REDUCING ELECTRICAL NOISE IN

INSTRUMENT CIRCUITS

Bruce E. Klipec, Member, IEEE

Reducing Electrical Noise in Instrument Circuits

BRUCE E. KLIPEC, MEMBER, IEEE

Abstract— **The use of computers and other sensitive electronic equipment in process instrumentation systems has demanded that more attention be given to electrical noise pickup in instrument circuits. This paper presents the results of tests conducted on ways of reducing the four types of noise encountered in electronic instrument circuits.**

The superior performance of aluminum-Mylar tape shields in comparison with copper braid and copper served wire shields for static noise rejection is described.

The effect of twisting wires to cancel magnetic noise is compared to various shielding materials. Twisting the wires is shown to be the most effective practical way of reducing magnetic noise.

The control of common mode noise by proper grounding of shields in thermocouple circuits is shown. The use of single grounding points in shield circuits grounded at the couple is recommended. Multipair cables with individual isolated pair shields are recommended.

Comparative results on crosstalk elimination in multipair cables are presented. Individually shielded pairs are recommended as the most practical means of crosstalk rejection in instrument circuits.

INTRODUCTION

WITH THE TREND toward more complete instrumentation in process plants using more sophisticated and more sensitive instruments than in the past, the reduction of electrical noise pickup by instrument circuits has become a real problem for the instrument engineer.

In the past, there has been a feeling that the noise would average out and the true reading could be obtained. However, as new instruments appear with lower voltage levels than before and in striving to get increased resolution out of existing instrument circuits, noise presents problems. Averaging a signal to obtain the true reading becomes impossible when one tries to resolve voltage differences which are several orders of magnitude lower than the level of noise on the signal. When noise is present on the signal, recording equipment which uses amplifiers to condition the input signal will show loss of sensitivity and dead-banding. This is because the noise obscures small changes in signal level. As the noise level increases, saturation of the amplifier occurs, shifting the operating point of the amplifier into a nonlinear region. When this happens, any averaging that takes place is incorrect.

Process computers are in use, which sample inputs for very brief periods of time, ranging from about five points

per second to a thousand points or more per second. These computers do not look at an individual data point long enough to average data. Any appreciable noise which is on the signal will cause errors in the reading the computer obtains.

Electrical noise in instrument circuits is a very real problem. In order to reduce noise, it is necessary to classify it into several types according to how it is caused and when to combat each type by the most effective means available.

The purpose of this paper is to discuss four types of noise which bother process instrumentation. These types are I) static, 2) magnetic, 3) common mode, and 4) crosstalk. Each type of noise will be discussed from the standpoint of how it induces noise into process instrument circuits and how each type is reduced by several methods. Comparative results from tests conducted on different means of reducing each type of noise will be presented.

STATIC NOISE

The first principal type of noise affecting process instrument circuits is known as static noise. Electric fields radiated by power lines and other voltage sources around a process plant are capacitively coupled to the wires in an instrument circuit as shown in Fig. 1. The coupling to the external voltage sources results in an alternating noise signal being superimposed on any signal that is transmitted on the wires in the instrument circuit. The most effective way of combating static noise is to break the coupling between the external voltage sources and the instrument circuit by means of a static shield which is grounded as shown in Fig. 2. When a shield is placed around the pair of wires, the external voltage sources couple to the shield rather than to the pair within the shield.

