A POSITION SENSITIVE PROPORTIONAL COUNTER
FOR NEUTRON RADIOGRAPHY

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A prototype position-sensitive proportional counter was investigated for use in neutron imaging applications. The counter uses a converter foil of ^6LiF and a collimation grid to achieve improved resolution compared to counters filled with a neutron-sensitive counting gas. The proportional counter consists of a grid of 36 1-mil pyrolytic carbon coated quartz fibers on 2.5 mm centers. Because of the high resistance of the collector wires and the distributed capacitance to ground, the rise time of a pulse will increase with distance along the collector. This rise-time information is used to determine the position of an event to accuracies less than 1 mm along the wire. Standard nuclear instrumentation techniques are utilized with readout on a multichannel pulse height analyzer or on a storage scope.

Tests performed with alpha particles showed that a geometry using collector wires off center by 0.5 mm produced the best resolution. The best resolution achieved was 0.59 mm FWHM, but the off-center geometry was not used for the neutron imaging experiments because of difficulties in achieving stable operation. Neutron images produced by this counter had an unsharpness of 5.5 mm (3.3 mm FWHM) and a contrast of 55%; this was with a ^6LiF converter foil (100 μ). Images with ^{10}B and Gd converter foils showed unsatisfactory contrasts.

Introduction

Neutron radiography has become a useful tool for determination of hydrogenous materials within x-ray absorbing media (explosive bolts), for examination of fissile materials (fuel rods), and for other miscellaneous applications where visualization of a neutron scattering or neutron absorbing material is involved. Radiography is generally thought of as a technique utilizing a high resolution image produced on film. Although many applications require such a high resolution image, others can utilize an image which does not resolve fine details. Such applications are: detection of uniformity of fissile material within a fuel rod, and the detection of the presence and amount of a neutron absorbing or scattering material in particular configurations. Position-sensitive counters are attractive for such applications since they can be produced in large areas, they have good resolution and they provide digital information suitable for on-line computer analysis. This paper presents data from the development and

application of a prototype position-sensitive counter sensitive to thermal neutrons.

In the past few years, position-sensitive proportional counters have been developed and applied in many areas; however, the first and still the major area of application is in particle physics. The first chambers were multi-wire chambers with complex read-outs utilizing the signals from individual wires.^{1,2} Resolution was limited to the wire spacing which was on the order of 2 mm with a minimum of 1 mm. Modifications of this basic technique include a series of staggered chambers³ and drift chambers^{1,4} which improved the resolution (0.2 to 0.5 mm FWHM; full width at half maximum) and reduced the complexity of the electronics. A recent development uses multiwire chambers in which the induced pulses are read out by delay lines.^{5,6} Resolutions with these chambers can be as high as 0.2 mm FWHM; however, approximately 1.1 mm FWHM is typical⁶ with the arrangement generally employed. A unique type of position-sensitive counter uses high resistance anode wires and measures the rise time of the output pulses to determine the position of interaction.^{7,8} Resolutions of as high as 0.15 mm FWHM have been reported for these units.⁸ It was decided to use this method, the Borkowski method,^{7,8} in the development of our prototype counter.

Imaging of neutrons requires the use of a converter material which absorbs the neutrons and releases a charged particle which can interact with a detecting medium, usually film. Resolutions achieved with film methods are as high as 10 μ .⁹ Many imaging methods other than film have been investigated⁹ including image intensifiers which have a high contrast resolving power of about 0.35 mm. Proportional counters⁷ and spark chambers have been investigated for spatial resolution of thermal neutrons; however, these units have generally utilized a filling of neutron sensitive counting gas (BF_3). This limits the resolution to about twice the range of the alpha particles from the reaction $^{10}\text{B}(n,\alpha)^7\text{Li}$ in the gas (6 mm at 70 cm Hg). Our counter uses a converter foil and an alpha collimator to achieve a higher inherent resolution.

