**Feasibility Study to Assess the
Use of the Four Quadrant
Eddy Current Test Method
For Inspecting 0.042-inch
Diameter Mild Detonator
Fuse**

J. M. Prince

March 1986

**Prepared for
Monsanto Research Corporation
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

FEASIBILITY STUDY TO ASSESS THE USE
OF THE FOUR QUADRANT EDDY CURRENT
TEST METHOD FOR INSPECTING 0.042-
INCH DIAMETER MILD DETONATOR FUSE

J. M. Prince

March 1986

Prepared for
Monsanto Research Corporation
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

This final technical report covers work performed under a related services agreement with the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 from April 1, 1985 to February 28, 1986. The work was administered under the direction of Mr. J. Don Hastings and Mr. E. Dane Harvey, Monsanto Research Corporation, Miamisburg, Ohio 45342.

The contractor was the Nondestructive Evaluation and Measurements Section of Pacific Northwest Laboratory, operated by Battelle Memorial Institute, Richland, Washington 99352. The principal investigator was Mr. Jim Prince. Other investigators were Wayne Lechelt, Doug Riechers, and Jim King.

CONTENTS

	<u>Page</u>
INTRODUCTION	1
PROJECT RESULTS	3
THE 4QEC PROBE CONFIGURATION	3
PROBE OPERATING FREQUENCIES	4
THE SENSE AND REFERENCE PROBE APPROACH	4
PROBE DEVELOPMENT	6
SIGNAL PROCESSOR DEVELOPMENT	8
Driver Coil Signal Processor	8
Quadrature Secondary Coil Signal Processor	12
TEST SAMPLE DEVELOPMENT	14
SUMMARY AND CONCLUSIONS	15
APPENDIX: SMALL DEFECT PHOTOS ON ALL 11 OF 1-INCH SAMPLES	

LIST OF FIGURES

	<u>Page</u>
1. 4QEC Probe Configuration	2
2. Coil Impedance for Thick-Walled Tubing	5
3. Original Dual-Coil Driver Small Defect Response	7
4. Final Dual-Coil Driver Small Defect Response	7
5. 4QEC Probe Assembly	9
6. Signal Processor Breadboards	9
7. Driver Coil Small Defect and Average Wall Signal Processing	10
8. Average Wall Thickness Data	12
9. Quadrature Secondary Coil Core Offset Signal Processing	13
10. Typical Core Offset Data	14
11. One-Inch-Long Fabricated Test Samples	15

INTRODUCTION

The objective of this project was to assess the 4QEC (four quadrant eddy current) test method's sensitivity to wall conditions in 0.042-inch-diameter MDF. Specifically, the wall conditions of interest are core offset, average wall thickness, and cracking and inclusions in the wall.

The 4QEC test method was developed by Pacific Northwest Laboratory (PNL) several years prior to this study under work performed for Lockheed Missiles and Space Company (contract TR10B7690M). The method was evaluated for Lockheed on 0.073-inch-diameter MDF with a prototype 4QEC inspection system also developed by PNL. The 4QEC technique is based on the unique drive and secondary coil configuration shown in Figure 1. Eddy currents are induced in the MDF wall by the encircling driver coils, which are driven in phase, and sensed by the four secondary coils. Each secondary coil makes independent measurements of wall thickness in each of four 90-degree quadrants around the MDF. Highly sensitive crack detection is provided by differentially processing the signals from the dual driver coils.

The work performed on this project and described in this report has modified the previously developed 4QEC technology for use on 0.042-inch MDF by miniaturizing the probe and utilizing multi-frequency signal processing. Multi-frequency signal processing was implemented to allow liftoff-noise suppression without the use of complex impedance-plane two-axis rotation techniques.

The signal processing approach followed by PNL uses 1 MHz and 100 kHz simultaneously for generating liftoff and wall parameter data, respectively. However, the 100 kHz data also contain a liftoff-noise component along with the wall thickness information. To suppress the liftoff noise, the 1 MHz data, which are not affected by wall thickness, are processed with the 100 kHz data for

FIGURE 1. 4QEC Probe Configuration

a maximum wall-signal to liftoff-noise ratio. Small crack and inclusion data are generated by differentially processing the 100 kHz signals from the dual-coil sense probe driver.