There are many different forms of static shielding available. No matter what kind of shield is used, there is still some leakage capacitance for residual coupling between the voltage sources and the instrument pair. This is shown as C_1 in Fig. 3. The amount of leakage capacitance relates to the effectiveness of the shielding material. In order to evaluate the effectiveness of different types of shielding materials, it is necessary to evaluate how much leakage remains. The leakage capacitance is so small with any type of shield that it is almost impossible to measure it directly with any accuracy. In order to measure the leakage with different types of shielding materials indirectly, the following method was used.
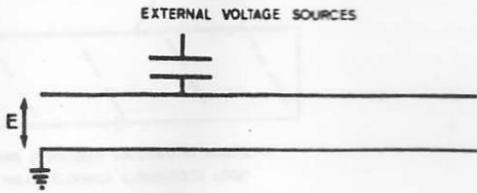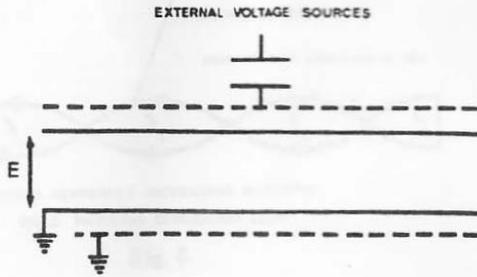
EXTERNAL VOLTAGE SOURCES
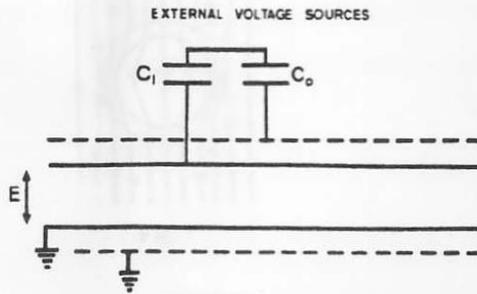
Fig. 1.

EXTERNAL VOLTAGE SOURCES

Fig. 2.

EXTERNAL VOLTAGE SOURCES

C_i C_o

Fig. 3.

1000 Hz
20 v pp

MANDREL

R

R = 600 OHMS
E_U = NOISE PICKUP WITH SHIELD UNGROUNDED
E_G = NOISE PICKUP WITH SHIELD GROUNDED

$\dfrac{E_U}{E_G}$ = NOISE REJECTION RATIO

SHIELD EFFICIENCY (db) = 20 $\log_{10} \dfrac{E_U}{E_G}$
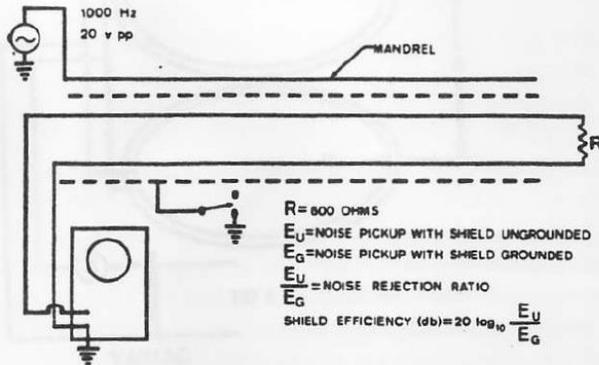
Fig. 4.

TABLE I
STATIC NOISE TEST RESULTS

Sample	Noise Reduction Ratio	Shield Efficiency
Braid shield	103:1	40.3 dB
Served shield	376:1	51.5 dB
Aluminum-Mylar tape and drain wire	6610:1	76.4 dB

Fifty-foot samples of shielded pairs made up of the shielding materials to be evaluated were wrapped over a 4-inch diameter aluminum mandrel. One end of the pair was connected to a 600-ohm resistor, the other end to an oscilloscope. The circuit diagram is shown in Fig. 4.- The mandrel was driven with a noise voltage of 20 volts peak to peak at a frequency of 1000 hertz. The noise pickup with the shield ungrounded and again with the shield grounded was recorded. The ratio between the ungrounded pickup and grounded noise pickup represents the noise rejection ratio for the shielding material and is a measure of the shielding effectiveness. The higher the ratio, the better the shielding material. The shields tested are listed in Table I along with their respective noise reduction ratios and shield efficiency ratings. The shield efficiency is the ratio between the ungrounded and grounded noise voltage pickup in decibels. This method for expressing shield effectiveness was chosen after trials of several other test methods for its repeatability and independence of other variables. For example, merely expressing grounded voltage pickup in terms of volts for each type of shield does not make the results independent of conductor size, insulation thickness, jacket thickness, and tightness of wrap on the mandrel.