The Counting SystemThe Counter

The prototype counter we have developed is patterned after the Borkowski method,^{7,8} and consists of a plane of 36 wires on 2.5 mm centers

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suspended between two parallel plates. The wires are 1-mil pyrolytic-carbon-coated quartz fibers 13 cm long. The counter was built in such a manner that the spacing of the wires and plates could be varied; however, a spacing of 4 mm between the plates and the wires is generally used. A pressure chamber houses the counter which allows variation of the gas pressure to limit the range of the alpha particles and increase the resolution.

A departure in our counter is the use of a collimated plate of neutron-sensitive material rather than a neutron-sensitive counting gas such as BF_3 . Ideally, one would like to employ an infinitely thin converter of 100% efficiency in intimate contact with an infinitely thin detector of 100% efficiency. This situation is approached by film and a thin converter foil which allows one to achieve the minimum dispersion of the converted particles and the maximum resolution. If one places the converter foil against the face of a position-sensitive proportional counter or uses a neutron-sensitive counting gas, resolution is limited by the range of the particles within the gas and the thickness of the counter. By placing a multi-hole collimator between the converter foil and counter and minimizing the thickness of the sensitive volume of the counter, one can limit the dispersion caused by the particles from the conversion process. A second factor which aids in improving the resolution is the self-collimating property of a foil which is infinitely thick with regard to the range of the converted particle. Calculations indicated that this alone gives about a factor of two improvement over the resolution expected from simple geometrical considerations of the collimator.

Our prototype counter is built in a manner that allows changing of the converter material and collimation. Figure 1 shows calculated efficiency and resolution for various collimator ratios. The curves have similar shapes since they both depend on the solid angle of the collimator. Our collimators were expected to give a geometrical efficiency of about 1 to 7% and a resolution of 0.6 to 2 mm FWHM (unsharpness of 1.0 to 3.3 mm). The actual counter efficiency was expected to be from 5 to 15% of the geometrical efficiency depending on the size and type of converter screen. The collimators used are etched stainless steel grids. In general, it is not feasible to obtain collimation ratios of better than 2:1 diameter to length; however, it was felt that the grids could be stacked to achieve the ratios desired. The actual grids employed were 1-mil stainless steel with 2.5-mil holes on 4-mil centers covering an etched area of 3 X 4 in. Figure 2 shows a schematic illustrating operation of the counter and Figure 3 shows a photograph of the counter itself.

In actual practice it did not prove feasible to stack the etched grids and achieve a uniform response with improved collimation. Careful alignment of the grids while observing the

Moire' pattern, indicated that nonuniform collimation was unavoidable. Also, the higher collimation ratios will be detrimental to our image contrasts. However, as higher collimation ratios become available in large area grids, their use will be investigated.

Counter Electronics

Signal Generation

The method used to derive the position information from the counter is essentially the technique reported by Borkowski and Koon.⁸ A detailed description of the technique will not be given here; however, the basic operation of a one-dimensional counter is illustrated in Figure 4. Negative high-voltage on the counter plates causes the ionization from an alpha particle entering the counter to produce a negative pulse at the position X on the high resistance collectors which are near ground. Because of the high resistance of the collector wires and the distributed capacitance to ground, the rise time of this pulse will increase as the distance from position X increases. By observing the rise time of the pulse at both ends of the counter, one can determine the position of the input pulse. The rise-time measurements are made by doubly-differentiating the observed pulse at each end of the counter and locating the zero point crossover of the differentiated pulse. In our system, timing single-channel-analyzers were used to measure the crossover points. By delaying one of these timing signals and using them to start and stop a time-to-amplitude converter, an output pulse is obtained whose amplitude is directly related to the position of the original input pulse along the counter wire.

The two-dimensional counter is merely an extension of the single-dimensional technique in which a series of the high resistance collector wires are connected at the end points by resistors as shown in Figure 5. The output at each of the corners is amplified and properly summed to produce the X-axis and Y-axis timing pulses. The X position and Y position voltage pulses are generated in the same manner as in the one-dimensional counter.

Signal Analysis

Storage and/or analysis of the X and Y position voltage information from the two-dimensional counter can be accomplished by various means. Our system uses both a multichannel analyzer and a storage oscilloscope as the analysis devices.