PROJECT RESULTS

THE 4QEC PROBE CONFIGURATION

As shown in Figure 1, the 4QEC probe configuration consists of a six-coil arrangement. Two encircling coils are utilized as dual-driver coils which are driven from a constant amplitude sinusoidal current source in phase with each other. These coils generate a flux component that induces eddy currents in the MDF wall. The eddy currents in turn generate their own flux component, which has a phase and amplitude dependence on MDF wall conditions. Since the driver coils are driven from a constant current source, their coil voltages are determined by the net flux linking with them. The net flux is the vectorial summation of the driver and eddy current generated components. Thus the driver coils are utilized to detect the net wall conditions (average wall thickness, cracks, and inclusions) in the length of MDF that they cover. Driver coil design parameters include coil inductance, length, and diameter.

The four secondary coils are affected by the net flux in their respective 90-degree quadrants. These coils are operated into high impedance circuitry so that the induced voltages in the coils do not generate currents and thus undesirable flux components. Also, they are wound on ferrite cores to maximize their sensitivity to the net flux developed by the driver probe/MDF specimen test arrangement. The design parameters for these secondary coils are coil inductance and shape as well as position in the probe which provides optimum quadrature sensitivity and coverage.

PROBE OPERATING FREQUENCIES

Since the MDF is electrically a nonferromagnetic ($\mu_r = 1$) thick-walled tube, much experimental data is available^(a) to help select the proper operating frequency to use to get the desired data (i.e., wall thickness and/or liftoff). The graph shown in Figure 2 illustrates the change in coil impedance (ΔZ) from its unloaded value (X_{LO}) to its loaded value (MDF in the encircling coil) as a function of operating frequency to limit frequency ratio (f/f_g) and wall thickness. The limit frequency, f_g , for a cylindrical test specimen can be calculated as follows:

$$f_g = \frac{50.66}{\mu_r \sigma d^2} \text{ kHz}$$

where: μ_r = relative permeability of test material
 σ = conductivity of test material $\times 10^7$ mhos/meter
 d = diameter of test specimen, mm

From this we calculate the limit frequency for 0.042-inch (1.07-mm) MDF made from 99.99% aluminum ($\mu_r = 1$ and $\sigma = 3.77 \times 10^7$ mhos/meter) to be $f_g = 11.8$ kHz. From the graph in Figure 2, we can see that an operating frequency of 100 kHz ($f/f_g \approx 9$) provides excellent wall thickness data in thicknesses about 10 mils (0.010 inch). On the other hand, for liftoff data that would be independent of wall thicknesses greater than 5 mils, the operating frequency is 1 MHz ($f/f_g \approx 90$).

THE SENSE AND REFERENCE PROBE APPROACH

In an industrial environment it is necessary that highly sensitive measurement instrumentation be engineered to be independ-

(a) Nondestructive Testing Handbook, Vol. 2; R.C. McMaster, Ronald Publishing, Section 38.

FIGURE 2. Coil Impedance for Thick-Walled Tubing

ent of changes in that environment such as temperature. For this reason differential coil signal processing has been utilized for this application. Also, in order for each of the four quadrant coils to provide independent absolute wall thickness data, it is necessary to provide true reference signals from a reference probe, which is a replica of the sense probe. The sense and reference probes, along with their respective drive circuitry, are physically located so that they are subject to the same environment. The signal from the quadrature coils (high, low, left, and right) in the sense probe are differentially processed with the respective coil signal from the reference probe. This approach, along with the appropriate signal processing, has demonstrated the high sensitivity and stability necessary for MDF inspection.

PROBE DEVELOPMENT

The majority of the probe development involved the design of the driver coils with the objective being to maximize the sensitivity to 0.006-inch-diameter drill holes in the MDF wall. The primary probe design parameters that affect the driver's small defect sensitivity are the overall dual-coil length, the individual coil length, and the distance separating the coils.

