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ELECTROMAGNETIC METHODS FOR INSPECTION OF FERROUS TUBING*

by

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ABSTRACT

Electromagnetic-Acoustic (EMAC) techniques have been applied to the nondestructive inspection of ferromagnetic tubing. EMAC combines the advantages of noncontact electromagnetic inspection with the flaw detection capabilities of ultrasonic inspection techniques. Laboratory studies have demonstrated the capabilities of the method for detecting cracks, pits, and wall thinning in carbon steel boiler tubing. Results of the studies demonstrate the feasibility of using internal EMAC probes for inspection of installed tubing. ~~Additional work is needed to fully develop the potential of this inspection method.~~

Multiparameter eddy current techniques show promise for detecting wall thinning in ferromagnetic tubing. A two frequency multiparameter eddy current system was shown to provide the parameter separation capability necessary for the detection of wall thinning in the presence of shallow internal pitting and surface scale. Machined steps in the wall of carbon steel tubing were detected with the multiparameter system.

An internal magnetization probe has been applied to ferromagnetic tubing. The internal magnetization probe concept may be used to produce increased penetration of eddy current signals, to reduce magnetic permeability variations in ferrous tubing, and can be incorporated into EMAC inspection probes.

Further development of one or more of these electromagnetic inspection techniques may provide a means for field inspection of installed ferrous tubing.

ELECTROMAGNETIC METHODS FOR FERROUS TUBING INSPECTION

INTRODUCTION

Ferrous tubing is commonly used in such applications as steam boilers and heat exchangers, where periodic inspection of the tubing is desirable. Conventional ultrasonic or radiographic nondestructive inspection techniques can be difficult to implement due to the space and access restrictions normally encountered in these installations. The presence of boiler scale on the tubing surfaces presents additional problems to most inspection techniques and the ferromagnetic properties of the tubing material can cause undesirable effects in conventional electromagnetic inspection systems.

Battelle Northwest recently completed a program* to investigate advanced electromagnetic nondestructive inspection techniques for application to the problem of in-situ ferrous tubing inspection; Specifically, 1 inch diameter, ~~0.000~~ 0.10 inch wall carbon steel boiler tubing. The approaches selected for investigation ~~were~~ included eddy current methods (multiparameter eddy current, ~~pulsed eddy currents~~ and magnetic saturation & in combination with single frequency eddy current) and electromagnetic-acoustic (EMAC). Laboratory tests were conducted to determine the defect detection capability of each method for such tubing defects as pitting, cracking, and wall thinning. The EMAC inspection technique was shown to be the most promising method of those investigated for ferrous tubing inspection.(1) Simulated pits, cracks and wall thinning in actual boiler tube samples were detected by this technique. This paper summarizes the results of the laboratory evaluation and presents specific examples of the flaw detection capabilities of the EMAC method.

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Principles of Operation

Electromagnetic-acoustic (EMAC) methods refer to the technique of using electromagnetic coils for generating and detecting acoustic waves in electrically conductive materials. Although the basic concept of EMAC transducers was observed several years ago[2] EMAC methods have remained relatively undeveloped in the United States as applied to nondestructive testing. The basic operational principles of an EMAC transducer can be illustrated by the example shown in Figure 1. An eddy current-type electromagnetic coil is placed under the pole of a magnet and is excited with current pulse. The eddy currents generated in the conductive test piece as a result of the changing electromagnetic field around the coil, interact with the magnetic field in the material to produce ~~a~~ Lorentzian forces in the test material. The Lorentzian forces within the test material generate elastic (acoustic) waves which propagate away from the point of origin. The reception of acoustic energy by the EMAC method is reciprocal to generation. Acoustic energy passes through the magnetic field, establishing an eddy current flow within the material. The resultant electromagnetic field caused by the eddy current flow is detected by the coil located under the permanent magnet.

The particular type or types of acoustic waves generated by an EMAC transducer is dependent upon the orientation of the eddy current flow in the material with respect to the magnetic field flux lines. Longitudinal, shear and surface waves can be generated by EMAC transducers.[3] The primary advantage of EMAC generation and reception of acoustic signals over conventional ultrasonic methods is that EMAC transducers require no liquid couplant and no physical contact with the test material. ~~nor is any liquid couplant required.~~ Since the acoustic signal is generated and detected within the material being tested, the problems normally associated with the material couplant interface in conventional ultrasonics are not encountered. EMAC transducers are relatively insensitive to general surface roughness and can be applied to both ferrous and non-ferrous metals.