One notes immediately the relation between shield coverage and shielding effectiveness with the total coverage aluminum-Mylar tape shield showing between one and two orders of magnitude better shielding ability than the 85 percent coverage braid and the 90 percent coverage served shields.

A detailed description of the wire constructions evaluated for static shielding efficiency will be found in the Appendix.

MAGNETIC NOISE

Process plants are loaded with stray magnetic fields. Any time current goes through a conductor, a magnetic field is produced radially around it. As a result, all power lines, motors, generators, relays, etc., radiate magnetic fields of erratic and varying strengths.

Any time a loop of conductors, as shown in Fig. 5, such as the pair of wires connecting a transducer out in the plant with receiving equipment in the control room, is subjected to a magnetic field, current is produced in the loop to oppose the magnetic field. This noise current flowing through the resistances in the instrument loop produces a noise voltage which is, in turn, superimposed on the voltage being transmitted by the pair of wires.

Two methods have been used to fight magnetic noise. The first is to simply twist the pair of wires as shown in Fig. 6, By twisting the wires, instead of having one loop, a series of adjacent loops in the instrument circuit is formed. Any magnetic field which goes through the instrument pair will tend to be cancelled out by the adjacent loops, as the currents induced by magnetic fields into adjacent loops in each wire are in opposite directions. The second method
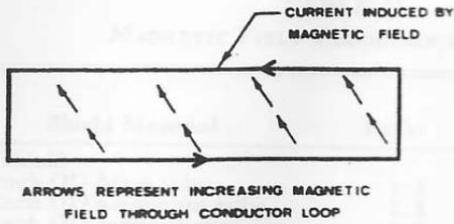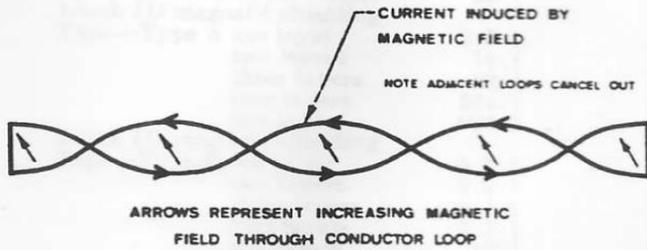
CURRENT INDUCED BY
MAGNETIC FIELD

ARROWS REPRESENT INCREASING MAGNETIC
FIELD THROUGH CONDUCTOR LOOP

Fig. 5.

CURRENT INDUCED BY
MAGNETIC FIELD

NOTE ADJACENT LOOPS CANCEL OUT

ARROWS REPRESENT INCREASING MAGNETIC
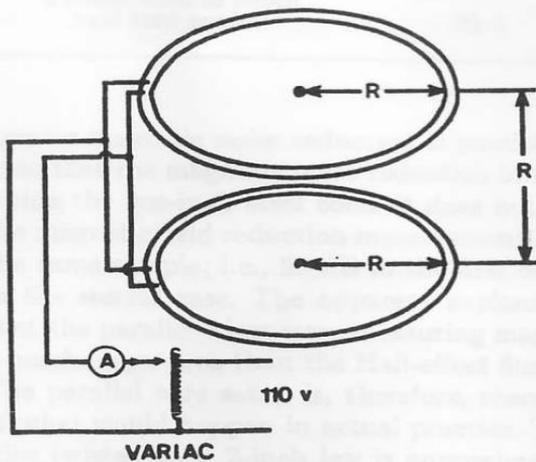FIELD THROUGH CONDUCTOR LOOP

Fig. 6.

Fig. 7.

110 v

VARIAC

Fig. 8.

which has been employed is to surround the instrument circuit with a material which either absorbs or diverts the magnetic field from the pair of wires as shown in Fig. 7. From time to time, it has also been postulated that merely placing a conducting material around an instrument pair would tend to cancel any magnetic fields through the production of eddy currents within the shield material. The following two tests were devised in order to evaluate, first of all, the amount of shielding afforded by different types of metallic materials

and, second, the amount of cancellation of magnetic noise pickup provided by twisting the pairs of wires.

