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Current Status of the AC Ionization Chamber

G. K. Rusch

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GENERAL ELECTRIC

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CURRENT STATUS OF THE AC

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IONIZATION CHAMBER

G. K. Rusch

July 1961

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Abstract

A new-concept AC ionization chamber was under development at ANP at the time of primary contract termination. This report describes the instrument and supporting electronics as conceived at termination of the program.

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CURRENT STATUS OF THE AC IONIZATION CHAMBER

Introduction

The AC ionization chamber described in DC 60-2-80¹ has considerable potential in the current range from 10^{-11} to 10^{-4} ampere . Several designs are possible, and the sensors can be tailored to specific requirements when necessary. One design appears potentially competitive with DC ionization chambers and micro-micro ammeters for low-level-flux monitoring. This design would be useful in low-power reactor assemblies such as critical experiments. Another design appears to have the high-temperature flux-monitoring field to itself.

General Considerations

The mode of operation described in DC 60-2-80 utilizes, to advantage, approximately fifty percent of the ion pairs formed. A DC ionization chamber utilizes essentially all of the ion pairs formed. Other than this it appears that for most practical, neutron-sensitive, chambers the available current per unit neutron flux is the same for the AC and the DC ionization chambers.

The signal voltage developed by the AC ionization chamber is dependent upon the current obtained from the chamber and the effective electrical impedance to ground as viewed from the signal-grid-electrode. Thus both low-frequency operation and low effective stray capacity in the chamber's signal-grid-electrode circuit tend to increase the amplitude of the voltage signal derived from a given current. Fundamentally, the frequency chosen for the signal is limited at the lower limit by response time considerations and at the higher limit by signal-grid-electrode to ground impedance considerations.

The switching frequency is basically limited at the higher end by electron transit time in the gas, or by driving-power considerations, either effect can predominate depending upon the physical characteristics of a particular situation. If the switching frequency is not too high, it is possible to use the switching-voltage feed-cable capacity and the effective switching-grid-electrode to ground capacity as part of a resonant circuit. This greatly reduces the drive power required. To use the cable capacity as part of a resonant circuit the cable length should be less than one-quarter wave length of the switching frequency. The lower limit of the switching frequency is determined by the problem of separating the switching voltage from the signal voltage. It is desirable to minimize the overall system complexity.

As implied, there is coupling of the switching frequency voltage envelope into the signal-grid-electrode circuit. Since the envelope is the same frequency as the signal, it is necessary to avoid non-linearities in certain critical parts of the circuit or this envelope will be detected and appear as a background signal. Non-linearities are almost sure to be present in the output of the switching circuit, and care must be taken to prevent the resulting detected voltage from being capacitively coupled into the signal-grid-electrode circuit; multiple tuned circuits with a minimum of capacitive coupling between each other can be quite effective. Any detected voltage which does couple across the chamber grid capacity will be ninety degrees out of phase with the signal if the signal-grid-electrode load is purely resistive.

Detection of the switching frequency envelope can occur in the signal-grid-electrode circuit itself. The envelope is capacitively coupled across the chamber grid structure and appears with considerable amplitude in the signal-grid-electrode circuit. If allowed to appear at the grid of the first vacuum tube, or transistor, it would certainly be detected and cause difficulty. Indeed certain resistors, e.g. deposited carbon, cannot be used because of their non-linear properties. It has been found possible to use a balanced output from the switching circuit and to effectively cancel the fundamental of the switching frequency. This also tends to cancel voltages due to detection in the switching output circuit. However, it is not possible to simultaneously eliminate the fundamental and the detected voltage (i.e. that detected in the switching output circuit) from the signal-grid-electrode circuit by cancellation. In addition, harmonics of the switching frequency are present and can cause difficulties. Thus some filtering is necessary in the signal-grid-electrode circuit between the ionization chamber and the first non-linear element. It is desirable to accomplish this filtering with a minimum of additional capacity to ground and with a minimum reduction of the effective impedance to ground. In addition it is apparent that the signal itself should not be significantly attenuated.

