DIFFERENTIAL CURRENT PULSE PREAMPLIFIER FOR FISSION COUNTERS*

J. T. De Lorenzo, W. T. Clay, G. C. Guerrant

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Abstract

A current-pulse preamplifier with a differential input was developed for use with fission counters where there might be severe electrical interference. Tests with a vacuum tester coil show only a slight alteration of the normal noise background curve by the differential preamplifier but a great alteration by a single-ended preamplifier. Additionally, measurements show that if a differential current signal is obtained from the fission counter, the differential preamplifier can improve the signal-to-noise ratio (for electronic noise) nearly a factor of $\sqrt{2}$ over that of a single-ended unit. Tests of five prototypes built by a commercial manufacturer to RDT standards show good uniformity of performance, including gain stability, rise time, and linearity, well within the specified requirements.

Introduction

In-vessel, low-level flux monitors for future Liquid-Metal Fast Breeder Reactors (LMFBR's) will rely on the current-pulse operation of fission counters to suppress the gamma pile-up due to an intense gamma background produced by neutron activation of stainless steel and decay of the fission product inventory. A current-pulse preamplifier with a differential input was developed to increase the reliability of the measurement. When applied to a balanced input cable system, it can substantially reduce false counts caused by electrical interference.

With a differential pulse from the counter, it is also possible to more than offset the added electronic noise generated by the differential input stage. A factor of $\sqrt{2}$ is theoretically attainable if no correlated component of electronic noise is produced by the common impedance existing between the inputs.

Two prototypes were built, bench tested, and field tested in recent subcriticality measurements¹ at the Southwestern Experimental Fast Oxide Reactor (SEFOR). The results obtained with these prototypes enabled preparation of RDT Standard C 15-3T² for purchase of five preamplifiers from Gulf Electronic Systems (GES) of San Diego. These were tested successfully to meet the requirements of the Standard and will be put in service at ORNL, HEDL, and ANL.

Background

Historically, charge-sensitive preamplifiers have been used to obtain signals from nuclear particle detectors. However, when applied to fission counters for neutron detection in the presence of gamma background with dose rates exceeding 10^6 R/hr, their performance is impaired by the large pile-up of

gamma pulses. The pile-up develops from the characteristic long-tailed pulse produced by its pulse formation process, an integration of the current pulse of the counter. The normally excellent signal-to-noise ratio is also lost when a long input cable (9 meters or more) is required to separate the preamplifier from the reactor environment. Further complications arise from the use of long input cables, i.e., reflections are caused by an inability of the charge-sensitive preamplifier to terminate the cable.

The processing of the current pulse of the counter minimizes the pile-up problem, and current-pulse preamplifiers with single-ended inputs have been used successfully in subcriticality experiments³ and for measurements on fission counters operating in very high gamma fields⁴. With fission counters having an electron collection time of 100 nsec or less, the counting efficiency* for neutrons obtained with such preamplifiers is $> 93\%$ at 10^6 R/hr. Unlike the charge-sensitive preamplifier, the current-pulse preamplifier can be placed at any distance from the counter without any decrease in signal-to-noise ratio other than that produced by cable losses and can be made to terminate the input cable.

This current-pulse operation does, however, require large bandwidth amplification (5 MHz or more) to preserve the shape of the pulse. This requirement and the extremely small signal pulse (~ 50 μ V) transmitted by the input cable create a serious shielding problem, particularly when the cable is long. A current-pulse preamplifier with a differential input was designed to give a greater range of applicability as to tolerance level of electrical interference and length of input cable.

Circuit Description and Design Considerations

Figure 1, a simplified circuit diagram of the differential current-pulse preamplifier, shows that two identical input stages (A and A') drive the two input terminals of a μ A733, monolithic, differential wide-band amplifier. The differential output of this μ A733 is converted to a current output by the output stage.

Input Stage

The electronic noise of the μ A733 is too great for it to be used as the input stage for the application here. A current gain of 10 preceding the μ A733 is adequate to effectively eliminate any contribution by it to the noise of the preamplifier.

MASTER

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

* Counting efficiency is the following ratio: the number of counts registered/the number of neutron-induced pulses in the counter.