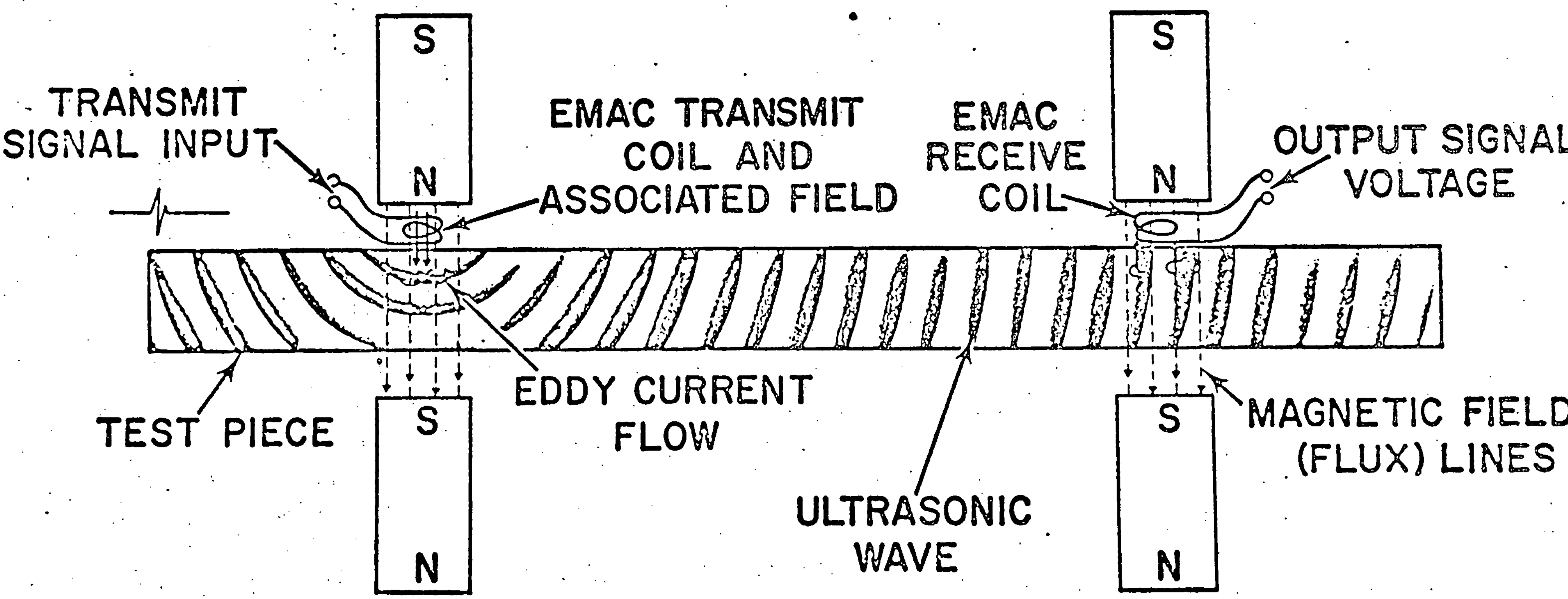

FIGURE 1. EMAC Transducer Configuration

Application to Ferrous Tubing

EMAC methods of inspection combine some of the advantages of ultrasonic and electromagnetic inspection techniques and eliminate or reduce some of the unfavorable aspects of each technique. For example, EMAC methods overcome the problems associated with coupling ultrasound into the tubing through a rough surface from a conventional piezoelectric transducer since the acoustic signal is generated beneath the surface of the material. This is a definite advantage for in-situ inspection of ferrous boiler or heat exchanger tubing because of the rough surface normally countered. The problems associated with conventional electromagnetic inspection and caused by varying permeability in the ferrous tubing are also less severe for EMAC inspection methods. These advantages over conventional inspection techniques make EMAC a strong candidate for boiler and heat exchanger tubing inspection.

In-situ inspection of boiler or heat exchanger tubing requires that the inspection be performed from inside the tube. A specially designed EMAC probe was fabricated for use in 1 inch O.D., 0.100 inch wall material. Figure 2 is a photograph of the probe. The probe consists of an iron core with wire brush-like pole pieces, an electromagnet coil, and an EMAC bobin type transmit or receive coil. The electromagnetic coil wound on the iron core body surrounds the EMAC coil which is centered along the core body. The iron core and wire brush pole pieces provide a low reluctance flux path into the tubing walls, allowing the electromagnet to establish the magnetic field in the tubing required for EMAC generation of acoustic waves. The EMAC coil can be used as an acoustic transmitter or receiver. Figure 3 is a sketch of the configuration in which two EMAC probes of this type were used to inspect laboratory specimens of actual boiler tubing. A transient - receive mode of operation was utilized. The ultrasonic signal generated by a pulsed excitation of the EMAC coil is a pulse traveling along the tube in both directions from the transmitter probe.