When considering the magnitude and frequency of the switching voltage it is sufficient to consider only the mobility of the electrons. The positive ions are not switched between electrodes; only their fields are switched and thus contribute to the observed signal current. While it is possible to use many different waveforms for both the switching voltage and the modulating voltage, some are more practical than others. A sinusoidal waveform seems desirable for the switching voltage since tuned circuits can then be used to reduce circuit loading and to suppress voltages arising due to the detection of the switching envelope. Either sinusoidal or square wave voltages appear adequate for the modulating waveform. The square wave probably is the better. An estimate of the magnitude of the grid-to-grid switching voltage required and its frequency can be obtained from the characteristics of previously constructed DC ionization chambers and fission counters. For example, a fission counter filled with a counting gas composed of 99% argon and 1% nitrogen has provided data to show that electrons can be collected through a distance of 0.25 centimeter in approximately 2×10^{-7} seconds when the electric field is about 1200 volts per centimeter². Thus, if the grid electrode spacing is 0.025 centimeter, approximately 30 volts grid-to-grid is required for a period of time in excess of 2×10^{-7} seconds to adequately switch the electron beam. The required voltage amplitude can be reduced if the switching frequency is reduced proportionally. There is, however, a limit beyond which the grid-to-grid voltage gradient cannot be reduced if saturated operation is to be maintained. This can be estimated from the value of the voltage required to assure that the current from the ionization chamber is independent of the applied voltage for a given ion density within the chamber. The "compensated ionization chamber" requires about 500 volts to assure saturation when the steady-state DC current is 10^{-4} amperes³. Since the electrode spacing is approximately one-eighth of an inch this amounts to a field of approximately 2000 volts per centimeter. Thus for this case, the voltage required for saturation is greater than that required for collecting the electrons in a time of 2×10^{-7} seconds. This would not be true at lower currents.

These, however, only are order-of-magnitude values since the grid-to-grid geometry in the AC chamber is not the same as the signal-electrode to high-voltage-electrode geometry in the DC chamber. In addition, the effective electron density will change in the AC chamber compared to that effective in the DC chamber with a resulting change in effective field strength within the counting gas. Thus, while the estimates are adequate for a starting point, complete characteristic curves will have to be obtained for each design.

High-Sensitivity Operation

For the purpose of this discussion it is assumed that the incident flux is not normally greater than that in which the instrument is designed to operate. Also it is assumed that high sensitivity implies moderate ambient flux levels. An example of the intended environment is a "zero power" critical assembly. Figure 1 shows a possible design for a sensitive-type AC ionization chamber. Figure 2 shows a quarter-inch section of the center electrode with the grid wires. The two grids are wrapped spirally in a double-thread-type double groove. The additional separation of the grid wires over that which is attained by other grid structures is not too important since the highest currents of interest will probably be less than 10^{-6} amperes. Thus the voltages (both switching and polarizing) required for saturated operation are still moderate. The chamber can also be as long as desired without complicating the design problem. For maximum sensitivity the chamber volume can be filled with B_2OF_6 gas⁴, although boron lined counters require less voltage for saturated operation. To keep the signal-grid-electrode impedance high (i.e. not appreciably affected by the signal cable capacity), a transformer with a large step-down ratio is used from the chamber. A step-down turns ratio of the order of fifty to one should be adequate for most applications if the input impedance rating is sufficiently high. At the amplifier end of the receiving cable the voltage is stepped up by a greater ratio. (See "Appendix"). It is probable that a double-shielded subminiature cable with a conducting coating (microphonic free) under the inner shield will give excellent results. The polarizing voltage source for the collector electrode should be free of ripple and of low impedance; a 300- or 600-volt battery supply is probably most desirable for the initial experimental work. The cable to carry this voltage to the chamber can be subminiature coaxial cable.

The switching voltage is derived from a double-ended source. Both polarity outputs are cabled to the chamber (preferably with double-shielded cables); one is connected to the switching-grid-electrode and the other through a small trimmer capacitor to the signal-grid-electrode⁵. The cable connected to the switching-grid-electrode also carries a small positive bias voltage. Both cables are part of the tuned output stage of the switching circuit. At this time it is felt desirable to accomplish the envelope cancellation ahead of the transformer since the transformers would probably act on the wave function in a rather complex manner. This would make subsequent cancellation difficult. The additional high-frequency filtering can best be done in the lower impedance circuit between the transformers; the cable itself can be used as a filter capacitor. The signal-to-amplifier noise ratio, the amplifier noise to standard deviation of the signal, the response time of the system, and the signal frequency, are interdependent. It is possible to change the frequency of operation for very low current levels and tailor the above considerations to a given set of requirements, possibly even automatically. However, a considerable amount of philosophy enters

* It may be desirable to have an additional amount of phase-shifting incorporated at the chamber.