The input stage, reported previously,⁵ is a modified version of a design by Rush,⁶ as follows: an emitter follower was added after the common-base input transistor to increase the forward loop current gain. The result is nearly a factor of 10 improvement in closed-loop gain stability at only a small increase in preamplifier rise time. Negative feedback to the input emitter causes the input impedance to be low (a few ohms), enabling the input transistor (Q1) to be biased to yield nearly its minimum specified noise figure. To achieve a termination for the input cable, resistance is added to the input circuit of Q1 so that the input resistance of the preamplifier is equal to the characteristic impedance of the input cable.

A commonly used design⁷ for a preamplifier of this type is one where the common-base transistor is removed from the feedback loop and the collector current is adjusted to create the required cable termination. Some reduction of electronic noise is possible with this arrangement, since the noise contributed by the termination resistor is eliminated. Some of this noise improvement is lost, however, because the noise gain for r'_b (the series base resistance of the hybrid π bipolar transistor model) is nearly doubled. Also, the quiescent operating emitter current of the input transistor is generally not the required value for the best noise figure for a high-frequency, bipolar, silicon transistor. Perhaps more important, even discounting the strong dependence of gain and input impedance on temperature of this input scheme, the absence of a physical resistor for a cable termination precludes a possibility of input protection.

In the authors' design, input protection is obtained by using two resistors (21.5 Ω each) for the cable termination and returning their midpoint to ground with diodes. Two diodes in series are required for the negative spikes to allow for the normal negative potential which exists at this point. This protection proved adequate on numerous occasions, and in each case the only failure was damage to the first 21.5 Ω resistor. If the reverse current of these diodes is less than the base current of the input transistor Q1, their contribution to the noise of the input stage will be negligible.

The preamplifier input current signal is amplified approximately by the ratio of $(R_f + R_L)/R_L$ and is delivered out of the collector of Q4. Resistor R_L is the collector load resistor of Q3, and R_f is the feedback resistor between the collector of Q3 and emitter of Q1. For the circuit values given in Fig. 1, the current gain of the input stage of the preamplifier is about 10.

The voltage signal applied to the μ A733 from stage A can be controlled by the impedance in the collector of Q4. At the negative input terminal of the μ A733, a variable capacitor and resistor are used for fine adjustment of the gain and bandwidth of stage A' (Fig. 1). With these two adjustments, it is possible to balance the transfer functions of the two stages to yield greater than 40 dB common-mode rejection from 50 kHz to 20 MHz. This performance at low frequencies does require some selection of the two input coupling capacitors (0.1 μ F, 1000 V). These capacitors set the low frequency cutoff of the input stages, and were selected to give a minimum time constant of 10 μ sec, assuming a signal source impedance equal to the characteristic impedance of the cable. Values less than 10 μ sec will produce undesirable undershoots following the current pulse.

The time constant resulting from the coupling capacitor between the input stage and the μ A733 is controlled by the 1.33-k Ω resistor which returns the collector of Q4 to the -15 V supply. Thus, a capacitor with values as low as 0.1 μ F can easily make this time constant nearly 100 times greater than the collection times of fission counters under consideration here.

The μ A733 Stage

The μ A733 stage is connected to give a differential voltage gain of 10. Terminals are available to increase this gain to as much as 100 at a sacrifice in rise time and possibly temperature stability.

The transient response of the μ A733 stage (for a differential gain of 10) is such that an overshoot ranging from 10 to 40% is generated when the input is driven by a voltage step with a rise time < 3 nsec. This overshoot is sharply increased with as little as 5 pF of capacitance across the output, because the output emitter-follower of the μ A733 drives the feedback resistor of the shunt feedback stage located in the collector of the input differential stage. Thus, any capacitance on the output will peak the shunt feedback stage in the μ A733, enhancing the overshoot. To reduce the overshoot of the preamplifier to a tolerable level of less than 10%, some slowing of the input pulse to the μ A733 stage is required, which is achieved by adding capacitance (C_A and $C_{A'}$, Fig. 1) to the output collectors of the input stages. As a consequence, the rise time of the preamplifier output pulse is 5 to 6 nsec and is limited by the performance of the μ A733. For fission counters presently intended for LMFBR application, this rise time is more than adequate. The advantages offered by the μ A733 in size, cost, reliability, and common-mode rejection capability justify its use in this application.