The first dual-coil driver design that was evaluated had an overall length of 0.135 inch, individual coil length of 0.055 inch, and a separation distance of 0.025 inch. The data shown in Figure 3 are the small defect responses recorded while scanning the length of the number 4 one-foot sample sent to PNL by Monsanto. The left side of the photograph corresponds to the marked (black) end of the sample. The right end of the signal corresponds to a position on the sample of approximately 10 inches from the marked end. The mechanical MDF drive system used in this study does not provide for the scanning of the last 2 inches of the material. The 2 inches corresponds to the distance from the drive wheel to the probe.

FIGURE 3. Original Dual-Coil Driver Small Defect Response

Other coil lengths were evaluated (0.035 and 0.025 inch) as well as other coil separations (0 and 0.01 inch). The dual-coil driver design that provided the best small defect signal-to-noise ratio has 0.025-inch-long coils separated by 0.01 inch for an overall driver length of 0.06 inch. Data taken with this probe, which is called the final probe design, is shown in Figure 4. These data, which are the response to sample 4 (also used for Figure 3), indicate an increase in the signal-to-noise ratio over

FIGURE 4. Final Dual-Coil Driver Small Defect Response

the data shown in Figure 3 of greater than 2:1. The final dual-coil driver design consists of 140 turns in 6 layers of 0.001-inch-diameter (#50) wire for each coil wound on a 0.055-inch-diameter form with an inductance of approximately $60\mu\text{h}$ with both coils connected in the series aiding configuration. The series aiding configuration is also how the dual-coil drivers are connected for operation.

Early in this project a single-coil driver was evaluated. Small defect data were processed by comparing the phases of the 100 kHz components of the sense and reference drive coil signals. However, this single-coil configuration did not provide the sensitivity required to detect 0.006-inch-diameter holes in the MDF wall and, therefore, it was not evaluated any further.

The 4QEC probe's four secondary coils are symmetrically located around the dual-driver coils, as shown in Figure 1, with each coil consisting of 330 turns in 6 layers of 0.001-inch-diameter wire wound on a 0.015-inch-diameter by 0.1-inch-long ferrite rod giving an inductance of approximately $250\mu\text{h}$. A completed 4QEC probe assembly is shown in Figure 5.

SIGNAL PROCESSOR DEVELOPMENT

The 4QEC signal processing consists of two independent circuits: 1) the driver coil signal processor for small defects and average wall thickness, and 2) the quadrature secondary coil signal processing for core offset. The signal processor breadboards are shown in Figure 6.

Driver Coil Signal Processor

The driver coil signal processor, shown in Figure 7, processes the sense and reference dual-coil driver signals to provide data

FIGURE 5. 4QEC Probe Assembly

FIGURE 6. Signal Processor Breadboards

FIGURE 7. Driver Coil Small Defect and Average Wall Signal Processing

corresponding to the presence of small defects and the average wall thickness in the sample being tested.

The small defect data are processed by detecting the phase difference between the two drive coil 100 kHz signals generated in the sense 4QEC probe. The small defect null is adjusted for zero volts out with a clean sample in the sense probe. Therefore, the output remains at zero unless either of the driver coils senses something different than the other, such as a 0.006-inch hole in the MDF wall as it is passed through the sense 4QEC probe. Typical small defect response data are shown in Figure 4. Data on the other one-foot-long samples provided by Monsanto are shown in the Appendix.

The average wall data are processed by detecting the phase of the 100 kHz signal developed by vectorially subtracting the reference driver voltage from the sense driver voltage. The phase of this signal is detected by comparing it to the 100 kHz reference. The average wall output signal is nulled on a sample of nominal wall thickness.

The average wall test data, shown in Figure 8, were taken using two of the fabricated one-inch samples called FAB #1 and FAB #2. The marked end of FAB #1 has a well centered core (within 0.001 inch) having a diameter of approximately 0.020 inch. The marked end of FAB #2 has an approximately 0.025-inch-diameter core with an offset of approximately 0.005 inch. These dimensions were measured optically using a graticuled microscope. However, the data taken at the center region of each piece indicate that the ID is not true with the OD over the length of the pieces and that they should be radiographed to create a higher confidence in the 4QEC average wall as well as core offset sensitivities.