In order to generate a magnetic noise field, the apparatus diagrammed in Fig. 8 was used. Two RCA degaussing coils were mounted in the classical Helmholtz coil arrangement. The coils were connected to produce magnetic fields in phase with one another. With this arrangement, a roughly cylindrical volume midway between the two coils contains a fairly uniform magnetic flux density. Through all the tests, the total coil current was maintained at 3 amperes. For the first series of tests, the results of which are shown in Table II, various magnetic shielding materials were placed midway between the two coils in a plane parallel to them. Magnetic flux density measurements were taken with a Hall-effect gaussmeter, at a point exactly dead center within the shielding materials and halfway between the two coils on the line connecting their centers. Table II gives the magnetic flux reduction ratio and shield effectiveness for each of the materials evaluated.

No reduction in magnetic field was observed with the brass, aluminum, or copper tubes. Conduit was shown to be by far the most effective shielding of the common materials evaluated. The two magnetic shielding tapes that were tested are designed for use in electronic circuits as component shields. These two tapes were merely evaluated for comparison purposes, as their high cost precludes using them as a magnetic shield for wire and cable, even with only one layer. The tape listed as Type A is a high-permeability tape which is designed for use in areas of relatively low magnetic field intensity. Type B, on the other hand, is designed for use in high field intensities which were not encountered in this test. The field measurement with no shield present was approximately 75 gauss.

The second series of tests that was run with the magnetic test setup was to compare twisted wires of various lays with a parallel pair using the same wires. The results are summarized in Table III.

It is important to point out that for any of the twisted wires, it was possible to completely null out the magnetic field; in other words, slide the pair back and forth to adjust the cancellation in the loop so that no magnetic noise was picked up. The figures presented in Table III represent the magnetic noise which appeared with the wires oriented for maximum magnetic pickup rather than minimum. By doing this, the figures shown in the table represent the minimum amount of magnetic noise reduction provided by twisting. It is also important to point out that the magnetic field generated by the Helmholtz coil arrangement is not a uniform field over the length of the wire tested but rather reaches a maximum over a comparatively short distance. This means that the effectiveness of twisting is demonstrated by the noise reduction attained even when the instrument circuit crosses over power lines as opposed to being laid parallel to them. Where long runs of parallel conductors are used and the field is uniform over a longer distance, greater magnetic noise reduction is possible. One will also note that the magnetic noise reduction in the parallel wire inside the one-inch steel conduit does not match

TABLE II
Magnetic Field Reduction by Shields

Shield Material	Ratio	Field Reduction
No shield	...	0 dB
½-inch OD brass tube	1:1	0 dB
½-inch OD aluminum tube	1:1	0 dB
½-inch OD copper tube	1:1	0 dB
1-inch rigid steel conduit	138:1	42.8 dB
1-inch ID BX armor—steel	28:1	28.8 dB
¾-inch ID BX armor—steel	22:1	27.0 dB
1-inch ID magnetic shielding Tape—Type A one layer	3.5:1	10.8 dB
two layers	14:1	22.7 dB
three layers	92:1	39.3 dB
four layers	324:1	50.2 dB
five layers	966:1	59.7 dB
1-inch ID magnetic shielding Tape—Type B one layer	5.3:1	14.5 dB
two layers	8.2:1	18.3 dB
three layers	9.1:1	19.2 dB
four layers	9.2:1	19.3 dB
five layers	12:1	21.6 dB

TABLE III
Magnetic Noise Reduction in Wire by Twisting vs. Shield

Test	Ratio	Magnetic Noise Reduction
Parallel wires	...	0 dB
Twisted wires, 4-inch lay	14:1	23 dB
Twisted wires, 3-inch lay	71:1	37 dB
Twisted wires, 2-inch lay	112:1	41 dB
Twisted wires, 1-inch lay	141:1	43 dB
Parallel wires in 1-inch rigid steel conduit	22:1	27 dB

up with the magnetic field reduction measurement in Table II with the same sample; i.e., 27 dB in the first case and 42.8 dB in the second case. The apparent explanation for this is that the parallel wires were measuring magnetic field over a much larger area than the Hall-effect flux density meter. The parallel wire setup is, therefore, more representative of what would happen in actual practice. This shows that wire twisted to a 2-inch lay is approximately five to six times more effective than 1-inch rigid steel conduit in reducing magnetic noise pickup in wire and cable.