Output Stage

The output stage incorporates a differential pair of bipolar transistors, with the collector current from one transistor feeding a two-transistor shunt feedback stage, Q7 and Q8. The output current from this shunt feedback pair is coupled through Q9, a common-base stage connected to the emitter of Q8. The design of the combination of Q7, Q8, and Q9 is similar to the design of the input stage previously described, except that in this output stage the common-base transistor was eliminated from the forward loop. The expression for the current gain (collector current from Q5 to collector current from Q9) is modified and is $\sim (R_f + R_L)/(R_L + 2r_e)$. Resistor R_f is the 1-k Ω resistor between the collector of Q8 and the base of Q7, and R_L is the series combination of the 196- Ω resistor in the collector of Q8 and the incremental impedance of the three diodes D4, D5, and D6, shunted by the 267- Ω resistor connected to the -15 V supply. The term $2r_e$ is the combined emitter resistance of Q8 and Q9. These three diodes are biased to compensate for changes in r_e to reduce the nonlinearity of the output stage.⁸ The compensation effect proceeds as follows: as the output current increases with signal (reducing r_e), the current through the diodes is reduced, resulting in a higher diode incremental impedance which offsets the effect of the reduced value of r_e . It is not difficult to obtain a nonlinearity of < 0.25% for output currents of 10 mA. The three diodes also increase the dc stability of the output stage by partially compensating for the effects of V_{be} changes in Q7, Q8, and Q9.

The preamplifier was designed so that one can use jumpers to connect the filter for the fission counter bias voltage to either the positive or negative input through points designated by A and A' in Fig. 1. With either connection, the opposite terminal is returned to ground by using another jumper to complete the dc connection to the counter. In the authors' design (not shown), this ground connection comprises back-to-back diodes, permitting connection to virtual-ground electrometers for a dc measurement.

A photograph of one of the units constructed by GES (Fig. 2) shows the double-walled construction and compartmentalization of the various stages with feed-through filters for power line isolation.

Performance

The five units constructed by GES conformed to RDT Standard C 15-3T.² A summary of the test results is given in Table 1. Most of the tests are self-explanatory. A few may require further elaboration. The pulse rate effect is determined by examining the preamplifier output pulse for distortion when driven by a 10 MHz rectangular pulse with a 50 nsec width. The induced noise level test is made by examining the preamplifier noise through a 100 nsec RC-CR filter when a 100 mA current pulse is injected into the outside case of the preamplifier. The input protection test is made by

TABLE 1

SUMMARY OF TEST RESULTS OF FIVE GES PREAMPLIFIERS

Parameter	Input	Test	Data*
Gain (A/A)	+	250, 272	
	-	250, 270	
Rise Time (nsec)	+	5.6, 6.4	
	-	5.4, 6.0	
Output Saturation Level (V)	+	1.0 (typical)	
	-	1.0 (typical)	
Undershoot (%)	+	0.8, 0.9	
	-	0.8, 0.9	
Pulse Rate Effect (Normal)	+	yes	
	-	yes	
Integral Nonlinearity (%)	+	0.38, 0.89	
	-	0.38, 0.88	
Gain Stability (%/°C)	+	-0.024, -0.045	
	-	-0.027, -0.039	
Noise (pA/√Hz)		25.0, 27.1	
Induced Noise (Normal)		yes	
Reflection at Input (%)	+	7.0, 7.5	
	-	6.0, 7.5	
Input Protection (Normal)	+	yes	
	-	yes	
Common Mode Rejection	0.05 MHz	40.3 dB (typical)	
	0.10	43.1	
	0.20	44.7	
	0.50	46.3	
	1.00	46.6	
	2.00	46.6	
	5.00	47.3	
	10.00	45.3	
	20.00	44.7	

* The first of two values given is the minimum, the second is the maximum.

discharging a 0.01 μ F capacitor (charged to 1000 V) through the input of the preamplifier. The undershoot is measured for a rectangular test pulse with a width of 100 nsec and referred to the full rated output of 0.5 V (across a load resistance of 50 Ω). The noise test is made with a 50 Ω resistor connected across each input.