Preamplification of the negative voltage signals is accomplished with a wide-band coupled preamplifier.¹⁰ The preamplifier design specifies matched input FET's which allow the output dc ambient voltage to be adjusted to ground potential. However, slightly unbalanced FET's and the resulting dc ambient output level can be tolerated by proper design of the summing amplifier.

In our case, wide-band operational amplifiers were used as summing amplifiers with an offset bias adjustment at the input summing junction of each amplifier input.

An integrating time constant of 2.5 sec in the main amplifiers was found to produce the most satisfactory results for uniformity of counter sensitivity. For most conditions a unity amplifier gain was sufficient to provide satisfactory doubly-differentiated pulses to the single channel analyzers.

Standard timing single-channel-analyzers (SCA) were used to define the crossover point of the amplifier pulses. The internal adjustable delays available in the timing SCA's were of sufficient magnitude to delay the "stop" signal. Delays on the order of 0.8 μ sec for the X-axis and 0.25 μ sec for the Y-axis were typical. As one might expect, the threshold energy levels were observed to have a significant effect upon the uniformity of response of the counter. Uniform counter response was obtained only when the threshold level was adjusted as low as possible while maintaining good signal-to-noise ratios.

A 2048-channel multichannel analyzer was utilized as one data display and analysis method. A 64 (X-axis, 1.6 mm/point) by 32 (Y-axis, 2.3 mm/point) array with CRT readout proved satisfactory as a means of generating an image and was also valuable in evaluating the counter resolution and counting efficiency.

In a second method, the outputs of the time to amplitude converters (TAC's) are used directly to produce an image on a beam storage oscilloscope. Figure 6 illustrates the technique used to place the position information on the screen of the CRT. The X and Y counter axis TAC's outputs are properly processed and fed into the X and Y oscilloscope axes, respectively. Pulse stretching of these pulses is required to allow the intensity modulation circuitry to react and intensify the writing beam (in our system the maximum X-axis modulation is 1 MHz). The intensity modulation circuit is activated by a coincidence gate which detects coincident pulses in the X and Y directions.

For direct image production, the oscilloscope has a significant advantage over the multichannel analyzer. The resolution of the analyzer is limited by the discrete number of channels (in our case, 2048) into which information can be stored. In the case of the oscilloscope a practically infinite resolution is available, limited only by the beam diameter on the CRT face. The relatively large CRT face of the beam storage scope (4 in. by 5 in.) produces a large image. Operation of the storage scope has been satisfactory; however, it does not prove as convenient as an analyzer when the signal-to-noise ratio (contrast) is poor.

Results

To compare results we have defined an un-

sharpness value U to give an idea of resolution, and contrast C to indicate the signal-to-noise ratio. The unsharpness is the distance from the edge of the maximum value to the edge of the minimum value on the image of an edge of an object, of high contrast. This is a measure of the smearing of the image of a sharp edge and the more common FWHM is about 0.6 of the unsharpness values in our experiments. This seemed to be the best measure of our resolving capability since we are interested in resolving general details in objects and not point sources. The unsharpness will be a function of object contrast, beam divergence, counter resolution and collimation of the secondary radiation. The collimation will be the major consideration in our experiments. The contrast is defined as the difference in magnitude between the image produced by the desired radiation and the background divided by the magnitude of the desired image and is expressed as a percent. An ideal contrast would approach 100% and this is realized when the counter is used with high-intensity alpha sources. The contrast will be a function of the relative strengths of desired and background radiation, electrical noise, collimation, converter foil efficiency and object contrast.