When looking at the data presented in Table III, it is easy to see that the shorter the lay the better the magnetic noise rejection. There is a tendency at that point to decide to use as short a lay as possible in wire. From a practical standpoint, however, the shorter the lay the slower the wire is produced and the higher the cost goes. In re-examining Table III, note that the noise rejection gained in going from 2- to 1-inch lay is a lot less than from 4 to 3 or 3 to 2 inches. Two inches is a plateau, so to speak. It is also the point where costs start to climb out of

proportion if a shorter lay is desired. Two-inch lay is about the optimum length of lay from both a cost and noise rejection standpoint.

COMMON MODE NOISE

Until now, we have been discussing noises which are induced in an instrument circuit independent of the connections made to it. Common mode noise is different in that it results from electrical connections which must be made to the instrument circuit. Common mode noise is produced because of the fact that different points throughout a process plant will be at a different ground potential. This is due to power currents flowing in ground circuits which, due to the resistances between various points in the plant, produce voltage drops in the grounds and, hence, different ground potentials throughout a plant. Typical ground potential differences in a process plant run anywhere from 1 to 10 volts.

Common mode noise is particularly troublesome with thermocouple circuits. Most thermocouples in use today are the grounded type where the tip of the junction makes contact with a protective sheath or well which is, in turn, electrically grounded to the vessel in which it is mounted. If a ground exists back in the recording instrument, as shown in Fig. 9, a circulating current is set up between the ground at the couple, which is at a different potential than the ground at the recording instrument, and the recording instrument. The ground symbol in the diagram represents the ground at the recording instrument and the voltage generator represents the fact that the ground at the couple is at a different potential from the ground at the recording instrument.

In order to combat this first type of common mode noise, recorder and computer manufacturers have gone to differential input devices in which neither input terminal is grounded and, in fact, a very high impedance exists between input terminal and ground. This is shown schematically in Fig. 10. With high impedances between each input terminal and ground, no common mode currents flow due to the ground in the recorder and no common mode voltage interference shows up on the thermocouple signal from this source. This type of protection against common mode noise is covered by the specification which most recorder and amplifier manufacturers place on their instruments as 100 or 120 dB common mode rejection.

Even with the best recorder made, however, one can still have common mode noise problems regardless of how good the common mode rejection circuits are, because of another way that common mode noise can get into the thermocouple circuit. Figure 11 shows the capacitance which exists between each of the conductors within a thermocouple extension wire and any metal object which may be near it, whether it is a shield, cable tray, power line, or whatever. The fact that all the metal objects around this pair are at a different potential than the couple tip causes common mode currents to flow into the conductors, producing a voltage drop along the conductors. The difference in resistance between each conductor in the pair causes a different voltage drop in each conductor. This common mode
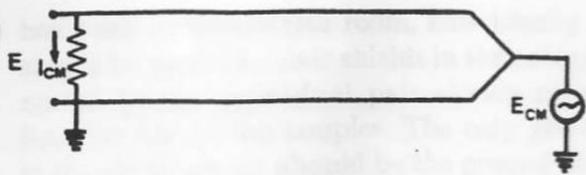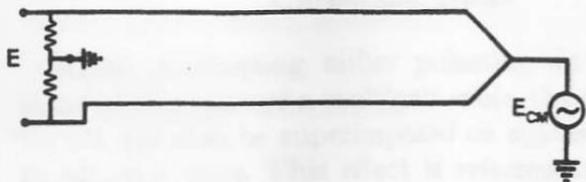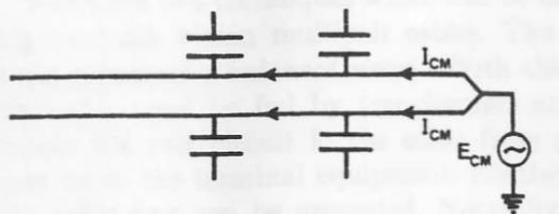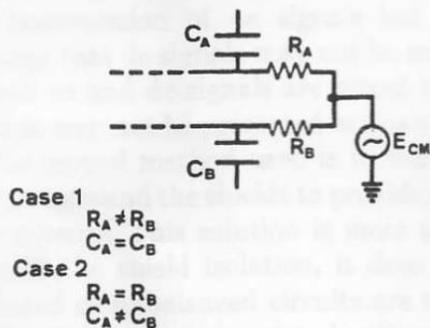
Fig. 9.