FIGURE 8. Average Wall Thickness Data

Quadrature Secondary Coil Signal Processor

The quadrature secondary coil signal processor, shown in Figure 9, provides the core offset data vertical and horizontal components. This is accomplished by processing each of the four quadrature (high, low, left, and right) sense and reference coils differentially with one another to develop the quadrature wall thicknesses. This process involves phase detection on the 100 kHz component of the differential signal and amplitude detection on the 1 MHz component. These components contain wall thickness with liftoff noise and liftoff information, respectively. The liftoff noise in the 100 kHz quadrature wall component is suppressed by mixing the appropriate amplitude and polarity of the liftoff information in the 1 MHz component.

The core offset is created in two components, vertical and horizontal. The vertical component consists of the difference between the high and low quadrature wall signals and the horizontal is the difference between the left and right. Some typical core offset data are shown in Figure 10. These data are created by connecting the vertical and horizontal outputs to the Y and X

FIGURE 9. Quadrature Secondary Coil Core Offset Signal Processing

FIGURE 10. Typical Core Offset Data

inputs, respectively, on a storage oscilloscope and rotating the test sample in the 4QEC sense probe. The fabricated one-inch test samples FAB #1 and FAB #2 were used for these data.

TEST SAMPLE DEVELOPMENT

A set of one-inch-long test samples, shown in Figure 11, were fabricated using EDM (electro-discharge-machining) techniques. The material used for these samples was a 1- by 3- by 0.25-inch block of aluminum alloy 1100, which has an electrical conductivity of approximately 59% IACS. Four-nines aluminum (unworked) has a conductivity of 65% IACS. This small difference in conductivity does require re-nulling of the electronics when the material in the sense probe is changed from real MDF to the EDM samples and vice versa. However, for the evaluation of the 4QEC test method on MDF wall conditions, this small difference in conductivity should have very little effect on the system's sensitivity.

In order to fabricate 0.042-inch OD and approximately 0.02-inch ID samples from a block of aluminum, ID holes were first put through the one-inch direction using an EDM hole maker. The next

FIGURE 11. One-Inch-Long Fabricated Test Samples

step was to cut the OD profiles around the ID holes using a wire-EDM system. However, the positions of the ID holes in the block could not be controlled well enough to reference the OD cuts from the block outside surfaces. The only other alternative is to individually reference each OD cut with its own ID hole. To do this the wire-EDM system must be able to obtain electrical contact with the wall of the hole. Electrical contact was not possible because the hole-making EDM process created a non-conductive surface on the finished hole. As a result, the one-inch samples were not fabricated with enough precision to quantize the core offset and average wall readings.

SUMMARY AND CONCLUSIONS

Experiments were performed that provided data indicating that the 4QEC probe and associated signal processing can determin

the presence of core offset, average wall thickness variations, and small defects in the 0.042-inch-diameter MDF wall.

Based on these data it is our conclusion that the 4QEC test method can also provide quantitative information on the MDF wall conditions. However, to do so will require that the data be correlated with radiographs of the various core offset and average wall thickness test samples. This would be part of a follow-on project and would also be required in the calibration of a fieldable 4QEC test system for 0.042-inch-diameter MDF.

APPENDIX

SMALL DEFECT PHOTOS

ON ALL 11 OF 1-INCH SAMPLES

Sample #1

Sample #2

Sample #3

Sample #4

Sample #5

Sample #6

Sample #7

Sample #8

Sample #9

Sample #10

Sample #11

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

ONSITE

8 J. D. Hastings
Monsanto Research Corporation
P. O. Box 32
Miamisburg, OH 45342

DOE Richland Operations Office

J. J. Sutey

30 DOE Technical Information Center 13 Pacific Northwest Laboratory
D. K. Lemon
J. M. Prince (5)
Publishing Coordination (2)
Technical Information (5)