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13. ABSTRACT *(Maximum 200 words)*

This report describes developments in magneto-optic imaging that make possible practical real-time imaging of surface corrosion under protective coatings in both steel and aluminum. The technology can also be applied to the detection of cracks. To accomplish imaging in steel a new method for producing rotating in-plane magnetization in steel parts was developed and combined with real-time magneto-optic imaging. Imaging in aluminum is accomplished by using an eddy-current excitation device for producing rotating in-plane eddy-current excitation. Small, relatively light-weight self-contained inspection systems suitable, in principle, for field applications have been produced. This project focused primarily on developing technology needed to accomplish inspections in steel. The resultant laboratory-prototype system for inspecting steel consists of a compact two-channel power-supply for "driving" novel surface-conforming "quadrature" magnetic-yokes, a hand-held imaging probe that "nests" inside the yoke, and a CCD camera-display system that provides real-time image monitoring and/or recording. Magneto-optic images of cracks or notches in steel pipes and steel plate, in addition to images of surface corrosion in both steel and aluminum are also illustrated. The potential for replacing some magnetic-particle based inspections (in steel) with the new magneto-optic imaging technology is briefly discussed.

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NAVY SBIR Phase I Final Report (February 2, 1998)

"Detection of Corrosion Under Paint Using Magneto-Optic Imaging"

Contract No. N66604-M-3560

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ABSTRACT. This report describes developments in magneto-optic imaging that make possible practical real-time imaging of surface corrosion under protective coatings in both steel and aluminum. The same technology can also be applied to the detection of cracks in these same materials. To accomplish imaging in steel (e.g., steel plate, pipe), a new method for producing rotating in-plane magnetization in steel parts was developed and combined with real-time magneto-optic imaging. Imaging in aluminum is accomplished by using an eddy-current excitation device for producing rotating in-plane eddy-current excitation. Small, relatively light-weight self-contained inspection systems suitable, in principle, for field applications have been produced. This project focused primarily on the development of technology needed to accomplish inspections in steel. The resultant laboratory prototype inspection system for steel consists of a compact two-channel power-supply for "driving" novel surface-conforming "quadrature" magnetic-yokes, a hand-held imaging probe that "nests" inside the quadrature yoke, and a charge-coupled device (CCD) camera-display system that provides real-time image monitoring and/or recording. Magneto-optic images of cracks or machined notches in steel pipes, steel plate, and cracks in steel under protective coatings such as paint are illustrated. Images of surface corrosion in both steel and aluminum are also illustrated. The potential for replacing some magnetic-particle based inspections (in steel) with the new magneto-optic imaging technology is briefly discussed.

Key Words: flux leakage, magnetic particle inspection, magnetic yokes, magneto optics, nondestructive inspection

1.0 Identification and Significance of the Problem or Opportunity

Conventional nondestructive inspection (NDI) methods for corrosion on metallic surfaces, are rendered difficult by the presence of protective coatings such as paint. For example, magnetic field-gradients associated with corrosion-pitting at a steel surface are generally far smaller than field-gradients associated with cracks. And because magnetic-particle methods are known to be ineffective, even for cracks, for paint thicker than 0.003 inches, these methods are necessarily ineffective for corrosion under paint. Near-surface ultrasonic methods (e.g., Lamb or Rayleigh waves) might suffice for this purpose, were it not for the requirement to scan transducers, which is generally a very time-consuming process. The NDI for corrosion under painted aluminum-surfaces, using conventional scanned eddy-current coils, is also time-consuming and ineffective. Variations in paint thickness over an aluminum surface (no corrosion) can produce "liftoff" signals that are essentially indistinguishable from signals produced by "uniform" paint thickness over a corroded surface. Thermal-wave imaging techniques are a very promising possibility for surface-corrosion detection. However, if water is present under the paint (without corrosion) false indications of corrosion are possible. A real-time NDI technique that is essentially unaffected by standard thickness' of protective-coatings (e.g., paint) would be a major advance. Real-time magneto-optic imaging is one such technique. Moreover, magneto-optic based techniques can address a wide range of different applications other than corrosion detection, such as crack detection. This versatility promises to make the technology useful in many different kinds of inspection applications of interest to the U. S. Navy.

The magneto-optic/eddy current imager (MOI) is widely used in the nondestructive inspection (NDI) of aging airframes.[1-5] By combining magneto-optic imaging and eddy current excitation, it is possible to obtain real-time eddy current images of fatigue cracks and areas of hidden (sub layer) corrosion in structures such as the *aluminum* fuselage of an aging aircraft. In principle, it should be possible to apply this established technology (in a suitable form) to the detection of surface-corrosion in aluminum. However, the desired inspection-instrument should also be able (ideally) to detect surface-corrosion in steel. *Currently, there is no MOI possessing both the capability to inspect aluminum and steel.*

Recent experimental developments in MOI technology now permit real-time flux-leakage type imaging of cracks and/or corrosion in *steel* (e.g., plates, pipes or tanks)[6-9] through insulation or protective coatings such as paint. Until recently the MOI could not perform such inspections. However, in a project for the Department of Energy (Grant No. DE-FG03-95ER82051) Physical Research, Inc. (PRi) significantly advanced the state-of-the-art for the NDI of steel. This was accomplished by developing a method for producing rotating in-plane magnetization in steel, and then combining this capability with real-time magneto-optic imaging. The original purpose of this work was to develop new NDI techniques for the inspection of steel nuclear-reactor pressure vessels (RPV's). However, this new capability is also applicable to the present inspection problem.

The foregoing demonstrated-capabilities mean that it should be possible, in principle, to combine in one instrument, the ability to inspect (in real time) steel and/or aluminum for surface-corrosion under paint. *No such hybrid instrument yet exits.* The purpose of the Phase I work was to describe how this "hybridization" was to be accomplished in detail (via preliminary designs) and then to demonstrate by actual experimental results, using a laboratory/field prototype, that the proposed technology is feasible and practical. The end-product of the overall project (Phases I, II and III) is envisioned to be a portable, battery-operated field-instrument, which is capable of being used by relatively-inexperienced shipboard-personnel to accomplish the desired surface-corrosion inspections on steel and/or aluminum.

2.0 Phase I Technical Objectives(as planned and as "evolved")

1) Design a portable, battery-operated, MOI-based field-instrument, which can be used by relatively-inexperienced shipboard-personnel to accomplish surface-corrosion NDI on both steel and aluminum.

2) Construct a laboratory/field demonstration system based on the design of 1).

3) By a series of laboratory experiments at PRi, and field (shipboard) experiments at the Puget Sound Naval-Shipyard in Bremerton, Washington, demonstrate the capabilities of the new MOI-based inspection system. These tests will be designed to answer the following questions: Does the system detect surface-corrosion on steel and aluminum under paint? If so, what are its limitations? How is the detection effected by paint thickness? Are there opportunities for improving the system that should be implemented in later phases of the program? What are

the human-factors issues surrounding the use of the system? For example, is the proposed battery-pack and other electronics sufficiently portable to be suitable for easy-use aboard ship? Is the proposed personal-viewing-system (a head-mounted display) acceptable under the expected outdoor-lighting (sunlight) conditions? What would be required of a field-hardened system (e.g., waterproofing)?

After the Phase I work began it gradually became apparent that the new technology could address many more inspection applications than the detection of corrosion under paint. The U. S. Navy has many inspection applications such as detecting cracks in steel propulsion shafts (see Task 6b below) and pressurized air flasks etc. that are currently being inspected with magnetic particle inspection (MPI) techniques. While MPI techniques are reliable, they are time consuming and messy. We believe that the demonstrated versatility of the new Navy-developed MOI-based inspection technology will make it a very useful complement to existing inspection technology. In some cases the speed and ease of use of the new technology should make it possible to replace existing MPI in a number of inspection applications deemed to be important to the U. S. Navy.

3.0 Phase I Work Plan

Before embarking on a discussion of the detailed Phase I work plan it will be necessary to have a good understanding of the capabilities and limitations of magneto-optic imaging methods.

3.1 Technical Background

In this section the necessary technical background for understanding magneto-optic imaging in general, and its application to aluminum and steel in particular, will be presented. Examples of (simulated) surface-corrosion MOI images will be presented.

3.1.1 Magneto-Optic/Eddy Current Imaging

By combining magneto-optic imaging and eddy current excitation in an unconventional manner, it is now possible to obtain real-time, eddy-current images of fatigue cracks and areas of hidden corrosion in structures such as the *aluminum* fuselage of an aging aircraft.[1-5] This existing technology-base was the starting point for the present Phase I effort and will now be described briefly.

The magneto-optic sensors consist of a thin film of bismuth-doped iron garnet $(Bi,Tm)_3(Fe,Ga)_5O_{12}$ grown on a three-inch diameter, 0.020 inch-thick substrate of gadolinium gallium garnet (GGG).[10-12] These films exhibit three physical properties that are crucial for a practical magneto-optic imaging device. First, they exhibit an important property called magnetic anisotropy. That is, they have an "easy"-axis of magnetization normal to the sensor surface. Second, if the magnetic fields along the easy-axis of magnetization are removed, the magneto-optic film will retain most of its established magnetization, i.e., it has a "memory." Third, these films possess a very large specific Faraday rotation, θ_f up to 30,000 degrees/cm of thickness, which makes it possible to directly view the images.

If normally incident, linearly-polarized light is transmitted through such a magneto-optic sensor, the plane of polarization of the light will be rotated by an angle called the Faraday rotation, which is $\theta \propto \theta_f \mathbf{k} \bullet \mathbf{M}$, where **k** is the wave-vector of the incident light, and **M** is the local time-dependent magnetization of the film at the point or region where light is transmitted. Note that **M** is always directed, "up" or "down," along the easy-axis of magnetization. Because the angle between **k** and **M** completely determines the sign of the scalar-product **k•M**, the sense of the Faraday rotation (relative to **M**) for a given state of magnetization **M** does *not* depend on the sign of **k**, i.e., the *direction* the light is being propagated through the sensor. Thus, the Faraday rotation relative to **M** will be *doubled* if the light is first transmitted through, and then reflected back through the sensor again, thereby enhancing sensitivity.

By properly viewing this reflected light through an analyzer, the local state of magnetization of any region in the sensor can be seen as a high-contrast dark or light area, depending only on the direction of the magnetization **M** and the setting of the analyzer. This is the basic property that allows the sensor to create images of the normal-component magnetic fields associated with eddy-currents in aluminum and/or flux-leakage fields in steel.