Fig. 10.

Fig. 11.

Case 1
$R_A \neq R_B$
$C_A = C_B$

Case 2
$R_A = R_B$
$C_A \neq C_B$

Fig. 12.

Fig. 13.

Fig. 14.

TABLE IV

COMMON MODE NOISE PICKUP

| | Shield | |
Sample	Grounded at Couple	Grounded at Control Room
Iron-Constantan	3 μV	230 μV
Chromel-Alumel	2 μV	110 μV
Copper-Constantan	2 μV	290 μV

drop adds in to the couple signal to produce common mode noise. One approach which has been proposed in the past is shown schematically in Fig. 12. With thermocouple extension wire, if the gauges are the same, the resistance of the two alloys in the extension wire does not match. Therefore, if equal charging currents flow in each conductor, unequal voltage drops produce a net voltage difference which becomes a common mode voltage. This is referred to as Case 1 on Fig. 12. The approach was to use different gauge sizes of wire so as to match the resistance of the two materials used in the extension wire. The thought was that equal charging currents would produce equal voltage drops which would balance each other out and add to zero noise produced on the couple signal. The problem is, however, that as soon as the gauge size of the wire is changed, the capacitance from the wire to its shield or
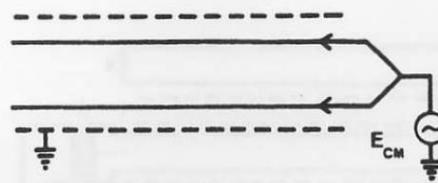
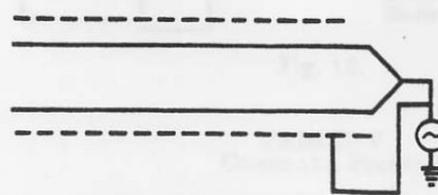conduit, tray, etc., changes and equal charging currents are not produced. This is shown as Case 2 of Fig. 12, The net result is that common mode noise is still produced. Figure 13 shows what happens when a static shield is placed over a pair of wires from a couple all the way back to the control room. In this case, the shield is grounded back at the control room, which means charging currents must flow in the extension wire conductors to charge the capacitance between the wires and the shield. This results in common mode noise.

Figure 14 shows the easiest way to overcome this problem. This is to install a pair which has a shield from the couple all the way back to the control room, but ground the shield at the couple instead of at the control room. By this hook-up method, the shield is maintained at the same ground potential as the couple; therefore, no charging currents will flow and no common mode noise is produced. Table IV shows the results of tests conducted with iron- constantan, chromel-alumel and copper-constantan extension wire where the shield was grounded at a couple as in Fig. 14, and where the shield was grounded at the control room as in Fig. 13. The sample length was 150 feet in each case. Ground potential difference between the couple and control room end was 3 Vpp at a frequency of 100 Hz.

The reduction in noise pickup with the shield grounded at the couple is very apparent. The reason that the common mode interference is different in each of the three alloys when the shield is grounded at the control room is because of the difference in the resistance in each of the alloy combinations.

In order to provide optimum common mode rejection when multipair cables are used from a junction box back to the control room, individually shielded pairs should be used.

The pair shields in the cable should be connected to the individual pair shields running from the junction box to the couples. The only ground connection in the shield circuit should be the ground at the couple.