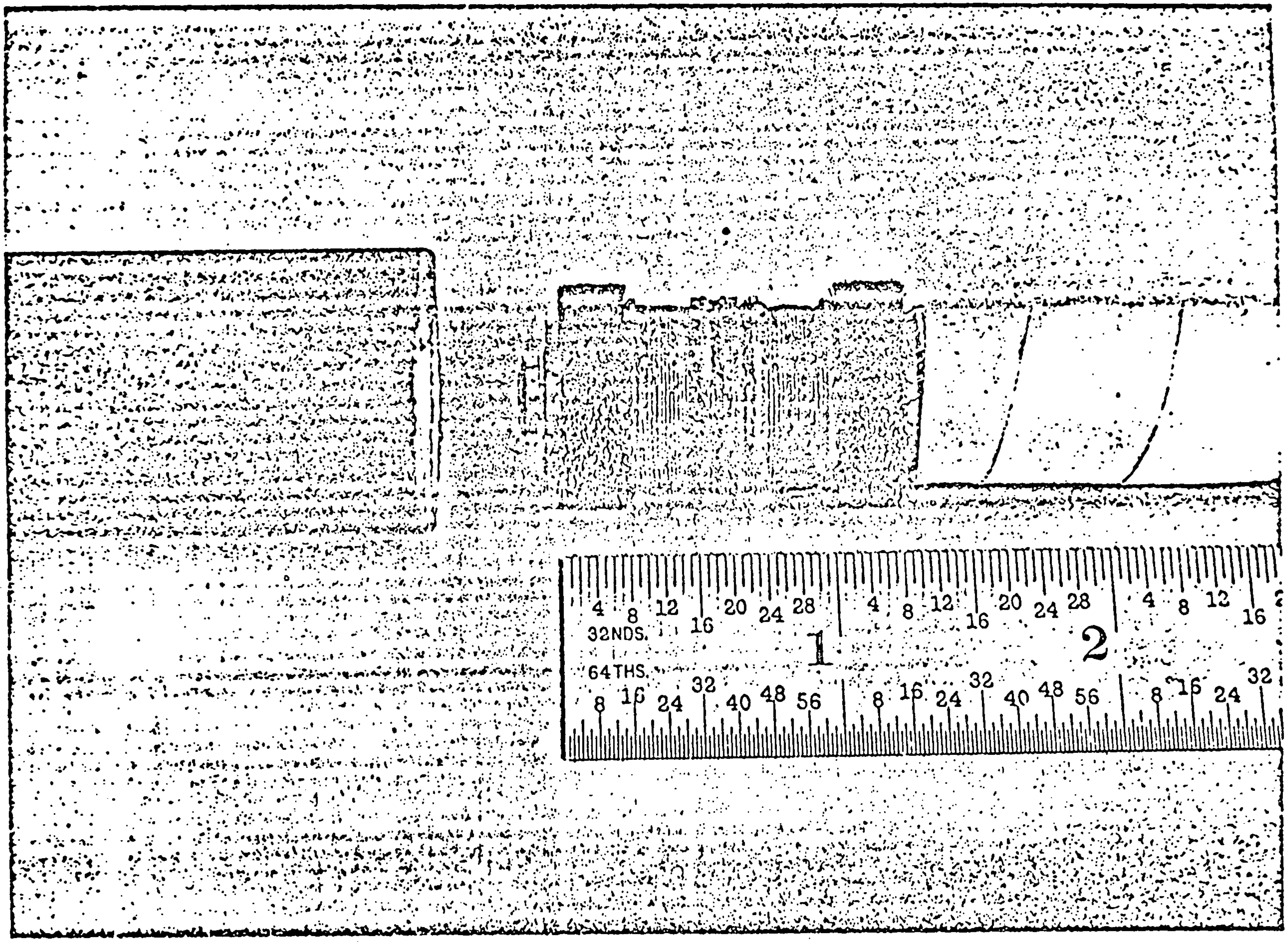

FIGURE ~~1~~ 2. Internal EMAC Transducer

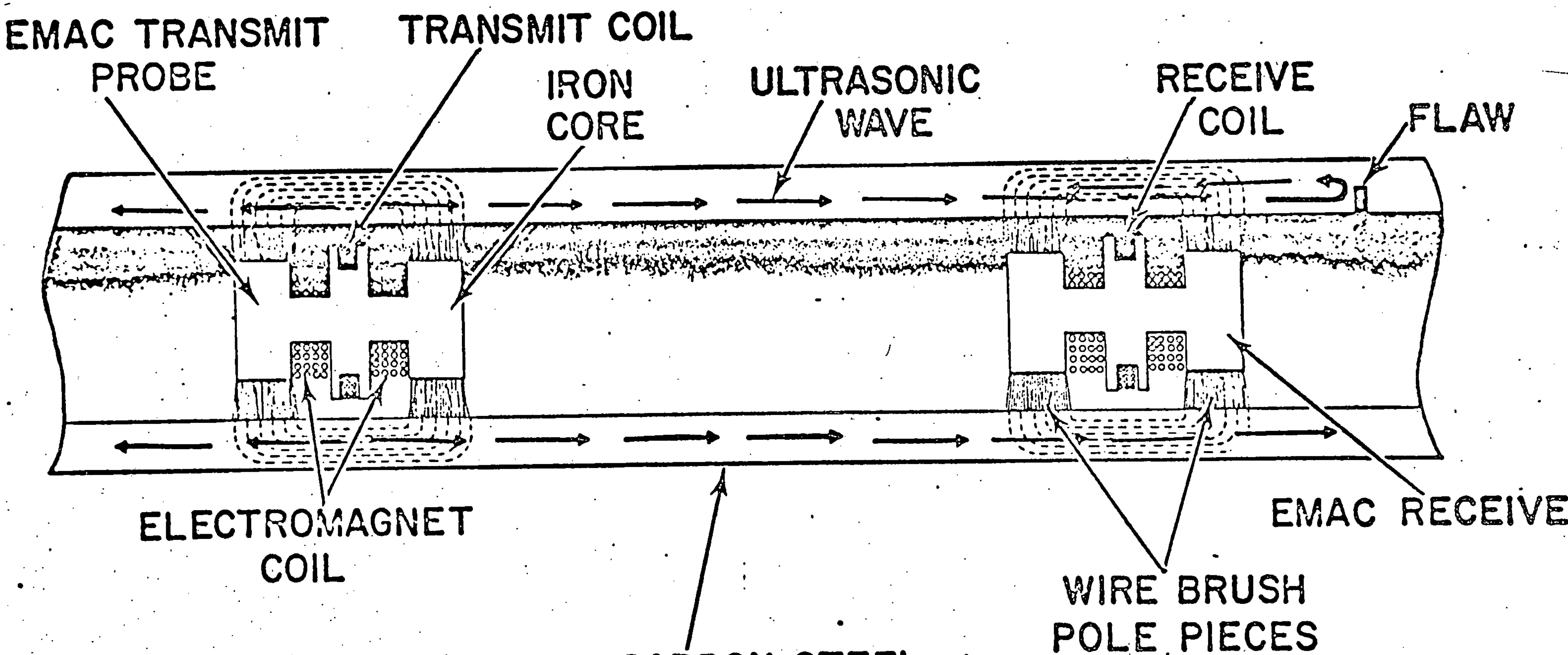

FIGURE 6. EMAC Transducers With Internal Electromagnet Field Sources
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The pulse is generated uniformly around the entire circumference of the tube. The portion of the ultrasonic pulse traveling toward the receive probe is detected as it passes the EMAC coil. The presence of a flaw located just beyond the receiver probe causes a portion of the ultrasonic energy in the tube to be reflected back toward the receiver probe where it is detected slightly later in tiem than the direct received signal.

An example of the signals obtained with this transmit-receive probe configuration is shown in the oscillograph of Figure 4A. Two internal EMAC probes similar to the one described above were separated by approximately 7 inches inside a 1 inch diameter carbon steel tubing specimen. The "direct received signal" is the signal resulting from the initial ultrasonic wave passing through the field of the receive EMAC coil. The "reflected signal" is the signal from the portion of the ultrasonic wave reflected at a 0.015 inch to 0.100 wall thickness step in the outside wall of the tubing. A substantial portion of the ultrasonic energy incident upon the wall thickness step is reflected back toward the receive transducer.