3.1.2 Rotating In-Plane Magnetic Fields

Before discussing the case of rotating in-plane magnetic fields in steel, we will review how analogous rotating eddy-current fields, which also involve relatively weak in-plane rotating magnetic fields, are established in non ferromagnetic conductors such as aluminum.

Rotating Eddy-Current Excitation

In the MOI, sheet-current induction is used to produce eddy currents in a conductor such as aluminum. This process involves a current-carrying copper foil adjacent to the (aluminum) part being inspected.[3-5]

Faraday's law of induction in differential form, [13]

$$\nabla \times \mathbf{E} = -1/c\, \partial \mathbf{B}/\partial t, \qquad (1)$$

shows that a time-varying magnetic field, **B** (produced by such a foil) in the vicinity of *any* non ferromagnetic electrical conductor (e.g., a corroded aluminum surface) will induce a time-varying electric field, **E**, and thus a time-varying conduction current $\mathbf{J} = \sigma \mathbf{E}$, in the same conductor. By Lenz's law, these source-free induced currents, or *eddy* currents, are always opposed in direction to the external currents which produce **B**. Note also that the induced current-density drops off exponentially from the surface of the conductor according to the rule $\mathbf{J} = \mathbf{J}_o \exp(-x/\delta)$, where x is the depth below the surface of the conductor and δ is the frequency and conductivity-dependent skin depth of the conductor.

It is significant that the magnetic fields associated with such sheet currents generally lie parallel to the hard-axis of magnetization of the magneto-optic sensor, which means that in the absence of cracks or corrosion in the test piece, the magnetic fields exciting the eddy currents have little effect on the state of magnetization of the magneto-optic sensor, i.e., they are not sensed. If this were not the case, these relatively large fields would completely overwhelm the much weaker fields produced by cracks and corrosion. Similarly, rotating in-plane magnetic fields (in steel) produced by special magnetic yokes (to be discussed) will have little effect on the magneto-optic sensor. Only the out-of-plane fields (parallel to the easy-axis of magnetization of the magneto-optic sensor) due to flux associated with cracks or corrosion and "leaking" out of the sample plane, will be detected.

Currents in the induction foil can be *unidirectional* or they can be made to *rotate*. And because the mathematical description of such rotating in-plane eddy currents is qualitatively similar to the case of rotating in-plane magnetic fields in a ferromagnetic material, we will now briefly describe rotating eddy-current excitation. Both rotating in-plane magnetic fields (for steel) and rotating in-plane eddy-currents (for aluminum) were made available in the Phase I "hybrid" MOI laboratory prototype.

If two sinusoidal voltages 90 degrees out-of-phase, are simultaneously applied in two perpendicular directions to an electrically-conducting foil (i.e., copper) a multidirectional or *rotating* eddy-current excitation of an electrically-conducting test piece (e.g., aluminum), located below the foil, will be established. A simple analysis shows that along any particular in-plane direction of the test-piece (located under such a foil), there will be an induced current-density at the surface of the form,

$$\mathbf{J} = \mathbf{J}_o \sin(\omega t+\Phi). \qquad (2)$$

Two different in-plane vector current-densities will exhibit a phase difference that depends only on the angle between them. Alternatively, by writing the current density **J** as,

$$\mathbf{J} = J_o \sin(\omega t)\, \mathbf{j} + J_o \cos(\omega t)\, \mathbf{i}, \qquad (3)$$

where **i** and **j** are orthogonal unit-vectors in the plane of the test-piece, we see that **J** can also be viewed as a linear sheet-current density which *rotates* with an angular frequency ω. We refer to this as a multidirectional or rotating eddy-current density. MOI images using rotating eddy - current excitation in non-ferromagnetic conductors (e.g., aluminum) have been shown to be superior to similar images made with linear eddy-current excitation. However, *even with very large currents in the induction foil (300 Amperes) the associated in-plane magnetic fields are far weaker than those required to magnetize and saturate a ferromagnetic material (e.g., steel).* Consequently the conventional MOI is *incapable* of inspecting steel with these dynamical fields. However, in the following, we will show how much larger in-plane magnetization (in steel) can be achieved and also demonstrate how this magnetization can be made to *rotate* in the plane of the part.

Rotating In-Plane Magnetization in Steel

By analogy with rotating eddy-current excitation, which produces relatively weak rotating in-plane magnetic fields, the direct application of quadrature magnetic-fields to a ferromagnetic part should result in an in-plane rotating magnetization. And this should produce excellent quality magneto-optic flux-leakage type MOI images in steel. Out-of-plane magnetic anomalies should be imaged with the MOI by simply adjusting the magnetic-field bias applied to the magneto-optic sensor to produce the best image.

3.2 Experimental apparatus and preliminary experimental results

Before describing experimental results we will briefly describe the experimental apparatus used to obtain these results.

3.2.1 Quadrature magnetic-yokes

To accomplish rotating in-plane magnetization in steel, an orthogonal magnetic-yoke arrangement as illustrated schematically in Figures 1 and 2. The four-pronged yoke (see Figure 2) was designed to fit around the base of a magneto-optic imager of reduced size similar to the one illustrated in the drawing of Figure 1.

The special quadrature magnetic-yokes were constructed from a silicon-iron tape wound as a rectangular-shaped toroid on a mandril, and later machined to form the coil mounting posts or "poles" (see Figure 2). In this type of design the magnetic-flux direction is always parallel to the silicon-iron sheets, which significantly reduces eddy-current losses and heating of the yoke material during operation. Yokes were designed to be operated at low frequencies (e.g., 50 to 200 Hz). Higher frequencies are undesirable because they result in reduced flux-levels and weaker magnetic anomalies (i.e., poorer MOI images). Frequencies lower than 50 Hz make it difficult to rapidly scan yokes without leaving magnetic “tracks”. It should be noted that the driving frequency need not be high to achieve good flaw-resolution since flaw-resolution in ferromagnetic conductors (e.g., steel) is controlled by the *geometry* of the flaw and not by the *skin depth* as in nonferromagnetic conductors (e.g., aluminum). That is, flux is forced to stay very close to a flaw owing to the large magnetic permeability of the ferromagnetic material. This situation favors flux staying inside the material and only "leaking" out in the near vicinity of flaws.

Two coils were provided on each of two yoke "poles" as shown schematically in Figure 2. Each pair of coils was driven, in parallel, by a sinusoidal-voltage at 60 Hz for most of the experiments. In particular, one coil-pair was driven by a sine wave, while the other was driven by a cosine wave (i.e., one coil-pair was driven in-quadrature to the other). By analogy with Equations (2) and (3) we see that this results in a rotating in-plane magnetic "induction" **B** (or rotating in-plane magnetization **M**) inside the surface of a ferromagnetic conductor, or indeed any ferromagnetic material having any electrical conductivity. Owing to the nonlinear character of ferromagnetic materials (e.g., magnetic hysteresis-effects) the exact description of the magnetization would be considerably more complicated than we have indicated here. However, for the present purpose of keeping the description simple, the important thing to understand is that it rotates in the plane of the ferromagnetic part (e.g., steel).

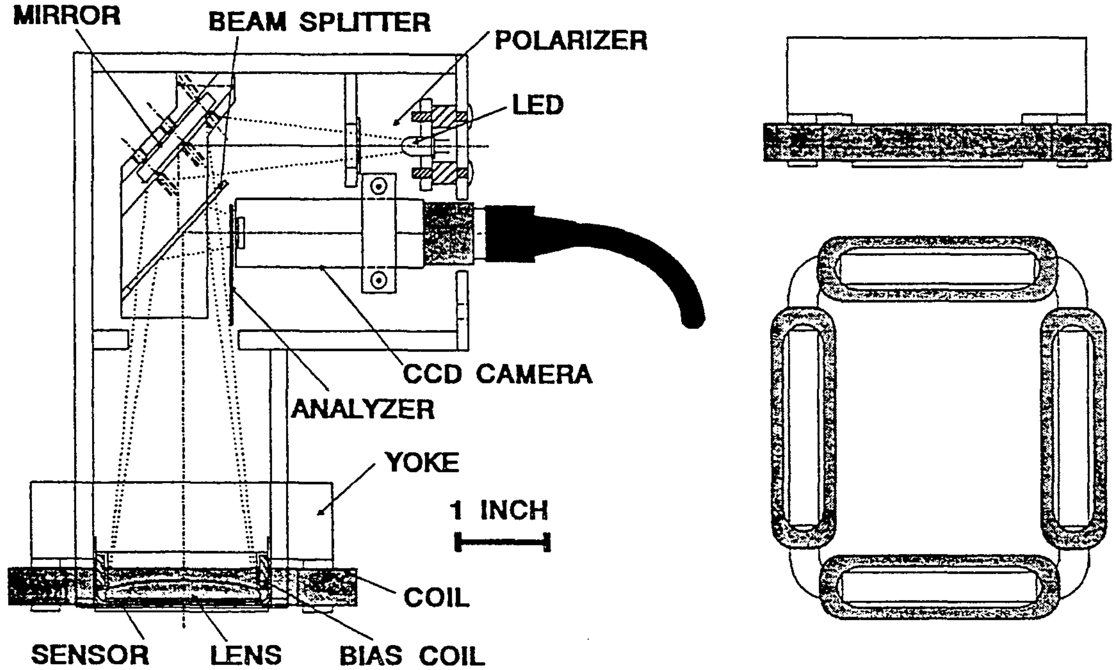


Figure 1. Conceptual design for a magneto-optic imaging system for both steel and aluminum. The system combines ; a magneto-optic/eddy current imager of reduced size; a "quadrature" magnetic-yoke for producing rotating in-plane magnetization, and a special dual-channel power supply (not shown) for driving the yoke coils (typically at 60 Hz). Images are captured by a CCD camera. Later in this report updated realizations of this basic concept will be illustrated.