CROSSTALK NOISE

When transmitting either pulsating dc signals or ac signals on one pair of a multipair cable, there is a tendency for the signal to be superimposed on signals being carried in adjacent pairs. This effect is referred to as crosstalk. This type of noise will show up in turbine flowmeter signals as well as others in a process plant.

There are two techniques which can be used in combating crosstalk within multipair cables. The first is to use what is termed a *balanced circuit.* With this, each pair of the cable must be fed by transformers at both ends to isolate the pair circuit in the cable from grounds which may be in the terminal equipment. Neither conductor in the cable pair can be grounded. Normally speaking, the center taps of the transformers at both ends of the pair circuit are grounded. The balancing system will work for the transmission of ac signals but has the big disadvantage that dc signals may not be sent on the pairs. Also, if both ac and dc signals are mixed within a cable, the dc circuits may not be protected in this way.

The second method used is to individually shield each pair and ground the shields to provide isolation between the pair circuits. This solution is more universally workable, as with the shield isolation, it does not matter whether balanced or unbalanced circuits are used and either ac or dc signals may be transmitted without any problem. With regard to process instrumentation, in most cases, the circuits must remain unbalanced; therefore, the latter solution is more desirable.

One myth which has grown up is that a nonshielded pair cable which has staggered lay on the individual pairs can be used for crosstalk isolation. Unfortunately, this is true only if balanced termination is used. The following test will demonstrate that even when a staggered lay cable is used, unbalanced termination produces crosstalk.

Figure 15 shows the circuit used to evaluate crosstalk pickup for both the unshielded pair cable and the shielded pair cable. Sample lengths of both cables were 100 feet. The test frequency was 1000 Hz and 20 Vpp was applied to the driven pair. Unused pairs in the cable were not terminated. The numbered terminals in the diagram were connected to ground during the different tests conducted on the cables in order to produce balanced and unbalanced circuits as well as grounding individual pair shields.

Table V summarizes the results of the testing. In the test of the unshielded pair cable, pairs having a 1½ and 2½-inch lay were selected for the crosstalk measurement. It is interesting to note that the unbalanced circuit isolation with the unshielded pair cable is the same as the unbalanced isolation
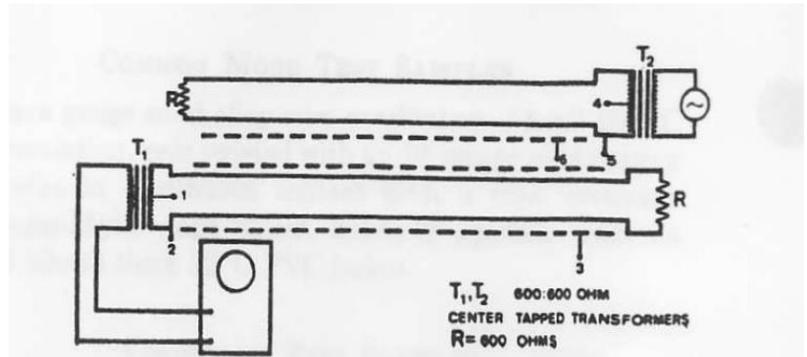

Fig. 15.

TABLE V
CROSSTALK PICKUP

Test	Voltage Pickup on Receiving Pair	Circuit Isolation
Nonshielded Pair Cable		
Unbalanced termination	100 mV	46 dB
Balanced termination	50 μV	112 dB
Shielded Pair Cable		
Unbalanced termination— no shields grounded	100 mV	46 dB
Balanced termination— no shields grounded	10 μV	126 dB
Unbalanced termination— driving pair shield grounded receiving pair shield	80 μV	108 dB
Grounded	40 μV	114 dB
Both pair shields grounded	10 μV	126 dB

with the shielded pair cable with the shields not grounded. In the shielded pair cable, the lay of the individual pairs was constant at $1^1/$, inches. One can, therefore, conclude that when unbalanced terminations are used, as with most process instrument circuits, the staggered lay does not help crosstalk isolation, In the case of the individually shielded pair cable, grounding both pair shields gave the circuit isolation required.