Alpha Counting

A number of tests were performed with both the one-dimensional and the two-dimensional counter using alpha sources to explore the effects of collimation, termination, type of preamplifier, etc. on unsharpness and counter performance. With an improperly terminated counter, the response is nonlinear along the counter (end efficiency = 50% of edge efficiency) and the unsharpness degrades toward the ends. With properly adjusted gains and properly terminated counters, the unsharpness and efficiency are quite uniform. Figure 7 shows counts taken as an alpha source was moved across the face of the two-dimensional counter and the peak heights are uniform to $\pm 4\%$. Experiments were performed with both charge-sensitive and voltage-sensitive¹⁰ preamplifiers with equivalent results when the units are properly terminated.⁷ The voltage-sensitive preamplifiers require parallel termination and the charge-sensitive preamplifiers require series termination. Termination was accomplished, where needed, by a combination of calculation and empirical adjustment of the terminating capacitor and resistor components. The shaping time-constants of the amplifiers have an effect upon the frequency response of the counters and must be adjusted for optimum counter response.

Table 1 shows some measured relative efficiencies and unsharpness values for various collimators. All unsharpness measurements were made along the wires (X-direction) since spacing of the wires (2.5 mm) will limit the resolution in the Y-direction. The offset counter geometry (Table 1) gave unsharpness values better than expected from simple improvements in geometry. This is due to weighting of the charge collection by the resulting nonuniform field. The unsharpness

TABLE 1

Measured unsharpness and efficiency for two different counter geometries using an alpha source (^{241}Am)

Collimator(a)	Unsharpness, mm		Relative Efficiency, %
	Offset(b)	Uniform(c)	
	Spacing	Spacing	
Mylar sheet	6.0	12.6	100
1:2.5 Collimator	3.9	6.1	57
1:2.5 Collimator + Mylar	3.2	5.1	38
1.2:1 Collimator + Mylar	1.6	2.2	10
10:1 Collimator	0.97	---	0.14

(a) Ratio of height to diameter of holes in collimator

(b) Front Grid to counter wires 3.5 $\pm$ 0.2 mm

Counter wires to back plates 4.0 $\pm$ 0.2 mm

(c) Front Grid to counter wires 4.0 $\pm$ 0.2 mm

Counter wires to back plate 4.0 $\pm$ 0.2 mm

values with a simple mylar sheet are better than expected since the range of the ^{241}Am alpha particle is about 42 mm in air. In general, the measured values were in good agreement with prior estimates from calculations. The contrast was on the order of 95% for our measurements with the alpha sources. The collimator with the mylar sheet compared to the collimator alone indicates the type of improvement in unsharpness expected from a thick source. The 10:1 collimator represents our best unsharpness and corresponds to a resolution of about 0.59 mm FWHM. This compares to values by other investigators of 0.4 mm,¹¹ 0.6 mm¹² and 0.15 mm.⁸ The collimator and source uniformity make some contribution to this value and one would expect a better resolution with a finer collimator and smaller, more uniform sources. Although smaller and nonuniform anode-cathode spacings gave better resolution at lower voltages, they lead to unstable operation of the counters. We found that 4 mm was the smallest practical anode-cathode spacing for use in our counter.

Neutron Counting

Our system was designed with the objective of instrumented imaging in low-flux beams of thermal neutrons, specifically from beams of ^{252}Cf neutrons. We use a beam of thermalized neutrons from a 150 μm ^{252}Cf source housed in a special moderator and shield. Our images were

made in a thermal flux of 1.6×10^3 n/cm²-sec with a neutron-to-gamma ratio of 7×10^4 n/cm²-mR. Figure 8 shows a radiograph of a cadmium test piece made in the same neutron beam in which the counter was operated. A $^6\text{LiF-ZnS}$ scintillation screen was used to make the radiograph and this is one of the fastest techniques possible, taking 20 min. to produce the image shown. The contrast is 94% and the unsharpness is less than 0.5 mm. The contrast value was determined by measuring film transmission with a densitometer.