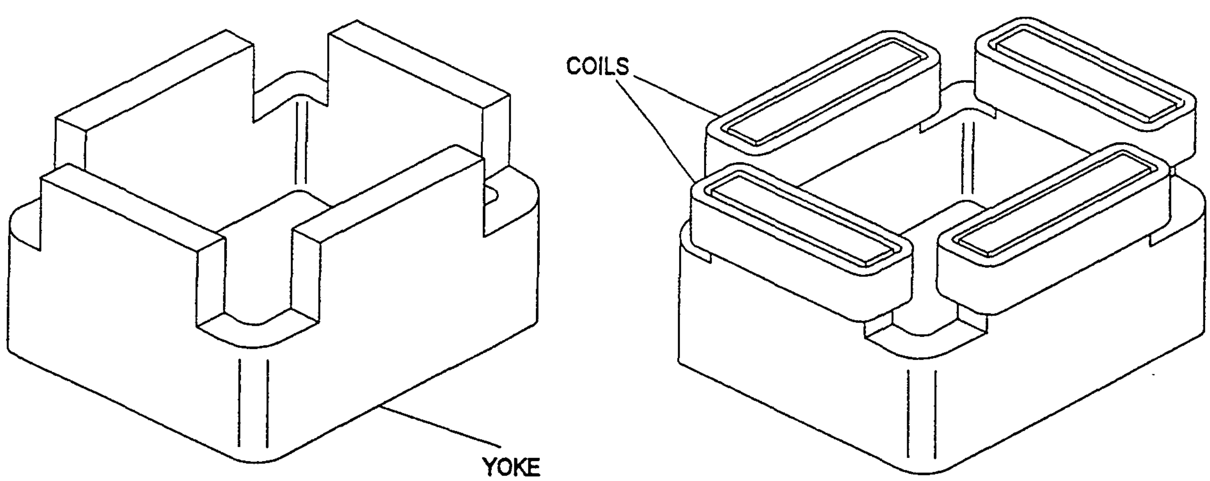


Figure 2. Four-pronged yoke (approximately 1/2 actual size) used to excite ferromagnetic parts (e.g., steel). In this case, the yoke was designed to accommodate a flat surface. However, curved surfaces can also be accommodated, if necessary, by machining the yoke-poles to conform to the surface being inspected. Later in this report yoke "shoes" and "shoe racks" designed to accommodate curved surfaces will be illustrated.

3.2.2 Power supplies

A number of different ways were explored to generate the quadrature sine/cosine signals required to drive a four-pronged yoke of the type illustrated in Figures 1 and 2. After careful consideration of various possibilities we chose to employ a power supply consisting of a dual-channel power amplifier driven by low amplitude sine, and cosine, input signals.

3.3 Preliminary (Prior to Phase I) MOI imaging experiments

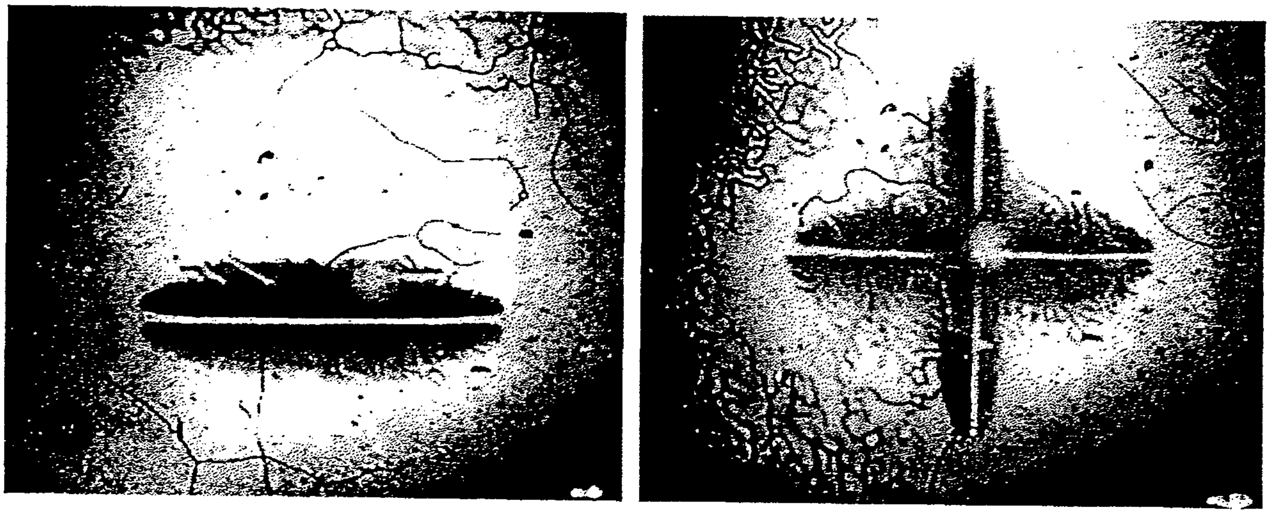
Using an experimental system conceptually-similar to that illustrated in Figure 1, typical images achieved using rotating in-plane magnetization are illustrated in Figures 3 and 4. Experiments were performed using quadrature magnetic-yokes machined to accommodate flat plates.

<u>Flat plates</u>

Using a four-pronged yoke designed to accommodate flat-plates, we demonstrated the feasibility of the new technique. Figure 3 illustrates results on a flat steel-plate containing synthetic crack-like defects. These results provide a dramatic illustration of how rotating, as opposed to unidirectional, in-plane excitation improves MOI images on steel.

A problem of practical significance for surface corrosion or crack inspections in steel, is the problem of liftoff (of magnetizing yokes) due to paint. Coatings such as paint increase the reluctance of the magnetic circuits (the yoke adjacent to a sample constitutes the magnetic circuit). The reluctance R is proportional to the liftoff distance D (paint thickness) and the cross-sectional area A of the yoke poles, i.e., $R = kD/A$, where k is an appropriate constant. Increased liftoff has two main effects on MOI images. First, owing to the increased reluctance, the magnetic-anomaly associated with a the corrosion or cracking will be reduced because there is less flux coupling to the material containing the flaw. Second, with increased liftoff, stray-flux escapes the region of the yoke poles and may interfere with the MOI images. Yoke-pole areas can be increased slightly if necessary to accommodate thicker than normal paint-layers.

A possible partial remedy for the problem of stray-flux is to employ mu-metal shielding of the sensor. With such shielding one easily images EDM-notch patterns through 0.060 inches of liftoff. This is remarkable since magnetic-particle inspections start to become difficult through paint coatings as thin as 0.003 inches.



a) "up-down" *b) Rotating*

Figure 3. MOI images of 0.5 inch-long EDM notches, in a "plus-sign" pattern, in a flat A-36 steel plate. In a) only the "up-down" arm of the quadrature magnetic-yoke was excited and in b) both arms of the yoke were excited (in quadrature) to produce rotating in-plane magnetization. Only half of the plus-sign is visible in a) whereas the entire pattern is visible in b).

Surface-corrosion in steel

Using a rotating in-plane magnetic field as described previously (see also Figure 3) a sample containing corrosion-like "pits" was imaged using the MOI. Figure 4. illustrates the result of this imaging experiment. Significant improvements in these images are to be expected when improved shielding, yokes with less reluctance, and improved, higher-contrast, optical-arrangements are implemented.

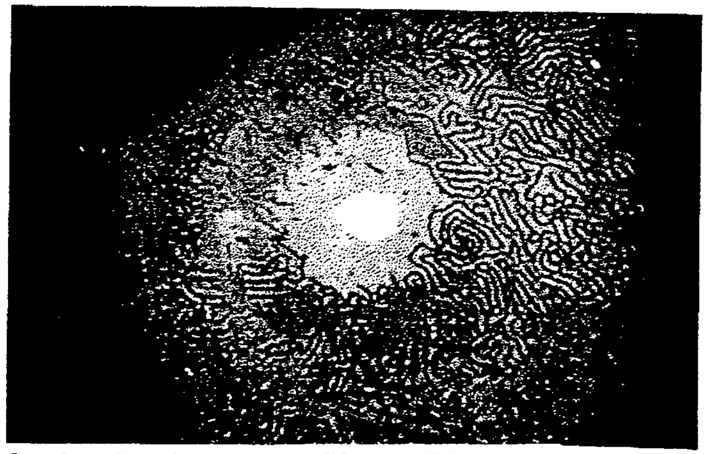


Figure 4. MOI image of a simulated corrosion-like "pit" in a 0.025 inch-thick plate of steel (probably A-36). The pit was produced by drilling a hole 0.25 inches in diameter by 1/8 inch deep into the plate surface. Note that the pit is clearly visible. Rotating in-plane magnetization was used and the frequency of excitation of the yoke-coils was 60 Hz. The image area shown is approximately 1.25 inches wide. Later in this report images of actual corrosion using the final laboratory Phase I prototype will be illustrated.

Surface-corrosion in aluminum

Using rotating in-plane eddy-current excitation as described in Sec. 3.1.2 (see also Figure 5) a sample of aluminum containing simulated corrosion-pits was imaged using the MOI. Figure 5 illustrates the result of this imaging experiment.

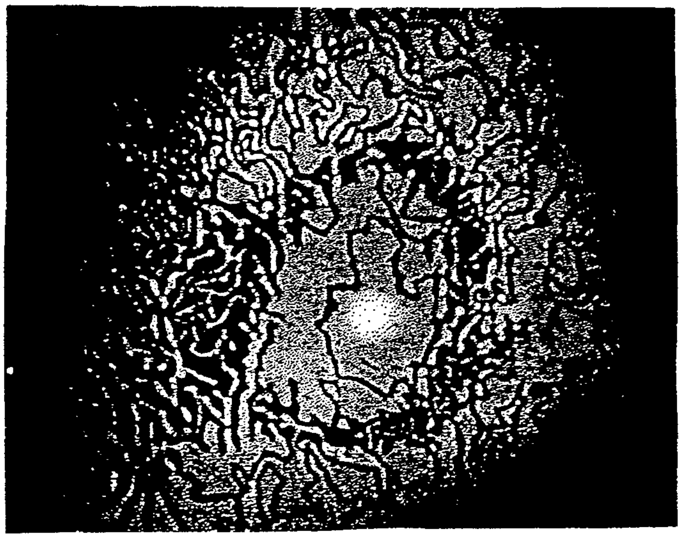


Figure 5. MOI image of a simulated corrosion-pit in aluminum. The pit (approximately 3/8 inch in diameter) was chemically-produced. The eddy-current excitation frequency was 40 Khz and the images area shown is approximately 1.25 inches wide. Later in this report recent images of more realistic chemically-produced corrosion will be presented.