Smaller tubing flaws can be detected in this same manner. Figure 4B shows the signal reflected signal from a 0.090 inch deep transverse saw cut in the outside wall of a 1 inch diameter, 0.100 inch wall tubing specimen. A much smaller percentage of the total ultrasonic energy transmitted down the tubing is incident upon this flaw as comapred to the wall thickness step of Figure 4, however, the reflected signal from the saw cut is easily detected. Similar results have been obtained for other simulated tubing flaws such as drill holes and transverse EDM notches.

Since the ultrasonic signal generated by the probe configuration described above travels parallel to the axis of the tubing, only those flaws which present a broad reflecting surface to the traveling wave will be detected. In order to permit detection flaws oriented along the axis of the tubing a different probe

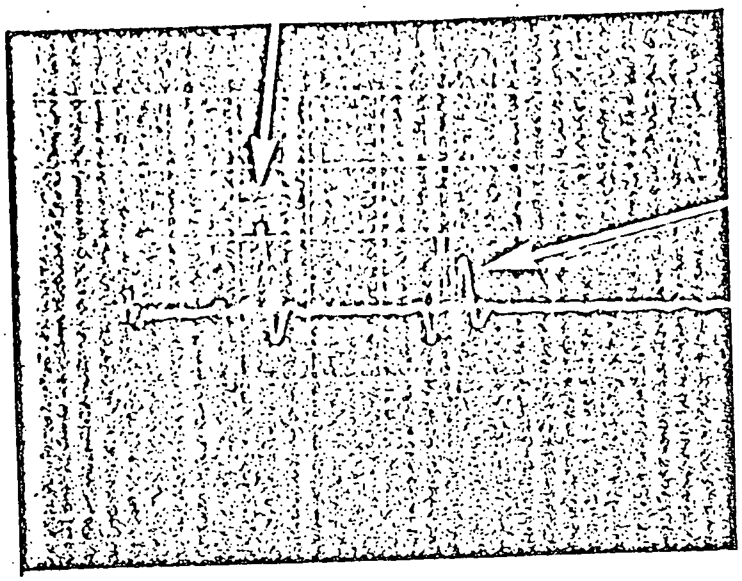


FIGURE ~~8~~ 4A. Signal Received wtih Internal EMAC Transducers Operating in Transmit-Receive Mode of Operation