Figure 1
Sensitive-Type AC Ionization Chamber

Figure 2
Quarter-Inch Section of the Center Electrode with Grid Wires

the picture at this point and it is probably undesirable to probe too deeply into this area prior to completion of the initial development work on the chamber. It is probable that signal frequencies of the order of 200 to 1000 cycles per second are suitable for the initial work. For example, at 200 cycles per second and with an effective signal-grid-electrode to ground capacitance of 200 uuf, the capacitive reactance to ground is almost eight megohms. If this constitutes the effective impedance of the signal circuit, a current of 10^{-11} amperes develops a voltage signal of 40 microvolts peak-to-peak. Thus a reasonably good signal-to-noise ratio can be obtained at this low signal level. In addition, if a response time of ten complete cycles is assumed, which is fifty milliseconds, a reasonably fast response is obtained at this signal level. Figure 3 is a block diagram schematic of a possible channel.

High-Temperature, Power-Level, AC Ionization Chambers

For power-level operation it is necessary to maintain reasonably small grid-to-grid spacing to minimize the drive voltage requirements. At present it appears that grid conductor widths and spacing widths should be equal and of the order of 0.001 to 0.005 inch. For some considerations the chamber capacity may be critical; however, in most cases a long cable will be attached directly to the chamber, thus effectively swamping the chamber capacity and making it negligible. (It is assumed that, due to the inclement environment, a transformer cannot be used at the chamber end of the cable; however, a transformer should be used at the amplifier end of the cable.) Where chamber capacity is not critical it appears that, within the limits of reliability, the grid-to-grid spacing should be minimized. It should be noted that an open grid element could have very undesirable effects on the chamber's characteristics, while shorted grids would of course make the device useless. Present thinking places the ion density, for linear operation, at about that which results in 10^{-4} ampere from the compensated ionization chamber. Thus the total sensitive area should probably be in excess of 100 cm². If the ion density is to be kept low and the sensitivity reasonable for a given volume, stacked parallel plates may offer advantages over cylindrical geometry. The insulators should be ceramic or some high-temperature equivalent. The grid structures probably will have to be machined with an electron beam from a metal-coated ceramic.

Referring to "Appendix" and eliminating the transformer N_1 (effectively letting $N_1 = 1$) and noting the effects of maximizing the amplifier input voltage with respect to N_2 , it is seen that the following is true.

$$N_2^2 = \frac{C_c + C_x}{C_{in}}$$

Substituting N_1 and the above in equation (8) of "Appendix", the following is obtained:

$$E_{in} = \frac{1}{j\omega} \left[\frac{1}{2\sqrt{(C_c + C_x) C_{in}}} \right]$$

It is expected that a signal frequency of 1KC and a switching frequency of the order of 100 KC will be adequate. A more-adequate picture of just what flux densities and total chamber currents are best for this type chamber is left to be answered by the experimentally determined characteristics of the chamber. It appears, however, that the current density within the AC ionization chamber should be limited to a value about an order of magnitude less than ~~that~~ with DC chambers. In addition it may be difficult to obtain sensitive areas as large

Figure 3
Block Diagram of a Response Channel

as those obtained with the DC chambers. Thus the total current signal will be from one to two orders of magnitude less than those customarily dealt with from DC chambers. However, this should not constitute a serious problem since the signals that can be attained are readily handled ~~when~~ AC amplification is used.

It is possible to obtain compensated AC operation by using a compensating volume and grid network. As a matter of fact, if the compensating chamber geometry is identical to the neutron-sensitive chamber geometry, one can obtain switching voltage cancellation in the signal circuit automatically just by adding the signals. It is assumed, of course, that the compensating chamber utilizes the opposite polarity from the switching voltage tank circuit than ~~that which the neutron-sensitive chamber uses.~~

APPENDIX

Consider the following equivalent circuit of an AC ionization chamber.

It is apparent that E_c is equal to the current obtained from the chamber times the effective impedance as seen from the chamber signal-grid-electrode. The effective impedance in this case is that determined by the capacitance C_c plus that reflected back from C_x and C_{in} through the transformers.