3.4 Task Breakdown (as planned).

From the outset PRi did *not* intend to perform an exclusively "notional" study as suggested in the Phase I solicitation. From past experience we believed that the separate (existing at the time of the Phase I proposal) MOI-technologies that were to be integrated, were sufficiently advanced that the notional-designs we were to produce in Phase I would also be assembled (in Phase I) into a crude prototype, which would, nevertheless, be suitable for both laboratory and preliminary field-testing. We believed that this accelerated pace would put PRi in a better position for Phase II and subsequent Phase III commercialization. It has been our experience that commercialization is a longer-term effort than is typically imagined. Hence, any head-start we could make in Phase I would bring us just that much closer to being able to commercialize the technology and make it available for use by the U.S. Navy and others. The experience of the Phase I effort has confirmed this approach as the remainder of this Phase I final report amply demonstrates.

Task 1. System design (as planned). Design a portable battery-operated magneto-optic based NDI system for inspecting both (painted) steel and aluminum for surface corrosion. Initially, existing in-house experimental apparatus will be used to test ideas and improve designs. Design improvements will include better mu-metal magnetic-shielding of the magneto-optic sensor, magnetic yokes with reduced reluctance (and less leakage fields), an improved optical system for better image contrast.

As performed: This design was completed, and as described below, partially implemented in the form of a laboratory prototype. While this is not a contract deliverable (the "system design" is the principal Phase I deliverable), it is suitable for demonstration purposes as demonstrated by our recent (January 16, 1998) field trip to the Puget Sound Naval Ship yard (see Task 6b below).

As mentioned a prototype power supply has been designed, built and tested. This power supply provides the excitation for the magnetic yokes used in imaging steel parts. The power supply consists of a sine/cosine generator that provides a pair of 60 HZ signals, 90 degrees out of phase, i.e. , a sine wave and a cosine wave. These signals are buffered and amplified by a pair of OP-Amps that are capable of driving the yoke coils up to 48 volts peak to peak at 5 Amps. Controls are built into the power unit to switch the power (to the yoke coils) on-and-off remotely from a hand-held imager. Drawing 218201 (see Appendix A) shows a tentative block-diagram of the complete inspection system (for steel and aluminum). The eddy current portion of the system (see discussion below) will involve an adaptation of the standard (commercially available) MOI 303 Magneto-Optic/ Eddy Current Imager. Eddy current excitation will be employed *only* when aluminum or other non-ferromagnetic conductors are being inspected. When steel is being inspected the magnetic yokes described above will be used. Both the yokes and the eddy-current excitation devices will be interchangeable

Task 2. Battery-pack (as planned). Design, construct and test a battery-pack suitable for powering the system described in Task 1. The power pack will consist of a rechargeable-battery capable of operating the MOI system for up to 8 hours, with a recharge-time of about 16 hours. The battery will power, and be recharged by a single charger/inverter unit. The inverter will be capable of supplying 400 watts of power. The estimated power consumption of the system is 250 watts. The battery, charger/inverter, and control chassis, will be mounted on a portable hand-truck type cart for ease-of-transporting in a shipboard environment.

As performed: The battery pack described above was constructed and performed better than anticipated (see Figure 6 below). Note that the description below constitutes part of the "system design" that is the principal Phase I "deliverable."

The battery is an Exide "Mega Torque Nautilus Gold" deep-cycle battery. It is installed on a Dayton 3W153B hand-truck with pneumatic tires. A steel enclosure was fabricated and installed on the hand truck as well. It holds the charger and inverter. The charger is an exide "Mega Cell" automatic charger. The inverter is a Statpower "Prowatt 250" 12 Volt DC to 120 Volt AC 250 Watt inverter. The front panel of the enclosure contains switches and two meters. One of the switches is the power switch for the charger. The other switch selects the charge mode or inverter mode to the battery. A 0-15 Volt meter monitors the battery voltage and a 0-10-Amp meter monitors the battery output current. A separate meter on the charger monitors the charging current, when it is in the charge mode. The system was tested at an optimum power consumption and ran for 16 hours on a single charge.

Task 3. System production and integration. (as planned). Construct the system described under Task 1.

As performed (see Figures 7 through 11): Note that the following drawings and associated written descriptions (including photographic illustrations) constitute part of the "system design," which is the principal Phase I "deliverable." -- A prototype system has been constructed and tested, to work with the battery-pack described under Task 2. It also will obviously work by plugging it into any 110 VAC source for laboratory use. The system is referred to as the MOI-211 Magneto-Optic Imager (Roto-Mag). Drawing 216107 (See Appendix A) is the system diagram. Its power source is a ± 24Volt 1.5A switching power supply which provides the power for the Roto-Mag coils as well as system power. System power is derived by using voltage regulators on the power board (see drawing 218303 in Appendix A). The system consists of three main printed circuit boards, the Roto-Mag Control board (RMC 304), the Roto-Mag Power board (MP 304), and the Bias board (Bias 304), each of which are described below. A dual concentric potentiometer (R108, 109) controls the power level of the coil excitation. A rotary switch (SW1A, B) selects one direction or the other or both as well as off.

The imager is a small vertical hand held device about the size of an electric shaver. It contains a 1-¼ by 1-½ inch magneto optic sensor which is in close proximity to the bias coil. The bias level is controlled by two push-button switches located on the front of the imager. These switches feed down the main cable to the bias board which generates the bias level and erase pulse which refreshes the image 30 times a second. This bias signal is sent back down the cable to the bias coil. An electro-luminescent panel (ELP) provides the illumination for the sensor. The imager also contains an Elmo MN401X camera head which connects to its camera control unit (CCU), located in the power unit. A 5 pin connector located on the top of the imager provides power to the ELP as well as the bias controls and bias current.

The yoke assembly contains the magnetic core, described elsewhere as well as the 4 coils which induce the rotating magnetic field. The assembly is housed in a Delrin shroud which gives it some aesthetics as well as providing protection for the coils. A junction box is attached to the back of the yoke shroud. This houses three connectors and a push-button switch. A 10 pin Lemo 3B connector is for the main cable from the power unit. A 5 pin Lemo 0B connector is for the short cable that connects to the top of the imager. A smaller 5 pin Lemo 00B connector is for the Personal Vision System (PVS) worn by the user. The push-button is to enable and disable the magnetic excitation current. The coils are hard wired into the 10 pin connector. Attached to the four legs of the yoke are removable shoes made of a material of high permeability, called "Ledloy". These are made to be removed so that different sets can be attached to accommodate flat steel or pipe of various diameters.

Drawing 218302 (see Appendix A) is a schematic of the ROTO-MAG control board, RMC304. U101 is a Thaler SWR300 sine/cosine generator. It is configured to generate a sine wave and a cosine wave at 60Hz. C104 through C108 are calculated to provide this frequency. The push-button switch on the yoke connector box, grounds the normally high input to U103, a one-shot switch "debounce" circuit that toggles flip-flop U104A which operates K101, a reed relay as well as turn on an LED on the front panel. Depressing the switch a second time will toggle the flip-flop again turning off K101. When K101 is turned on, the outputs of the sine/cosine generator are connected to the input of a pair of op amps (U105, 106)which drive the power amplifiers.

Drawing 218303 (see Appendix A) is a schematic of the ROTO-MAG power board MP304. It contains the two Apex PA01 power op amps. The 1K and 3K resistors determine the gain of the amplifier. The .12 ohm resistors are current-limiters. The voltage regulators are also located on this board. These are used to convert the ± 24 volt DC from the main power supply to ± 15 VDC, ± 12 VDC and +5 VDC used throughout the system. The board is attached to the back panel which has a heat sink attached to it, to dissipate the heat generated by the power components.

Drawing 218301 (see Appendix A) is a schematic of the Bias Board, BIAS304. U1 is a Motorola 68HC711D3 microprocessor which is programmed to generate the timing for the erase pulse as well as the bias level. The default rate is approximately 38ms duration between pulses. A sync input is used in some applications where the erase pulse needs to synchronize with an external source such as the eddy current excitation as used in the MOI303 and 304. In this application a sync pulse is derived from the sine wave to synchronize the bias erase pulse with every other sine wave. This is to reduce flicker in the image. U5 is a DAC08 which generates the variable bias level which is summed with the erase pulse at the input of U7. This drives an LT1010 which drives the bias coil. The input port of the microprocessor accepts levels from the up/down switches in the imager to control the bias level as well as jumpers on the board which control the pulse width. While not a problem for ROTO-MAG applications it is sometimes necessary to adjust the pulse width for optimum operation in eddy current applications. Also located on the board are three video buffers (U9A,B,C). These take the video signal from the CCU and distributes it to the PVS, a monitor output, and an optional LCD monitor output The inverter on the board is used to power the ELP light source in the imager.

Task 4. Prepare and acquire surface-corrosion samples (as planned). Prepare and acquire surface-corrosion samples for both aluminum and steel. Samples will be prepared by PRi and, if available, Navy samples will also be used. These samples will be used to test and improve the system prior to field tests.

As performed: Two types of samples were prepared—steel and aluminum. The steel corrosion samples consisted of two chemically-corroded steel plates (approximately 2 ft by 2 ft by 3/8 inch thick) exhibiting "pitting" corrosion on one side. On one plate, the corrosion in a portion of the plate was covered with a layer of ship-gray epoxy to mimic a protective paint layer and obscure the underlying corrosion. A second corroded steel plate was partially machined to remove the corrosion so that a comparison between corroded and non corroded images could be made. Aluminum samples previously prepared for inspection of aircraft corrosion consisted of a machined region simulating corrosion. Specifically, spherical segments were machined from one side of an aluminum plate at depths of 10%, 20%, 30% and 40% of the plate thickness, which in this case was 0.060 inches. Images (see Task 5 below) of the steel plates were made using rotating and linear magnetic-field excitation in addition to static magnetization, while images of the aluminum plate were made using rotating eddy-current excitation. In each case, the simulated corrosion was on the side of the plate nearest the imager. This mimics the situation where corrosion under paint is being examined.

Task 5. Laboratory experiments (as planned). Demonstrate that the system constructed under Task 3 is capable of detecting surface-corrosion on the samples described under Task 4 .