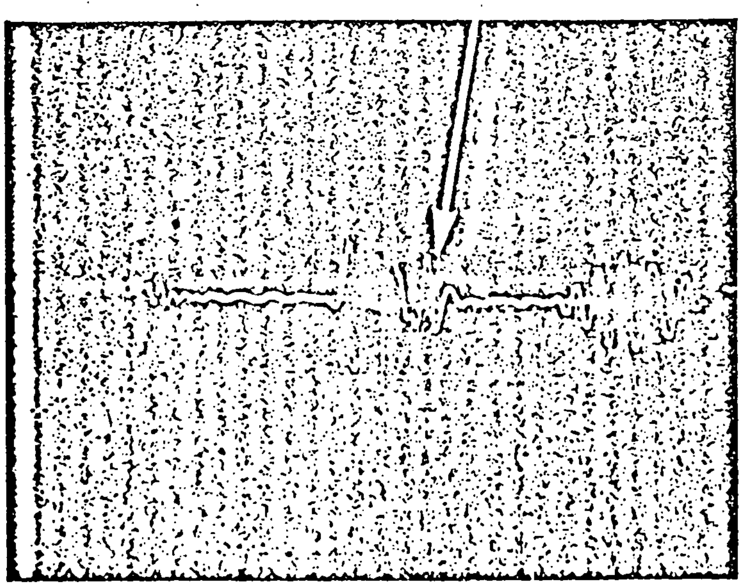


FIGURE ~~9~~ 4B. Signal Response with 0.090-in. Deep Transverse Saw Cut Positioned Near Receive Transducer design was used (see Figure 6). It consists of a small EMAC coil mounted on the tapered end of a small cylindrical permanent-type magnet. Two of these probes can be used in the transmit-receive mode of operation and located approximately 180° apart on the circumference of the tubing to detect flaws located parallel to the axis of the tubing. Simulated axial flaws in tubing specimens were detected in this manner by noting the signal attenuation do to flaws passing between the two probes. Figures 7A and 7B illustrate the normal signal received with EMAC point probes and the attenuation noted for a 0.072 inch deep, 0.250 inch axial EDM notch in 1.0 inch diameter, 0.100 inch wall carbon steel tubing. Note the multiple signals in the normal trace due to the multiple passes of the ultrasonic signal around the circumference of the tubing. EDM notches down to 0.024 inches deep were detected by this method.

EDDY CURRENT METHODS

Multiparameter Methods

Multiparameter eddy current inspection methods use the information obtained by simultaneous excitation of an eddy current inspection probe at two or more test frequencies to separate more test variables than can be separated with conventional single frequency eddy current methods. The increased test variable separation capability of multiparameter methods over single frequency methods permits discrimination against undesirable signal variations which might otherwise mask out the variable of interest. This increased separation capability is a definite asset for eddy current inspection of ferrous tubing because of the large number of variables present in the material which can cause undesirable signal variations. Varying permeability, scale, ovality, and other parameters in the tubing can mask the signals present due to flaws of interest such as cracks, pits or wall thinning.

A two frequency multiparameter eddy current system was used to determine the amount of signal improvement that could be obtained with the multiparameter

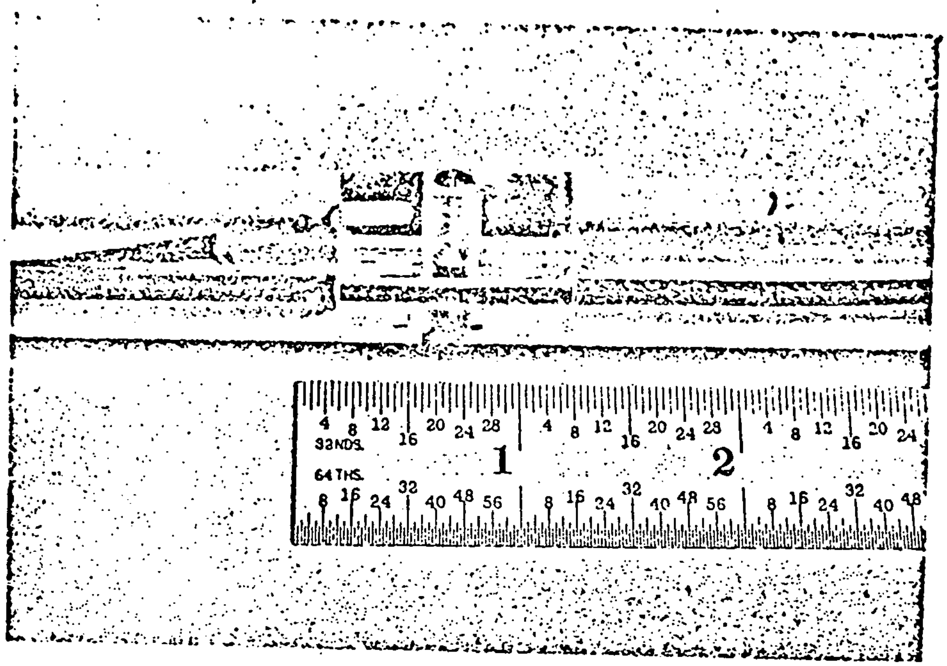


FIGURE 5. Receiver Portion of Internal Probe P-7 with Receiver Coil Wound on Tapered Cylindrical Magnet

