chamber Current

The complete solution of Eq. (2) is:

$$e_1(t) = \begin{cases} I (93 - 73.1 e^{-t/29.6} - 19.9 e^{-t/7.21}) & \text{for } 0 \leq t \leq 40 \text{ ns} \\ I (209 e^{-t/29.6} + (5.09 \times 10^3) e^{-t/7.21}) & \text{for } t \geq 40 \text{ ns} \end{cases}$$

where I is the initial (peak) value of the chamber current.

The calculated output voltage pulse shape is shown in Fig. 3B. Since all the free electrons between the chamber electrodes were assumed to be collected at a particular instant T , it is seen that for this particular case, the time between 10% points on the output voltage pulse is a poor measure of collection time. The fact that the shape of the predicted output voltage pulse is not grossly dissimilar to the shape of output pulses actually observed suggests that the chamber current may remain more or less constant for ~ 40 ns, and then fall off to zero over some finite period of time.

3.2 Linearly Decreasing Pulse of Chamber Current

A linearly decreasing chamber current pulse shape, as shown in Fig. 4A, is considered since it has been employed in various analyses.³⁻⁷ This current pulse shape assumes that the free electrons are collected at a constant rate from the instant of creation until $t = T$.

Assuming that $T = 106$ ns, which is the calculated electron collection time for this detector when the collector potential is in the range of -500 V to -800 V,⁸ the complete solution for Eq. (2) is calculated to be:

$$e_1(t) = \begin{cases} I (115 - 93.4 e^{-t/29.6} - 21.3 e^{-t/7.21} - 0.877 t) & \text{for } 0 \leq t \leq 106 \text{ ns} \\ I (642 e^{-t/29.6} + (3.29 \times 10^6) e^{-t/7.21}) & \text{for } t \geq 106 \text{ ns.} \end{cases}$$

Fig. 4 Response to Linearly Decreasing Pulse of Chamber Current

The calculated output voltage pulse shape is shown in Fig. 4B. The general shape of the trailing edge of the calculated output voltage pulse is closer to that of the observed voltage pulse (first convex, then concave) than in the previous case, but the peak seems very broad. Similarly, the time between 10% points is not a good indication of collection time.

3.3 Trapezoidal Pulse of Chamber Current

The trapezoidal pulse of chamber current shown in Fig. 5A can be considered as the superposition of a positive step function of amplitude I , a linear ramp commencing at $t = T_1$ of slope $-I / (T_2 - T_1)$, and a linear ramp of slope $I / (T_2 - T_1)$ commencing at $t = T_2$. Assuming $T_1 = 35$ ns and $T_2 = 65$ ns, the complete solution of Eq. (2) becomes:

$$\begin{aligned}
 & I(93 - 73.1 e^{-t/29.6} - 19.9 e^{-t/7.21}) \quad \text{for } 0 \leq t \leq 35 \text{ ns} \\
 e_1(t) = & I(278 - 308 e^{-t/29.6} - 633 e^{-t/7.21} - 3.1 t) \quad \text{for } 35 \leq t \leq 65 \text{ ns} \\
 & I(341 e^{-t/29.6} + (3.86 \times 10^4) e^{-t/7.21}) \quad \text{for } t \geq 65 \text{ ns.}
 \end{aligned}$$

The predicted output pulse shape for $0 \leq t \leq 125$ ns is shown in Fig. 5B. The predicted pulse shape could undoubtedly be optimized by further adjustment of the assumed values of T_1 and T_2 . However, the shape parameters of the predicted output pulse already agree rather well with those of the observed pulses. It is again noted that the time between 10% points on the predicted output voltage pulse (~ 113 ns) is considerably greater than the assumed duration of the chamber current (65 ns).

4.0 PULSE FORMATION PROCESS

U^{235} has a high fission probability when exposed to a thermal neutron flux. When a thermal neutron induced fission event occurs, U^{235} (N_{th} , F) f_p , two energetic and highly charged fission particles of roughly similar mass are emitted in nearly opposite and random directions. Less than half of the primary fission fragments are

(A)

TRAPEZOIDAL PULSE OF CHAMBER CURRENT.

	Predicted Pulse	Observed Pulse
10%-90% Risettime:	~27ns	~29ns
0%-100% Risettime:	~39ns	~38ns
Time between 10% points:	~113ns	~117ns
Time between 50% points:	~59ns	~60ns

(B)

CALCULATED OUTPUT VOLTAGE PULSE SHAPE FOR TRAPEZOIDAL PULSE OF CHAMBER CURRENT.