As performed: Numerous experiments with the rotating or linear magnetic-excitation showed that the corrosion on the steel plates described above (Task 4.0) could be detected in this way, but the resulting images tended to be localized at the center of the image area. A much better way to image corrosion on steel was simply to magnetize the steel with a rod-type magnet (0.5 by 0.5 by 6.0 inches poled along one of the short dimensions. This is accomplished by simply dragging the magnet along the surface to be inspected. Then the imager is used to form the image with the magnetic-field excitation turned off. Images produced in this way are an excellent way to detect the corrosion (See Figure 12). When eddy current excitation is employed aluminum corrosion is also easily detected as illustrated in Figure 13.

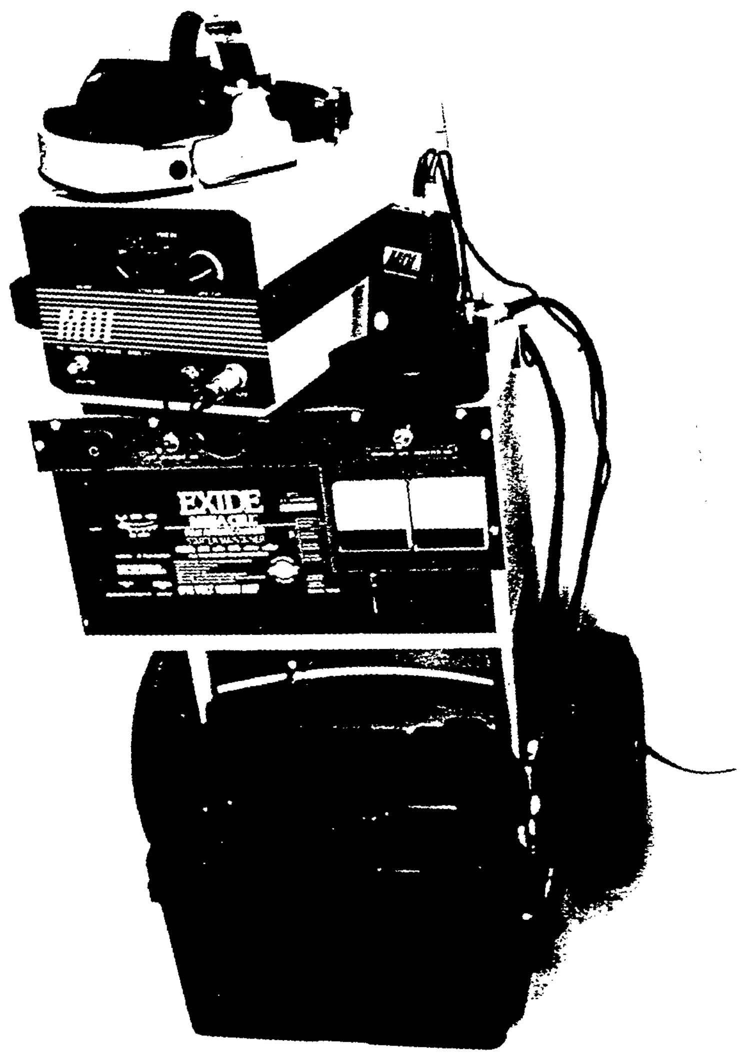


Figure 6. The portable battery-powered power supply developed under Task 2 is illustrated. This system has sufficient capacity to operate the system for up to 16 hours continuously.

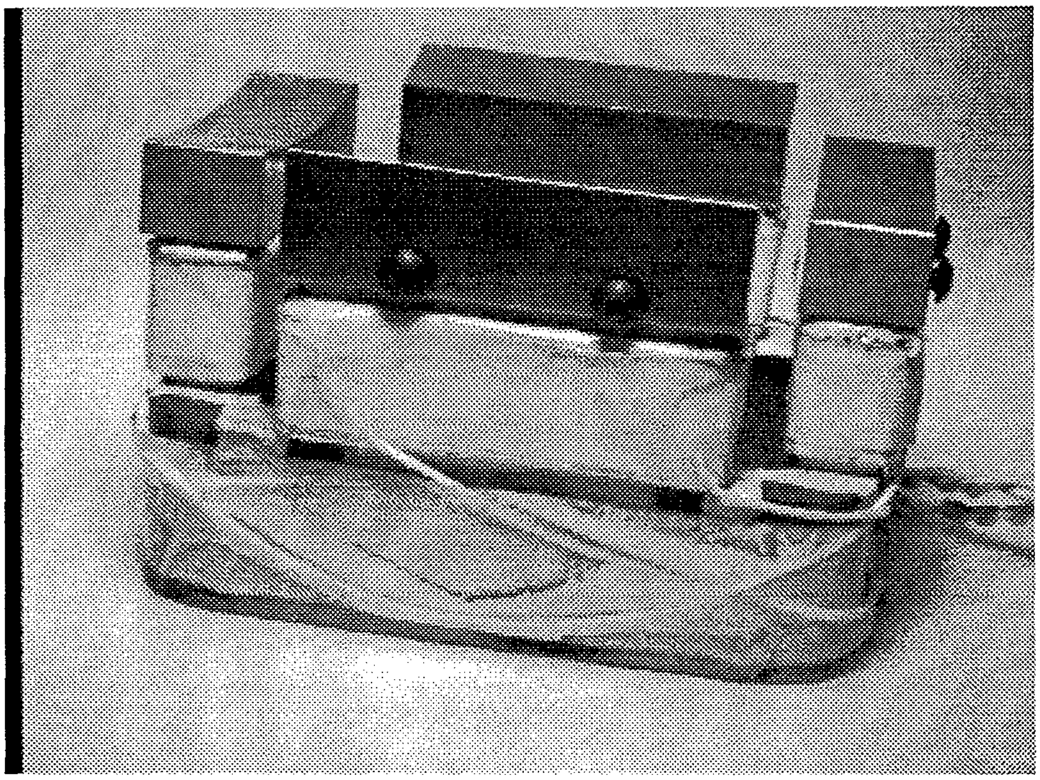


Figure 7. Magnetic yoke-core showing coils, yoke material and yoke "shoes." These shoes are designed to accommodate non-flat surfaces. Currently, a smaller, lighter, yoke is being manufactured along with a flexible-frame "shoe-rack" for easier installation of the shoes (see Figure 8 through 11 below).

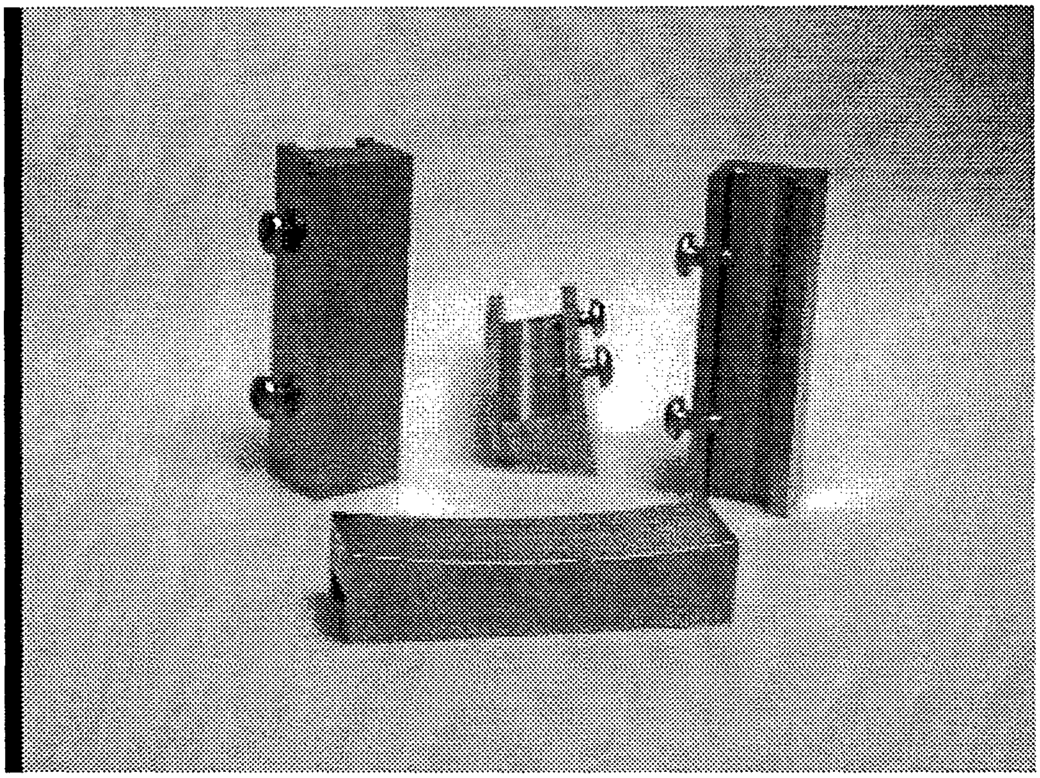


Figure 8. Machined "shoes" designed to accommodate surfaces having a curved shape—in this case a 12.75 inch diameter pipe. We are currently manufacturing what we call a "shoe rack," (see Figure 9 below) which is an assembly that contains all four shoes in a flexible frame. This frame is designed to be attached to the four-pole yoke core as a single unit, instead of having to attach each shoe one at time. Thus shoe-racks for different applications can, in principle, be prepared ahead of time and used repeatedly to perform inspections on "identical" parts, which they were designed to fit.