1ST RECEIVED SIGNAL

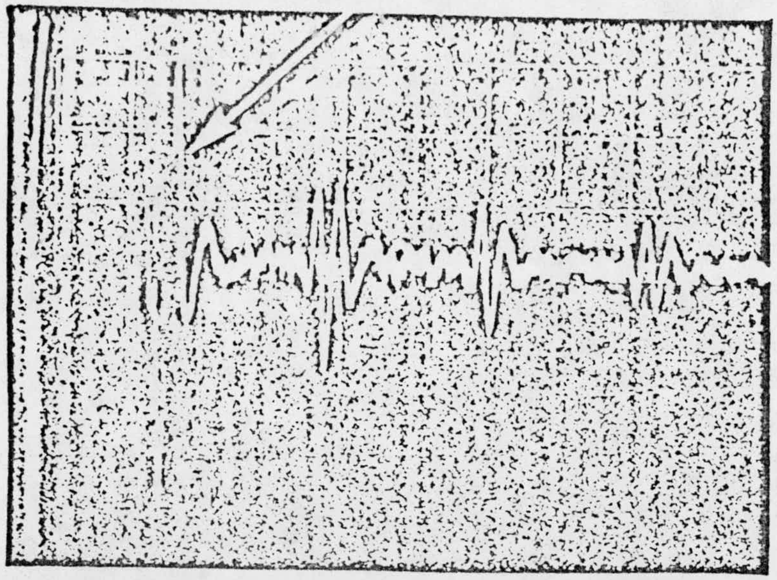
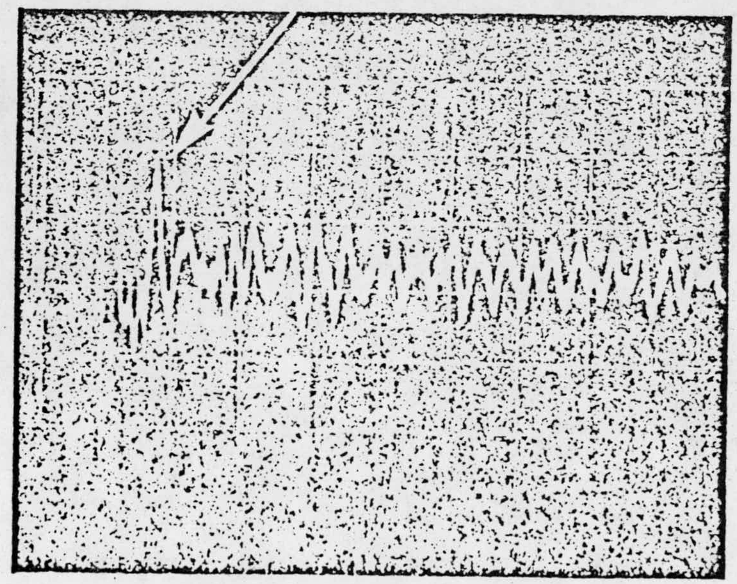


FIGURE 6A. Normal Signal Obtained with OD EMAC Transducer Configuration

1ST RECEIVED SIGNAL



5 mV/div, 10 μ sec/div

FIGURE 6B. Signal Response with 0.072-in. OD Longitudinal Notch Positioned Near Transmit Probe technique on ferrous tubing. The relatively low operating frequencies of 24.4 and 97.6 Hz were chosen to ~~provide the increased~~ allow greater penetration ~~capability required~~ of the electromagnetic signal into [illegible] ~~for penetration of~~ the high permeability carbon steel material. A differential bobin-type probe was used in the tests.

The ~~increased variable~~ parameter separation capability of the multiparameter system is demonstrated by the inspection chart record shown in Figure ~~8~~ 7. An internal inspection probe was drawn through a carbon steel tubing specimen containing machined steps in both the inner and outer tubing walls. Conventional internal eddy current inspection techniques applied to ferrous tubing would be expected to produce a very large signal response over inner wall thickness steps, but would have difficulty in detecting outer wall thickness steps. Figure ~~8~~ 7 shows the ability of the two frequency multiparameter system to reduce the normally large inner wall signals, while maintaining sensitivity to the outer wall thickness steps. The signals from four outer wall steps labeled D, C, and B represent three successive 0.010 inch step reductions of the outer tubing wall (thickness - 0.100 in.). The signal labeled A is from an outer wall step increase of 0.030 in. The signals E, F, and G represent three successive inner wall step~~s~~ reductions of approximately 0.005 in. and H is an inner wall step increase of 0.016 in. ~~Note~~ The significance here is that the magnitude of the signals from the inner wall steps has been reduced by proper adjustment of the multiparameter system to less than the magnitude of the outer wall steps. This method of discrimination against inner wall nonuniformities could be valuable for inspection of ferrous tubing when outer wall thinning (caused by such things as hanger wear) is suspected.