^6LiF and ^{10}B converter foils were used with the counter and consisted of the material mixed in epoxy and spread uniformly over the surface of a piece of aluminum foil. The surface of the material was granular with a maximum thickness of 75 μ for the ^{10}B and 100 μ for the ^6LiF . A ^6LiF foil with a thickness of 40 μ was tried with no improvement in sensitivity or resolution. However, it should be noted that the optimum foil thicknesses are much smaller since the range of the 2.05 MeV alpha from the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction is about 15 μ in Be which would be similar to LiF while the range of the alpha from $^{10}\text{B}(n,\alpha)^7\text{Li}$ (1.7 MeV) is even less. The triton from the ^6Li reaction has a greater range than the alpha and will contribute to the efficiency of the converter. Table 2 summarizes data taken with the foils and collimators and agrees quite well with the ^{241}Am data shown in Table 1. Gadolinium foils were also tried, but no images were obtained because of the low energy (70 keV) of the conversion electrons.

TABLE 2

Imaging parameters with the counter in a neutron field. Distance from front grid to counter wires and from wires to back plate held at 4.0 ± 0.2 mm.

Imaging Parameters	Unsharpness, mm	Contrast, %	Relative Efficiency, %
$^6\text{LiF} + \text{Mylar}$	10	63	100
$^6\text{LiF} = 1:2.5$ Collimator	5.5	55	58
$^6\text{LiF} + \text{Collimator} + \text{Mylar}$	7.4	32	40
$^{10}\text{B} + \text{Collimator}$	5.0	12	11

The unsharpness with the uncollimated ^6LiF foil corresponds to the range of the alpha particles in the gas (10 mm) and the poor contrasts are due to a high gamma background and some epithermal neutron imaging. Changing the discrimination levels could easily improve the contrasts without changing the sensitivity; however, this leads to nonuniformity of counter response. The uniformity of the counter was $\pm 6\%$ over the imaging surface which includes nonuniformities in the collimation and in the converter foil besides the counter nonuniformity.

Figure 9 is an image of the cadmium test object (10^7 nvt) shown in the neutron radiograph of Figure 8. The image was formed using the ^6LiF converter foil with the 2.5:1 collimator and has an unsharpness of 6 mm with a contrast of 55%. While counting, one can resolve the 1-cm diameter holes within 3 min and the 0.5 cm diameter holes within 20 min. It takes on the order of 300 min. to see evidence of the 2.5 mm diameter holes which are near the physical size represented by a single channel. The neutron counting efficiency is 0.25% which is less than half the expected efficiency. If the counter were filled with $^{10}\text{BF}_3$ counting gas, the efficiency of the counter would approach 8%.

Conclusions

A counter using a neutron conversion foil can be built for imaging in thermal neutron fields. The resolution and efficiency of the counter are not as good as expected and will not meet the imaging speed or resolution of an image intensifier system (0.25 mm FWHM; $4 \times 10^5 \text{ n/cm}^2$). The offset geometry used with the alpha sources would give an improvement in resolution without a loss in efficiency; however, the difficulties with stability of operation would have to be overcome. Resolution is better than one would obtain with a gas-filled detector at 2 atmospheres of pressure (6.2 mm FWHM versus about 3.4 mm FWHM) and would be even better with the offset geometry (2 mm FWHM). The use of larger collimation ratios would improve the resolution, but the loss in efficiency would degrade the contrast and the resolution unless the gamma contribution to the image could be reduced. Contrast (signal-to-noise ratio) is important in image formation and with negligible gamma contribution images with a resolution of 0.5 to 1.0 mm could be produced

with a neutron exposure of 10^7 n/cm^2 .

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COLLIMATOR &
CONVERTER FOIL
(TOP PLATE)

WIRE GRID

BOTTOM PLATE

SIGNAL

HIGH VOLTAGE
INPUT

PREAMPLIFIERS

ONE-DIMENSIONAL COUNTER OPERATION

POSITION SENSING ELECTRONICS

DATA ANALYSIS ELECTRONICS

TOP

FIGURE 7. Counts Taken With Alpha Sources Positioned Along The x Axis Of The Counter. This Illustrates The Uniformity Of The Counter Response.

FIGURE 8. Radiograph Of Cadmium Test Object Taken With A $^6\text{LiF-ZnS}$ Scintillation Screen.

FIGURE 9. Photograph Of The Image Formed On The Counter Using The Cadmium Test Object.