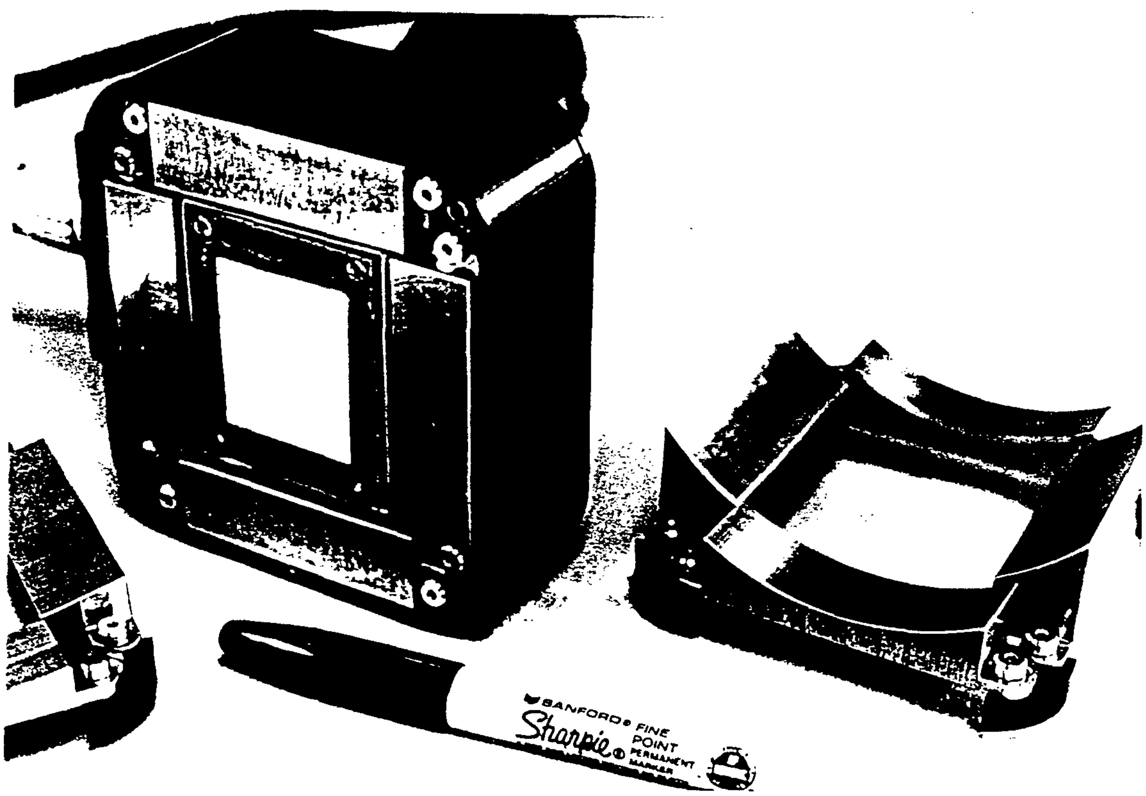


Figure 9. In this latest design (January 1998) individual yoke "shoes" are attached together in a flexible frame we call a "shoe rack" that can be easily attached or removed from the yoke poles. Shoe racks shown here are designed to accommodate pipes having an outside diameter of 12.75 inches or 4.5 inches.

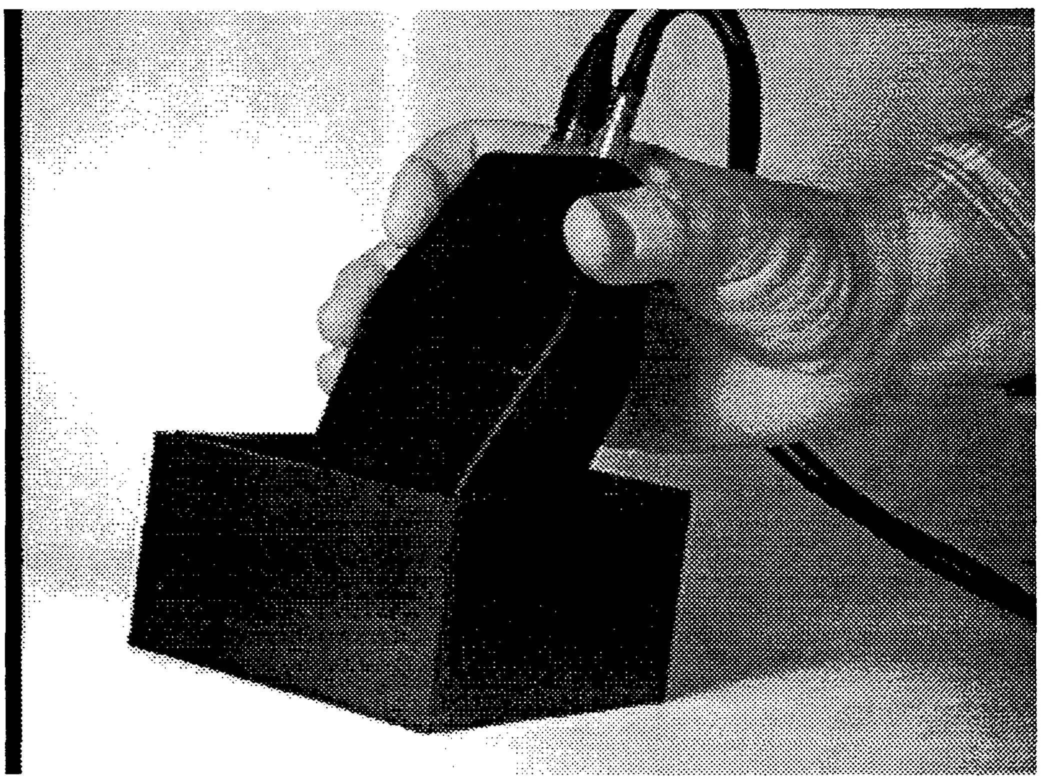


Figure 10. Earlier design for a yoke with protective shroud and imager of reduced-size nested in the yoke core. The final design (see Figure 11 below) involves a smaller yoke and shroud. We are also currently producing a design that involves a "right-angle" version of the imager (see Figure 1b in the attached ASNT paper—Appendix B).

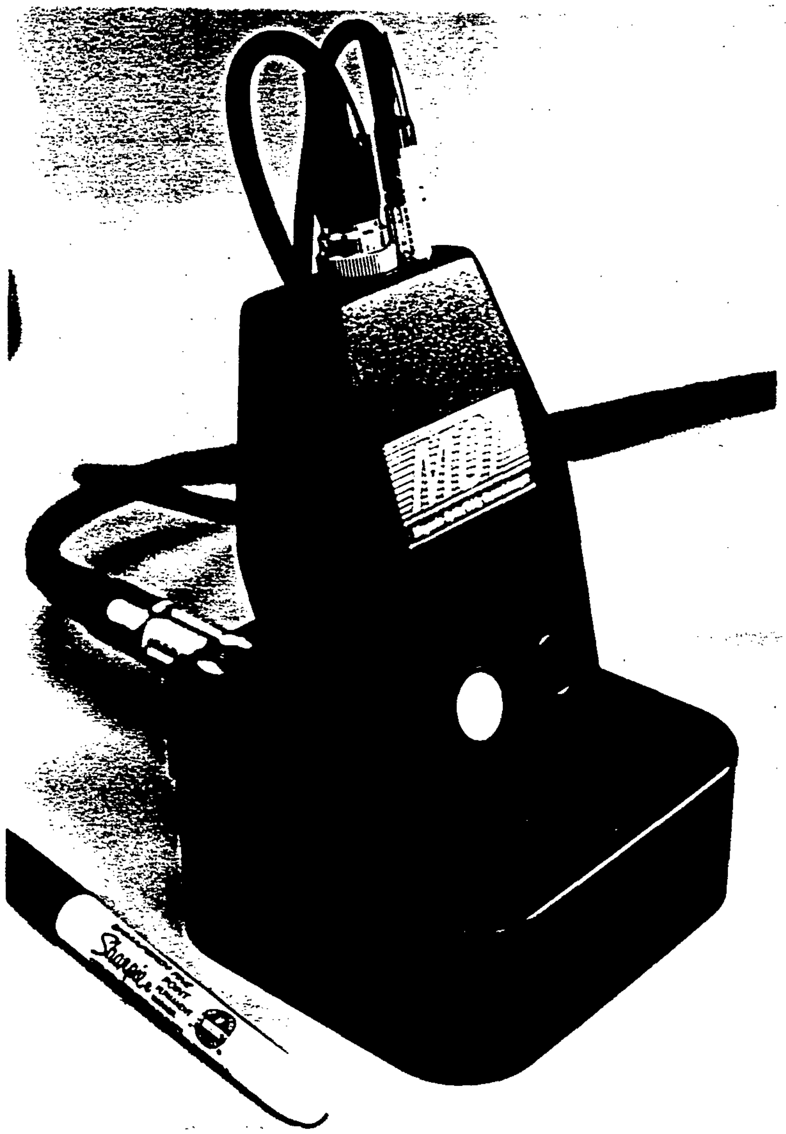


Figure 11. This is the latest design (January 1998) for a vertical-type imager with a protective shroud covering yoke coils. The "shoe" rack (not visible) is nestled inside the shroud. The two "buttons" on the "front" of the imager housing are used to adjust the sensor bias. A third button located near the cable connector on the back of the yoke (not shown in this view), enables the yoke power. This feature is necessary to insure that the yoke can easily be removed from the surface being inspected.