First calculating the value that C_{in} reflects back into the cable circuit (assuming ideal transformers).

$$(1) \quad E_{in} = N_2 E_x$$

$$(2) \quad N_2 I_{in} = I_x$$

$$(3) \quad Z_{xR} = \frac{E_x}{I_x} = \frac{E_{in}}{N_2^2 I_{in}} = \frac{Z_{in}}{N_2^2} = \frac{1}{j\omega N_2^2 C_{in}}$$

The total (excepting the reflected chamber capacity) impedance as viewed from the cable is that due to the capacity of the cable plus the reflected capacity $N_2^2 C_{in}$ thus:

$$(4) \quad C_{eff-x} = N_2^2 C_{in} + C_x$$

Performing the same operation in transferring the effective cable capacity to the chamber circuit we obtain the following:

$$(5) \quad C_{eff-c} = N_1^2 (N_2^2 C_{in} + C_x) + C_c$$

The voltage developed at the input of the amplifier is:

$$(6) \quad E_{in} = N_1 N_2 E_c$$

However E_c is:

$$(7) \quad E_c = -jIX_c = \frac{I}{j\omega C_{eff-x}} = \frac{I}{j\omega} = \left[\frac{1}{N_1^2 N_2^2 C_{in} + N_1^2 C_x + C_c} \right]$$

$$(8) \quad E_{in} = \frac{I}{j\omega} \left[\frac{N_1 N_2}{N_1 N_2 C_{in} + N_1 C_x + C_c} \right]$$

Now it is desirable to maximize the voltage with respect to the two turns ratios N_1 and N_2 .

14.

$$(9) \quad \frac{2E_{in}}{2N_1} = \frac{I}{j\omega} \left[\frac{N_2^2 N_1^2 C_x + N_1^2 N_2^3 C_{in} + N_2 C_c - 2N_1^2 N_2 C_x - 2N_1^2 N_2^3 C_{in}}{(N_1^2 C_x + N_2^2 N_1^2 C_{in} + C_c)^2} \right]$$

$$(10) \quad \frac{2E_{in}}{2N_2} = \frac{I}{j\omega} \left[\frac{N_1^3 C_x + N_1^3 N_2^2 C_{in} + N_1 C_c - 2N_1^3 N_2^2 C_{in}}{(N_1^2 C_x + N_1^2 N_2^2 C_{in} + C_c)^2} \right]$$

For maximum with respect to N_1 :

$$(11) \quad \frac{2E_{in}}{2N_1} = 0$$

$$\therefore (12) \quad N_1^2 = \frac{C_c}{C_x + N_2^2 C_{in}}$$

For a maximum with respect to N_2 :

$$(13) \quad \frac{2E_{in}}{2N_2} = 0$$

$$\therefore (14) \quad N_1^2 = \frac{C_c}{N_2^2 C_{in} - C_x}$$

For an optimum both equation (12) and equation (14) must be satisfied. However to do this it is necessary for C_x to be zero. An equivalent condition which exists when:

$$(15) \quad N_2^2 C_{in} \gg C_x$$

Assuming equation (14) is satisfied,

$$(16) \quad N_1^2 N_2^2 = \frac{C_c}{C_{in}}$$

It can also be shown then that:

$$(17) \quad E_{in} = \frac{I}{2j\omega \sqrt{C_c C_{in}}}$$

An example, utilizing order or magnitude values, indicates the order of magnitude of the turns ratios involved. Assume a chamber with a capacitance to ground of 200 uuf, a one-hundred and fifty foot signal cable with a total capacitance of 3750 uuf, and an amplifier input capacity of 30 uuf.

$$(18) \quad N_2^2 = 100 \frac{C_x}{C_{in}} = \frac{375,000}{30} = 1.25 \times 10^4 \gg \frac{C_x}{C_{in}}$$

$$(19) \quad N_2 = 112$$

$$(20) \quad N_1^2 = \frac{C_c}{N_2^2 C_{in}} = \frac{200 \times 10^{-12}}{1.25 \times 10^4 \times 30 \times 10^{-12}} = 5.33 \times 10^{-4}$$

$$(21) \quad N_1 = 2.32 \times 10^{-2}$$

$$(22) \quad \frac{1}{N_1} = \frac{100}{2.32} = 43.2$$

Or in words, a step down of 43 to 1 is used from the chamber to the cable; a step up of 112 to 1 is used from the cable to the input amplifier.

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- (1) G. K. Rusch, "A New Type AC Ionization Chamber," DC 60-2-80.
- (2) DC 56-6-93
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