Magnetic Saturation Methods

Magnetic saturation methods are sometimes used to reduce the undesirable effects of magnetic permeability variations in carbon steel in order to allow conventional eddy current inspection methods to be implemented. The methods normally employed to aid tubing inspection require an external magnetization

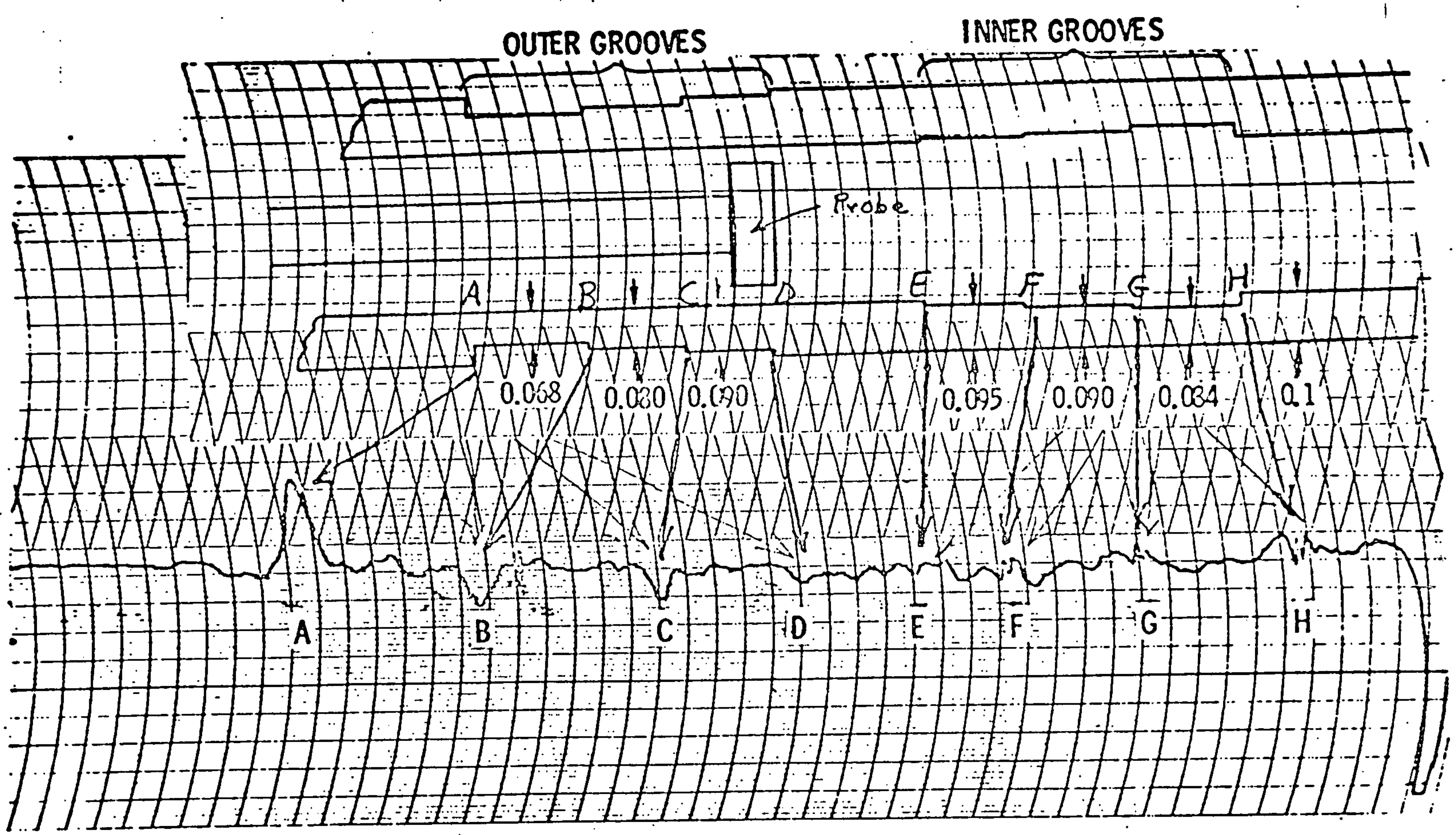


FIGURE 12. Discrimination Against Step Changes in Internal Tubing Diameter Using the Multiparameter Eddy Current Method. Frequencies: 24.4 and 97.6 Hz ~~Tubing Specimen T-4, Inspection Probe P-1~~

coil surrounding the tube, a method which does not lend itself to installed tubing inspection. An alternate approach is to produce a reasonably high magnetic field in the tubing wall by using an internal magnetization probe.