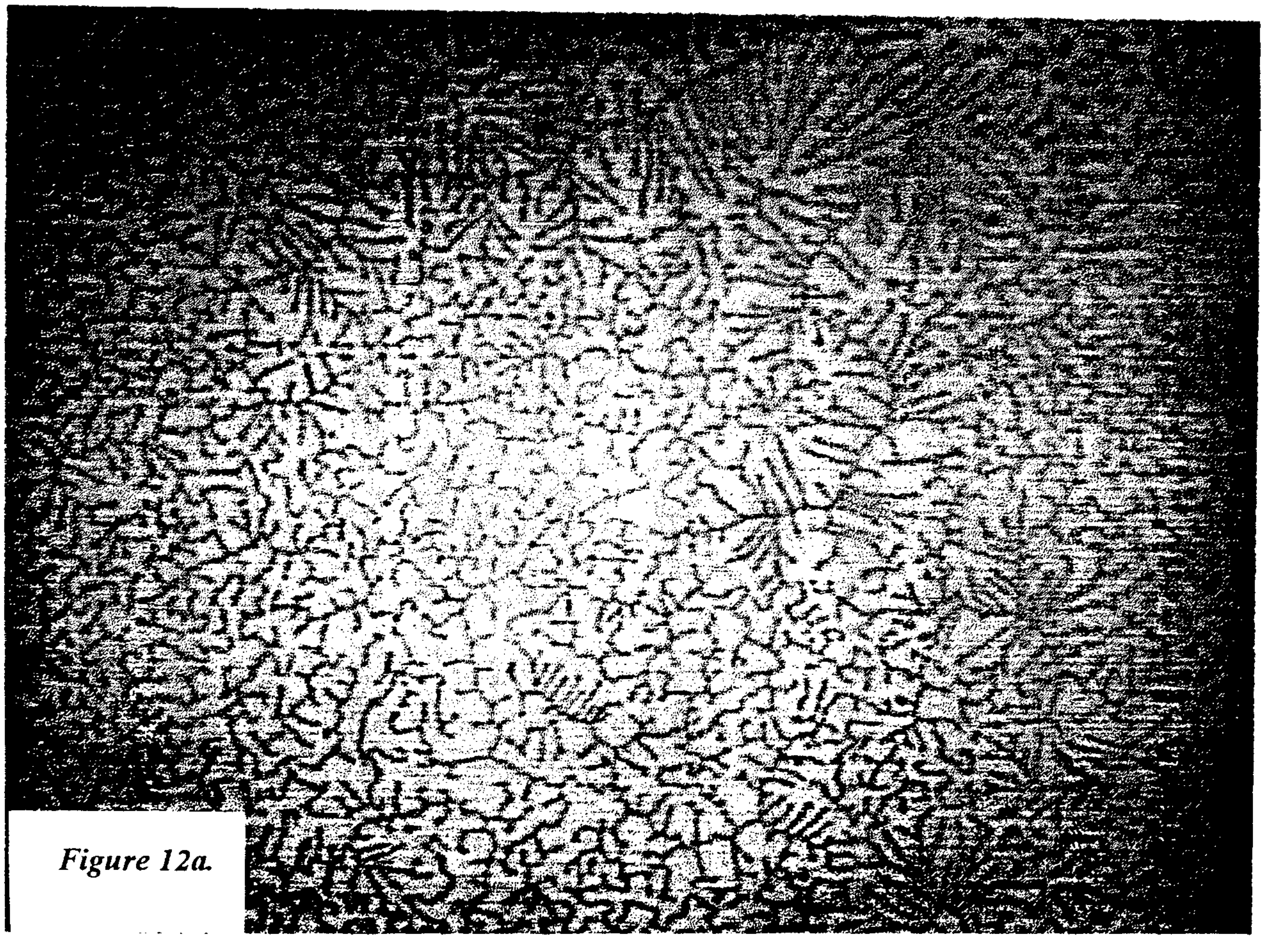


Figure 12a.

Figure 12. MOI images of chemically-corroded steel plates. In a) is the image of a region of a plate that is machined to remove the corrosion and in b) is the image for the same condition of MOI bias setting and state of plate magnetization. Note that the circular area in the lower right-hand corner of this image is a 0.25 inch diameter machined "pit" (approximately 1/16 inch deep) used as a control. Chemically-corroded areas are easily detected in b), as evidenced both by the image of the control "pit," and by the conspicuous absence of any corrosion indications on the machined plate. The image area in all cases measures approximately 1.25 inches by 1.5 inches.

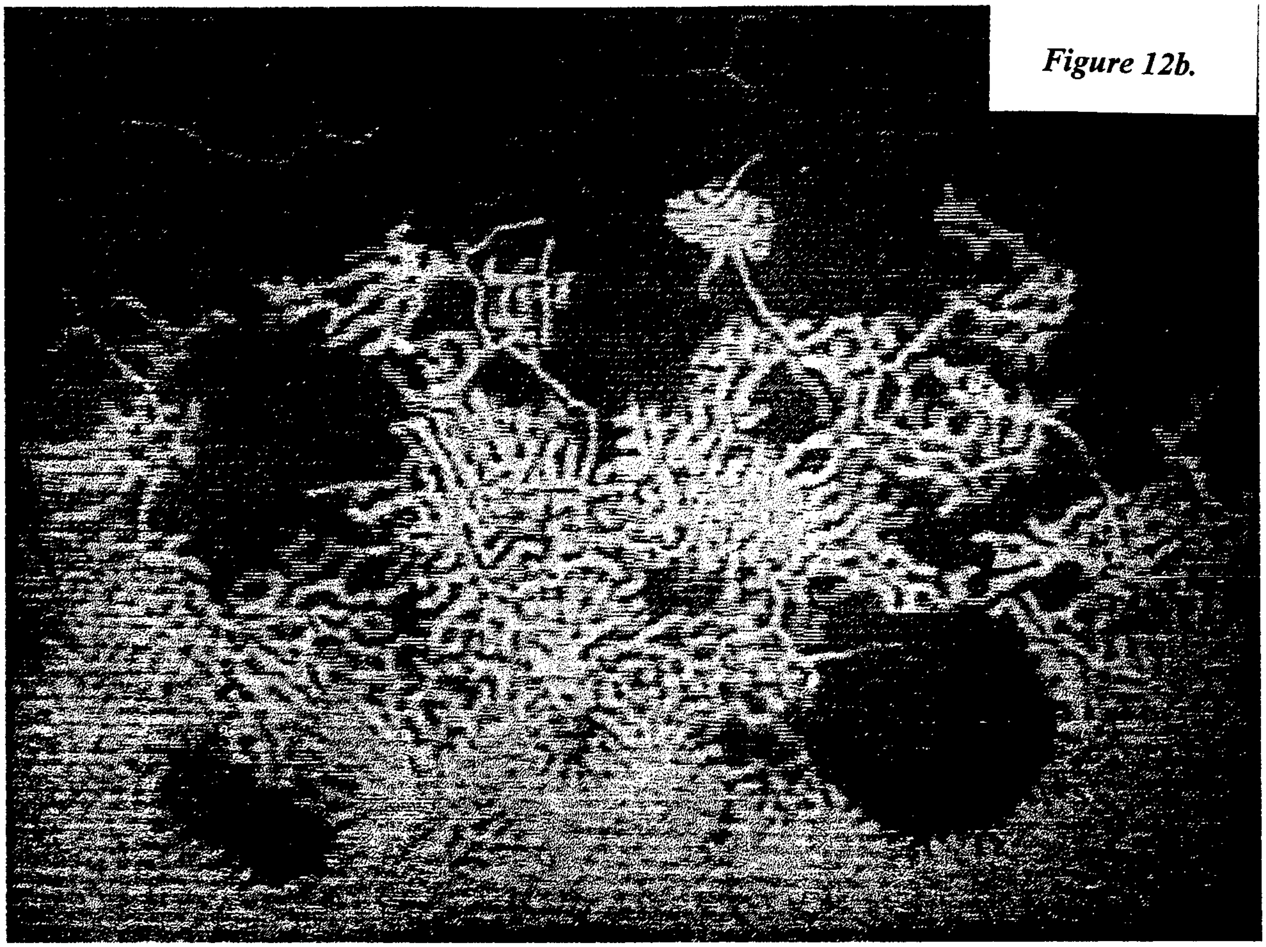


Figure 12b.

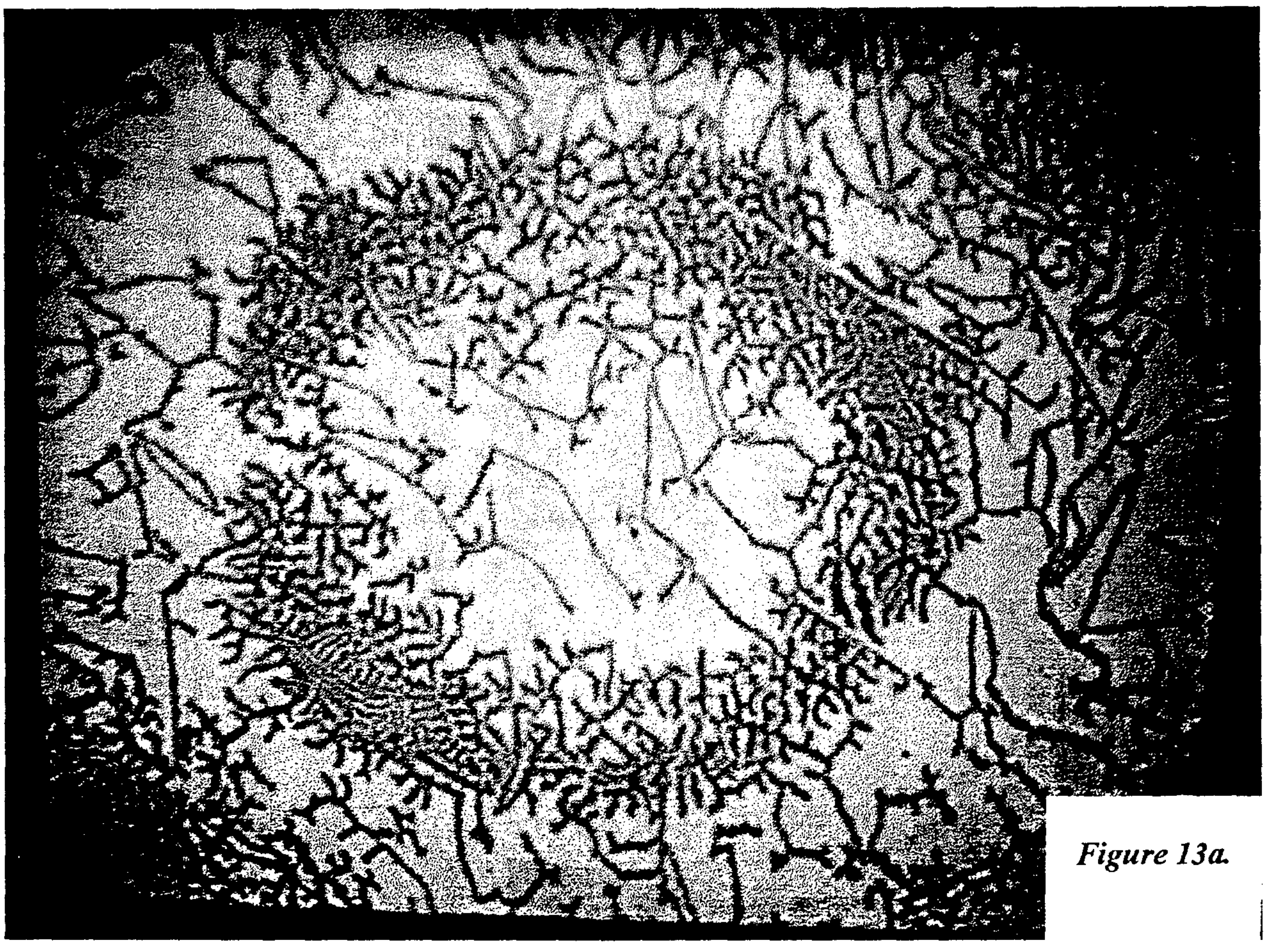


Figure 13a.