Fig. 5 Response to Trapezoidal Pulse of Chamber Current

emitted in the direction of the detector gas-filled sensitive volume. In addition, some fission fragments lose part of their kinetic energy in escaping the thin uranium coating. When a charged particle creates an ionization track in the gas, the resulting ions and electrons drift to the electrodes of respectively opposite polarity. Although the fission fragment spends some finite time in ionizing the gas (creating the track of electron-ion pairs), for most practical purposes the current pulse rise can be considered instantaneous at $t = 0$. Since the collection of resulting positive ions is much slower than that of the free electrons, to a first approximation they may be considered separately as independent collection events. The motion and collection of the charges, and the expected time dependence of chamber current, are depicted in Fig. 6 where for simplicity a parallel plate electrode geometry is shown.

4.1 Current Due to Electron Collection

4.1.1 For $0 \leq t \leq t_1$: where t_1 = time when the first negative charge reaches the positive electrode.

$$= \frac{d (d - R \cos \phi)}{\mu_e V_s}$$

The work done by the electric field in moving the negative charge toward the positive electrode by a distance dx will be:

$$dW = \underbrace{\rho R}_{\substack{\uparrow \\ \text{---quantity of charge moved (approximated to be a constant)}}} \underbrace{V_s \frac{dx}{d}}_{\substack{\uparrow \\ \text{---potential difference through which the charge is moved.}}}$$

Since $dx = \omega_e dt = \frac{\mu_e V_s}{d} dt$, where dt = time for charge to move a distance dx ,

then $dW = \frac{\rho R \mu_e V_s^2}{d^2} dt$, and the time rate at which the work is done

(A)
Electron-ion collection vs time

(B)
Chamber current vs time

Fig. 6 Ionization Event in Parallel Plate Fission Chamber

(i.e., the power dissipated) in the chamber will be:

$$\frac{dW}{dt} = \frac{\rho R \mu_e V_s^2}{d^2} \quad (\text{which is constant during the interval } 0 \leq t \leq t_1).$$

This power must be provided by the external power supply, therefore

$$V_s i_e(t) = \frac{dW}{dt} = \frac{\rho R \mu_e V_s^2}{d^2},$$

and

$$i_e(t) = \frac{\rho R \mu_e V_s}{d^2} \quad \text{for } 0 \leq t \leq t_1.$$

The magnitude of the initial current pulse remains constant for $0 \leq t \leq t_1$, that is, from the time of the first ionization event to the time when the last electron produced (first to arrive) arrives at the collector plate.

4.1.2 For $t_1 \leq t \leq t_2$: where t_2 = instant when the last electron in the track reaches the positive electrode

$$= \frac{d^2}{\mu_e V_s}$$

and

$$t_2 - t_1 = \frac{d R \cos \phi}{\mu_e V_s}$$

During $t_1 \leq t \leq t_2$, the electrons in the track are progressively collected by the positive electrode such that at any time t , the total negative charge remaining in the chamber will be:

$$\rho R \left[1 - \frac{t - t_1}{t_2 - t_1} \right],$$

a linearly decreasing function of t , which has the value ρR at $t = t_1$, and reaches zero at $t = t_2$. Therefore, the power dissipated in the chamber will be:

$$\frac{dW}{dt} = \frac{\rho R \mu_e v_s^2}{d^2} \left[1 - \frac{t - t_1}{t_2 - t_1} \right],$$

and the current through the chamber:

$$i_e(t) = \frac{1}{v_s} \frac{dW}{dt} = \frac{\rho R \mu_e v_s}{d^2} \left[1 - \frac{t - t_1}{t_2 - t_1} \right]$$

for $t_1 \leq t \leq t_2$.

4.1.3 For $t \geq t_2$: For times greater than t_2 there will be no negative charges left in the chamber, no power dissipated, and no current flowing through the chamber, i.e., $i_e(t) = 0$ for $t \geq t_2$.

4.2 Current Due to Positive Ion Collection

4.2.1 For $0 \leq t \leq t_3$: where t_3 = instant when the last of the positive ions reaches the negative electrode.

$$= \frac{d R \cos \phi}{\mu_p v_s}$$

Since the production of positive ions starts at close proximity to the negative electrode, collection of positive ions progresses such that, for

$0 \leq t \leq t_3$, the total positive charge remaining in the chamber at time t will be:

$$\rho R \left[1 - \frac{t}{t_3} \right].$$

The work done by the electric field in moving this positive charge toward the negative electrode by a distance dx will be:

$$dW = \underbrace{\rho R \left[1 - \frac{t}{t_3} \right]}_{\text{quantity of charge moved.}} \underbrace{V_s \frac{dx}{d}}_{\text{potential difference through which the charge is moved.}}$$