The increased signal penetration that can be obtained with an internal magnetization probe was demonstrated by using a probe similar to the EMAC probe shown in Figure 2. Solid pole pieces were used in place of the brush-like pole pieces. A pulsed voltage was impressed across the magnetization coil of the probe, producing a pulsed magnetic field in the tubing walls. The effectiveness of the magnetization upon the RF eddy current signal penetration into the tubing is very apparent in Figure 8. The photo shows the signal transmitted through the wall of a section of 0.100 inch wall ferrous tubing with and without the magnetization field present. The upper trace shows the current pulse through the magnetization coil of the probe. The lower trace is the amount of 1 KHz signal transmitted from a transmitter coil surrounding the tubing to the receiver coil located inside the tube. No transmitted signal is detected when the magnetization current is off; however, a significant amount of signal is transmitted when the current pulse is applied.

Although the signal penetration was increased with this internal magnetization probe, in our particular application the degree of magnetic saturation attained was insufficient to eliminate the fluctuations in the eddy current signals caused by material permeability variations. The remaining interferences due to permeability variations were sufficiently large to mask signals from small cracks and pits in the tubing wall. The internal magnetization probe concept may be more applicable to larger diameter tubing where the probe body could be enlarged to provide higher flux densities in the tubing wall. The pulsed magnetization current technique permits the use of relatively high currents in the magnetization coil. Continuous magnetization currents would necessarily be less because of the heat buildup at the probe due to I^2R losses. Pulsed magnetization techniques can also be used in EMAC inspection systems.

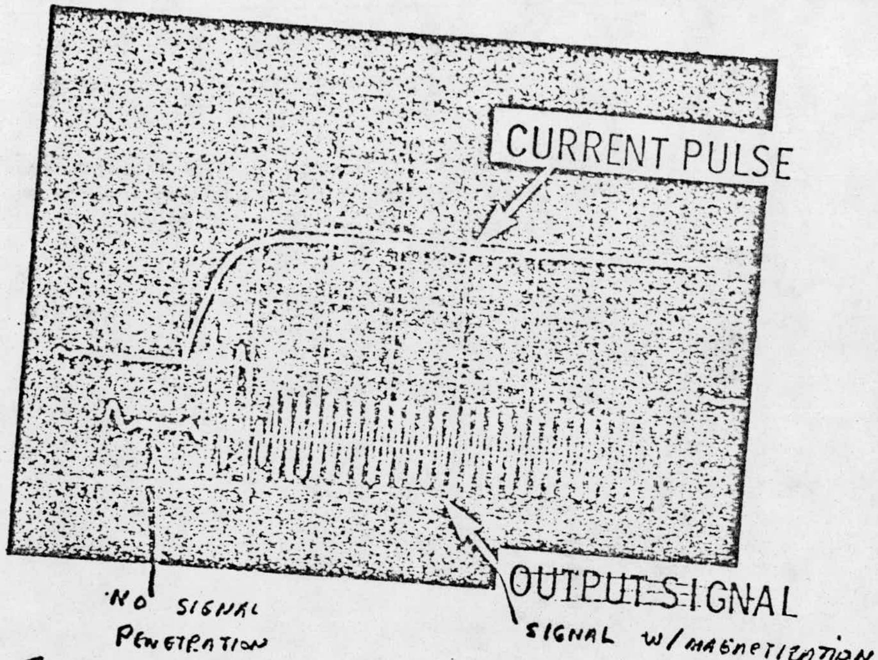


FIGURE ~~35~~ 8. 5.81 Ampere Pulsed Current and Output Signal

SUMMARY

Several of the electromagnetic inspection techniques investigated can provide useful inspection data concerning the status of installed ferromagnetic tubing. The most promising method for establishing the general condition and status of installed tubing is the EMAC inspection technique. The EMAC technique has several advantages over conventional ultrasonic and eddy current inspection techniques. For example, EMAC inspection techniques require no liquid ultrasonic couplant, allow full 360° inspection with a single probe, can perform inspection in presence of scale or general surface roughness, can inspect bended regions and areas of tubing ovality, and are less sensitive to permeability variations than conventional electromagnetic methods. Our laboratory studies have demonstrated the capability of specially designed EMAC inspection probes to detect cracks, pitting, and wall thinning in small diameter tubing specimens. Additional development of the EMAC inspection technique could provide a new means for making meaningful inspection of installed tubing.

Although Multiparameter eddy current techniques show promise for detecting wall thinning in ferrous tubing, the two frequency system used during our studies did not provide sufficient discrimination against magnetic permeability variations to distinguish small cracks or pits in the tubing. The parameter separation capability of the two frequency multiparameter system was sufficient to permit detection of outer wall thinning in the presence of small pits and scale on the interior tubing surface. This technique could be used specifically for detection of wall thinning in ferrous tubing when that condition is of primary interest. Additional discrimination capability could be obtained by increasing the number of operating frequencies in the Multiparameter system, however, Multiparameter systems operating at more than two frequencies can quickly become complex and not readily adaptable for field use.

Eddy current signal penetration depth can be increased significantly with internal magnetization probes. Similar probes could be useful in larger diameter tubing to approach magnetic saturation of the tubing wall. Conventional eddy current techniques could then be used to perform the tubing inspection. Pulsed magnetization techniques can also be useful in producing the magnetic field required in EMAC tubing inspection.

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