CONCLUSION

In the way of summarizing the main points proved by the four sets of noise tests presented in the paper, it is important to stress that all four types of noise must be considered when designing an instrument circuit and selecting the wire and cable to be used for hooking it up, Also, one must remember that where the shield is connected is just as important as whether one is used or not.

As far as static noise is concerned, the test described in the paper shows that the total coverage aluminum-Mylar shield with drain wire is one to two orders of magnitude more efficient as a static shield than braid or served shields.

The magnetic tests demonstrate that a twisted pair is a more

effective means of reducing magnetic noise than installing wire in conduit for use as a magnetic shield. Furthermore, nonferrous shields have no effect on reducing magnetic noise.

Besides buying recording equipment which has mode rejection built into it, one should provide an isolated shield over thermocouple extension wire used in a process plant to reduce common noise pickup. This shield should be grounded at the thermocouple head when a grounded couple is used. When multipair cable is used between a control room and a field junction box, an individually shielded pair cable should be used to reduce common mode noise pickup.

To minimize crosstalk pickup in unbalanced instrument circuits used in process plants, an individually shielded pair cable should be used.

APPENDIX
STATIC NOISE TEST SAMPLE DESCRIPTION

Sample 1: Twisted pair of 16 gauge stranded copper conductors, 20-mil PVC insulation, 34 gauge 85 percent tinned copper braid shield, 30-mil PVC overall.

Sample 2: Twisted pair of 16 gauge stranded copper conductors, 23-mil PVC insulation, 34 gauge tinned copper, spiral wrapped shield, 30-mil PVC jacket overall.

Sample 3: Twisted pair of 16 gauge stranded copper conductors, 15-mil PVC insulation, twisted with an 18 gauge stranded drain wire in continuous contact with a total coverage aluminum-Mylar tape shield, helically applied, with an overall 20-mil PVC jacket.

COMMON MODE TEST SAMPLES

Sixteen gauge solid alloy wire conductors, 15-mil 105°C PVC insulation, pair twisted with an 18 gauge solid copper drain wire in continuous contact with a total coverage aluminum-Mylar tape shield, helically applied, with an overall 20-mil thick 80°C PVC jacket.

CROSSTALK TEST SAMPLES

Nonshielded pair cable: Four pairs of 20 gauge 7-strand copper conductors with 15-mil 90°C PVC insulation on singles, twisted to 1½ to 2 ½-inch staggered lay; pairs cabled, cable shielded with 100-percent coverage 2.35-mil aluminum-Mylar tape shield with 20 gauge 7-strand copper drain wire, 45-mil black 80°C PVC jacket overall.

Shielded pair cable: Four pairs 20 gauge 7-strand copper conductors w'ith 15-mil 90°C PVC insulation on singles, twisted to 1½ inch lay, pairs shielded with 100-percent coverage 0.35-mil aluminum X 0.50-mil Mylar tape and 22 gauge 7-strand copper drain wire, separate overwrap of 1.5-mil Mylar tape; pairs cabled; cable shielded with 100 percent coverage 2.35-mil aluminum-Mylar tape shield and 20 gauge 7-strand copper drain wire, 45-mil black 80°C PVC jacket overall.

Bruce E. Klipec (M'65) was born in Bedford, Ohio, on October 29,1940. He received the B.E.E. degree from Cornell University, Ithaca, N. Y., in 1963.

After graduation, he joined Samuel Moore and Company, Mantua, Ohio, as an electrical sales engineer. In 1964, he became a market development engineer.

He has specialized in thermocouple extension wire and instrumentation wire and cable design, His summers, while in school, were spent working on electrical noise studies in the Research and Development Department of Samuel Moore and Company. He is presently working in the Production Engineering Department as Dekoron Product Engineer.

Mr. Klipec is a member *of* Eta Kappa Nu, Pi Delta Epsilon, Pi Eta Sigma, and the Instrument Society of America,