Noise Rejection Tests

The tests described in this section and in the following section, "Integral Bias Tests," were made with differential preamplifiers constructed by ORNL. Since these units are very similar to the GES preamplifiers, the results should also apply to those instruments except as discussed by the authors.

The noise rejection capability of the differential preamplifier was measured with a vacuum tester coil used as a wide-band source of radiative, electrical interference.² The differential preamplifier (with a balanced input cable) and a single-ended preamplifier were exposed simultaneously to the electrical radiation of the tester coil, and the noise pulses were counted as a function of pulse height. This simultaneous operation eliminated effects of variations of the noise generator, but it required a duplicate set of electronic instruments, i.e., amplifier, discriminator, and scaler to obtain the data. The single-ended preamplifier was a differential unit with one of the input stages deactivated.

Each preamplifier was connected to a small metal box that simulated a two-electrode fission counter and contained three capacitors to represent the interelectrode capacitance (Fig. 3). One of the two cables connected to the single-ended preamplifier was inactive, ending in a 50 Ω termination at the preamplifier. All four input cables (RG 58/U) were enclosed in a tinned copper common braid to complete the shielding and to ensure a more uniform noise field for the test. Data were recorded with two arrangements of the input cable bundle, a coil and a "hairpin," which were chosen arbitrarily and do not represent any specific application. There was no significant difference in the test results from the two configurations.

With the noise generator positioned to produce output pulses from the preamplifiers at near saturation level, the data shown in Fig. 4 were obtained. It shows that the electrical interference negligibly increased the electronic noise background of the differential preamplifier, but the background for the single-ended preamplifier was $\sim 10^4$ counts/sec at a pulse height level of 10 units and above. (A normal operating pulse height level with typical fission counters and gamma levels of 10^6 to 10^7 R/hr will range between 15 to 30 units.)

Additional measurements indicated that the limiting common-mode signal is near 5 mV. The preamplifier built by GES is expected to be superior to this by nearly a factor of 4 because of better regulated ± 5.6 V supplies for the two input stages.

Integral Bias Tests

The improvement in signal-to-noise ratio (Fig. 5) due to differential operation was determined from integral bias curves obtained with both differential and single-ended operation of a fission counter. Figure 5 shows that the "electronic plus alpha" noise curve intercepts the 10-count/sec coordinate at

9.3 pulse height units for the differential operation and 13.0 units for the single-ended operation. The pulse height units were normalized to account for the difference in gain of the two preamplifiers. The fission counter was an ORNL PCP-11-102 model with a parallel-plate assembly and an electron collection time of ~ 80 nsec.⁴ One set of plates was grounded to obtain the data for the single-ended operation. The main amplifier contained an RC-CR filter with a time constant of 27 nsec.

In an LMFBR application, there will be a large "noise" background due to gamma radiation. It can be shown, however, that the improvement in electronic noise obtained by use of the differential preamplifier is a significant factor, even at high gamma dose rates. Figure 6 shows data obtained with an experimental high temperature fission counter and a differential preamplifier at two gamma dose rates. Predicted curves for the single-ended case were obtained by determining a "net" gamma response from the experimentally obtained differential data, at selected values of count rates, with the relationship $\gamma_{\text{net}} = \gamma_{\text{obs}} - (\text{Differential Noise})^{1/2}$. This value of "net" gamma and the noise of the single-ended preamplifier were combined to generate the "noise" data for the single-ended case. At 5.8×10^7 R/hr flux, an $\sim 4.5\%$ improvement in counting efficiency was obtained with the differential operation. (The 10 counts/sec intercept of the gamma curve was projected to the neutron curve to determine the efficiency.) At the lower gamma flux level, the improvement was considerably less because of the flat characteristic of the neutron integral bias curve.