However, since $dx = \mu_p dt = \mu_p V_s \frac{dt}{d}$, then

$$\frac{dW}{dt} = \frac{\rho R \mu_p V_s^2}{d^2} \left[1 - \frac{t}{t_3} \right] = V_s i_p(t),$$

and the current flowing through the chamber as a result of the positive ions will be:

$$i_p(t) = \frac{\rho R \mu_p V_s}{d^2} \left[1 - \frac{t}{t_3} \right] \quad \text{for } 0 \leq t \leq t_3.$$

4.2.2 For $t \geq t_3$: there will be no positive ions left in the chamber, and $i_p(t) = 0$.

5.0 CURRENT PULSE SHAPE DISTRIBUTION

Neglecting electron-ion pair recombination, the neutron induced current pulse shape can be considered as the superposition of current pulses due to electron and positive ion collection respectively. Since $\mu_p \ll \mu_e$ (by at least three orders of magnitude), then $i_p(t)$ will normally be a pulse of small amplitude and long duration when compared to $i_e(t)$. In addition, the current contribution due to positive ions begins to decrease immediately, while the contribution due to electron collection remains unchanged until $t = t_1$. In fast ionization chambers, $i_p(t)$ is probably noticeable only as

a long, low tail at the end of the pulse of chamber current, whose effect can be minimized by differentiation of the output voltage pulse, and therefore, the net current pulse shape can reasonably be approximated to be the same as the current pulse due to electron collection only. If electron-ion recombination and non uniform charge density along the ionization track are considered, then similar shapes of current pulses are expected, but with slightly more negative slopes (proportional to the recombination rate) and round trailing edges (due to non uniform charge collection). It should be noted that not all fission counters are designed for fast counting applications, and that complimentary, slow response ionization chambers have been designed to minimize the fast pulse of electron current and this results in long duration pulses due to positive ion collection.⁹

The proposed model predicts a distribution of current and voltage pulse shapes similar to the distribution of the effective ionization track length ($R \cos \phi$). If $R \cos \phi \geq d$, then a linearly decreasing current pulse shape is generated. If $R \cos \phi \leq d$, then a trapezoidal current pulse shape is generated, with a constant current during W_e ($d - R \cos \phi$) nanoseconds, an electron collection time of $W_e R \sin \phi$ nanoseconds, and a pulse charge content proportional to the energy of the ionizing particle.

The proposed model also predicts that if the polarity of the applied voltage is reversed, there will be a change in the shape of the neutron induced current pulse, enhanced by the strongly inhomogeneous electric field in a cylindrical chamber. The output voltage pulse shapes of a Twentieth Century Electronics fission counter, Model P7A/22, S/N 7328 - 1, with positive and negative excitation voltages are shown in Fig. 7. The change in the pulse shape (e.g. concavity vs. convexity of the decreasing voltage due to electron collection) results from the reversal of the shape and polarity of the respective contributions electron and positive ion collections. Similarly, if each electrode has a fissionable material coating, then the shape of each pulse will depend on whether the fission event will occur in the positive or in the negative charged electrode.

Fig. 7 Output Voltage Pulse Shapes for Positive and Negative Excitation Voltages

The effect of excitation voltage polarity reversal on the output voltage pulse height distribution from a detector with fissile material coating one electrode, can be inferred from the pulse integral bias characteristics shown in Fig. 8. The pulse integral bias characteristics for a detector with fissile material coating on two electrodes is shown in Fig. 9. The output voltage pulse height distribution is strongly dependent on the distribution of fissile material within the chamber (e.g., thickness, number of electrodes coated, density, enrichment, etc.). Details of this dependence will be discussed in a separate technical note.

6.0 CONCLUSIONS

The simple proposed model for current pulse generation in fission counters readily accommodates the concepts of triangular and trapezoidal chamber current pulse shapes, as well as observed output voltage pulse height distributions. Since "collection time" is normally defined as the time elapsed between the ionization event and the collection of all electrons generated, it seems difficult to devise a practical method to obtain this value from the observed output voltage pulse shape. Any reproducible method for collection time measurement that does not consider the pulse shaping effect of the detector circuit may indicate only coarse changes in the collection time distribution, and therefore can be only a relative measure of system resolution.

Although the mechanism of neutron induced current generation might seem to be of only academic interest, its elucidation might contribute to optimization of the design of fission chambers and associated electronic systems for high noise and gamma pulse rejection capabilities.

MODEL P7A/22 F.C., S/N 7328-1

DATE

Fig. 8 Pulse Integral Bias Characteristics for TCE P7A/22 Fission Counter

MODEL CFUC-02 F.C., S/N 116

DATE

Fig. 9 Pulse Integral Bias Characteristics for CFUC-02 Fission Counter.

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