Discussion and Conclusions

Differential operation of the fission counter shows significant rejection of electrical interference and an enhanced signal-to-noise ratio for electronic noise. To achieve this rejection, the two input cables must be arranged carefully to assure that both are subjected to the same interferences. Two conductors, intertwined and within the same sheath would be the ideal configuration, but such a cable which would be suitable for the LMFBR environment is not available. The performance of two separate coaxial cables, possibly interwoven, would most likely be less than that indicated in Fig. 4. The limiting value of 5 mV for the common-mode signal level implies a need for a well-shielded input cable, although the shielding need would be considerably less than that required for a single-ended input.

The magnitude of improvement in signal-to-noise ratio is $\sim \sqrt{2}$. This was obtained from Fig. 5 by the ratio of intercepts of the two noise curves at the 10.0 count/sec level, i.e., 13.0 and 9.3 pulse height units, respectively, for the single-ended and differential operation. If one assumes no correlated component of electronic noise by the common impedance between the inputs of the differential preamplifier, the $\sqrt{2}$ improvement is possible because an increase in noise by a factor of $\sqrt{2}$ is offset by a factor of 2 increase in signal by the differential operation of the counter.

The enhanced signal-to-noise ratio for the electronic noise yields a higher counting efficiency in the presence of gamma radiation. The improvement of 4.5% at 5.8×10^7 R/hr gamma dose rate for the counter used in these tests would have been greater with a counter having a poorer neutron response. Such may become a reality as the counter deteriorates with time or as more rugged counters are designed for extreme

environments.

Instrument manufacturers have been assisted to supply a differential preamplifier suitable for use in source range monitors in LMFBR's. The preamplifier is designed so that by deactivating the appropriate input stage it can be used also as a single-ended unit with either positive or negative input signals.

References

1. A. R. Buhl, N. J. Ackermann, Jr., R. C. Kryter, and J. C. Robinson, Subcriticality Monitoring System Evaluation in SEFOR, U. S. Atomic Energy Commission Report ORNL-TM-3716 (February 1973).
2. U. S. Atomic Energy Commission RDT Standard C 15-3T, "Current Pulse Preamplifiers for Use With Fission Counters (with Amendment 1)," (June, 1973).
3. R. C. Kryter, N. J. Ackermann, Jr., and A. R. Buhl, Subcriticality Measurements in FTR-3; Homogeneous Mockup of the Fast Test Reactor, U. S. Atomic Energy Commission Report ORNL-TM-3715 (February 1972).
4. D. P. Roux et al., "A Neutron Detection System for Operation in Very High Gamma Fields," Nucl. Appl. Technol. 9 (5), 736-43 (November 10, 1970).
5. J. T. De Lorenzo, "Low Noise, Wide-Band, Current-Pulse Preamplifiers for Neutron Counters," IEEE Trans. Nucl. Sci. 18 (2), 114-16 (April 1971).
6. C. J. Rush, "New Technique for Designing Fast Rise Transistor Pulse Amplifiers," Rev. Sci. Instr. 35 (2), 149-56 (February 1964).
7. A. Goodings, D. Hogger, and R. D. Phillips, "Reactor Control Neutron Detectors for Operation at High Temperatures," Nucl. Instrum. Conf. Publ. No. 47, Sept. 23-25, 1968.
8. Private communication from J. K. Millard, formerly at ORNL and now with Hewlett-Packard, Colorado Springs.
9. J. T. DeLorenzo, W. T. Clay, and G. C. Guerrant, Common-Mode and Integral Bias Tests with a Differential Current-Pulse Preamplifier, U. S. Atomic Energy Commission Report ORNL-TM-4316 (August 1973).

Captions

- Fig. 1 Simplified Circuit Schematic of the Differential Current Pulse Preamplifier.
- Fig. 2 Photograph of Differential Preamplifier.
- Fig. 3 Noise Rejection Test Input Cable and Preamplifier System.
- Fig. 4 Integral Bias Curve of Noise Generated by Vacuum Tester Coil.
- Fig. 5 Integral Bias Curve for Differential and Single-Ended Operation of Fission Counter.
- Fig. 6 Integral Bias Curve of Gamma Background for Differential and Single-Ended Operation of a Fission Counter.

OAK RIDGE NATIONAL LABORATORY