Figure 13. ***MOI images of corrosion on aluminum plates.*** *The image in a) is of a region of an aluminum plate* ***0.060 inches thick exhibiting 10%*** *simulated corrosion in the form of a sperical "dome"* ***segment (0.75 inches in diameter)*** *machined in the aluminum.* ***In b) is an*** *image of 6.7 %* ***chemically-produced corrosion*** *in an aluminum plate 0.09 inches thick.* ***In*** *both cases the corrosion was easily* ***detected and imaged*** *using an excitation frequency of* ***50*** *KHz. The image area* ***in all cases measures*** *approximately 1.25 by 1.5 inches.*

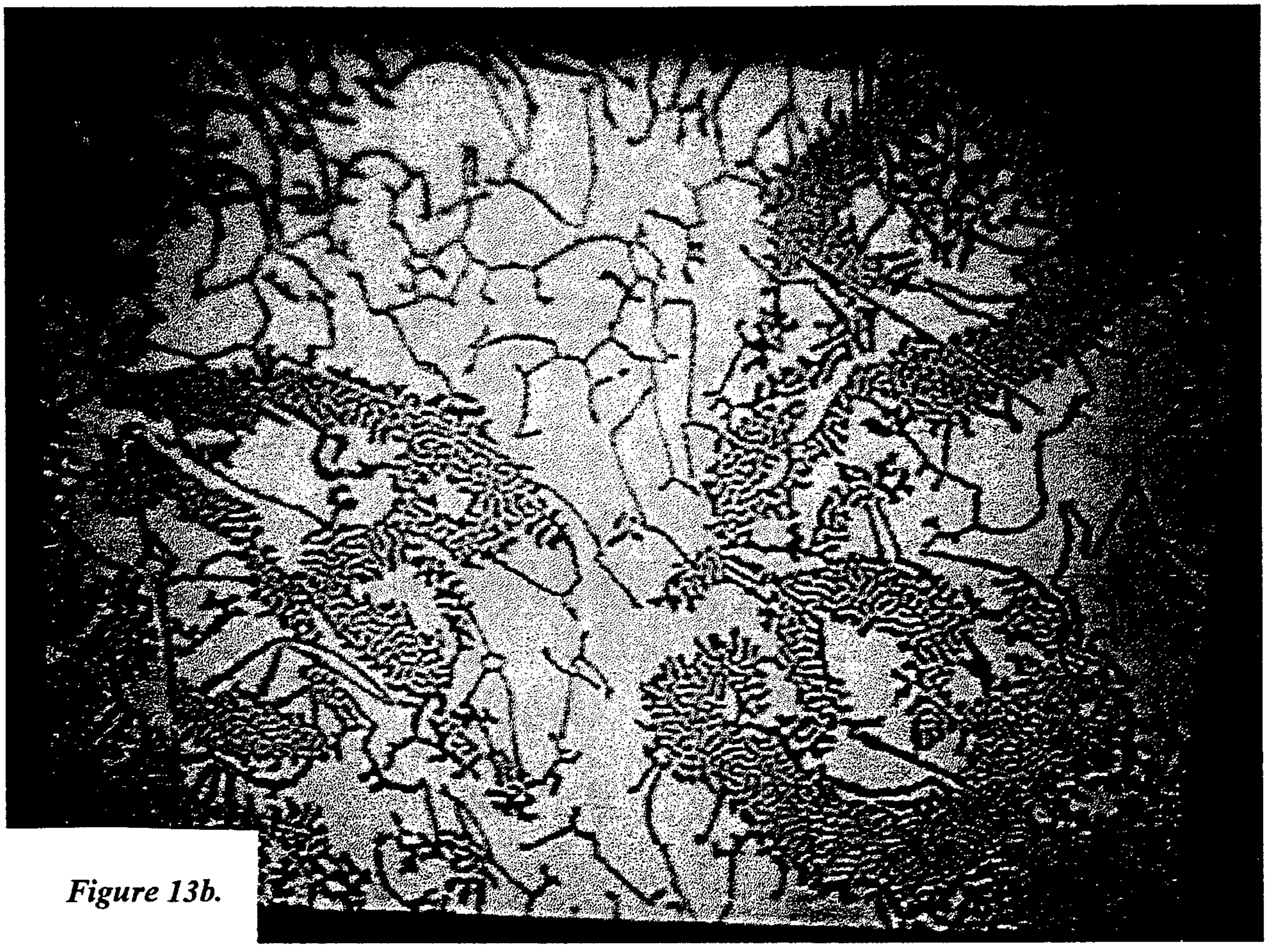


Figure 13b.

Several conclusions can be drawn from these experiments. First, it is clear that MOI-based imaging holds considerable promise for detecting corrosion under paint on both steel and aluminum. For example, while we have not quantified the capabilities for detecting corrosion in steel (this should be a Phase II task) images are excellent for levels of "pitting" corrosion that are expected to be representative of actual shipboard conditions. Second, while it is possible to do so, it is unnecessary to employ magnetic-field excitation when inspecting steel for corrosion under paint. Static field methods produce excellent corrosion images as noted above. The second conclusion means that magnetic-field excitation is probably better suited to applications involving the detection of surface-breaking cracks (e.g., cracks in propulsion shafts as described below under Task 6b). As an example of just how well the technology works on cracks, consider the MOI image (illustrated in Figure 14).

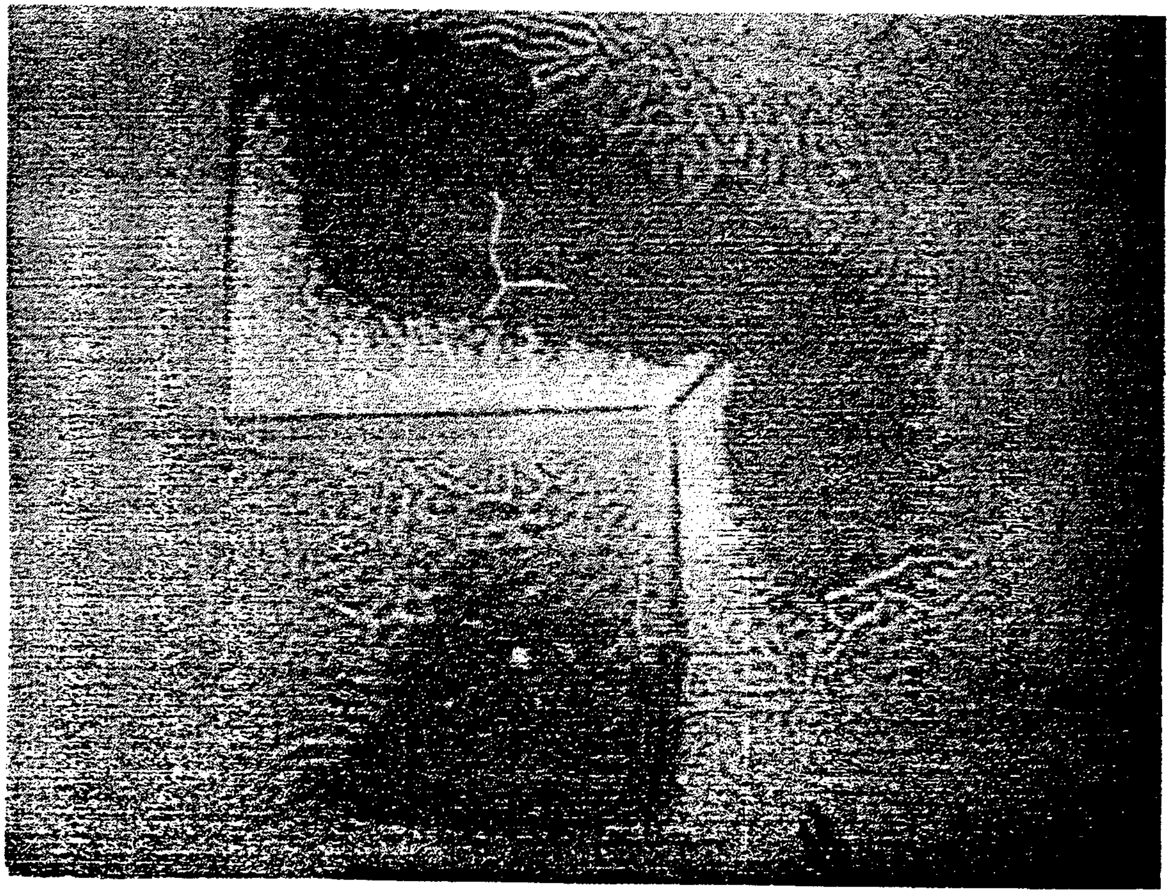


Figure 14. An MOI image made on a 4.5 inch-diameter steel-pipe specimen containing a 3/32 inch-long EDM corner notch (seen here at 45 degrees to the horizontal). In fact, notches as small as 1/32 of an inch in length--half the 1/16 inch length requirement of typical MPI inspections routinely performed on ship propulsion-shafts (see Task 6b below)-- are easily detected on a 4.5 inch diameter pipe. To accomplish this imaging, the quadrature magnetic-yoke was fitted with machined "shoes" that accommodated the pipe surface, thereby, allowing magnetic-flux to couple efficiently to the pipe material. The yoke was operated at 60 Hz in the "rotating" magnetic-field excitation mode.

Situations where the radius-of-curvature of the surface being inspected is greater than 4.5/2 inches will be much easier to image since the required "shoes" will, necessarily, contain less material (less reluctance) and the stray magnetic-fields that can spoil an image, and which are experimentally observed to result from highly curved surfaces (e.g., 4.5/2 inches), are greatly reduced. Therefore, such things as propulsion shafts with radii-of-curvatures some seven times larger (e.g., 33/2 inches) should be relatively easy to inspect using MOI technology (see Task 6b below).

Task 6. Perform preliminary field-tests (as planned). Working with the U. S. Navy we will arrange to perform shipboard-tests at the Navy shipyards in Bremerton, Washington. The purpose of these Phase I tests will be to establish inspection-parameters, identify the actual field problem(s), examine actual surface-corrosion on steel surfaces and, if possible, aluminum surfaces, as well. These tests will be designed to answer the following questions: Does the system detect surface-corrosion on steel and aluminum under paint? How is the detection effected by paint thickness? Are there opportunities for improving the system that should be implemented in later phases of the program? What are the human-factors issues surrounding the use of the system? For example, is the hand-truck concept (carries the battery-pack and other electronics) suitable for shipboard use? Is the personal-viewing-system acceptable under the expected outdoor-lighting (sunlight) conditions? What would be required of a field-hardened system (e.g., waterproofing)?

As performed: From the outset of the Phase I program, PRi indicated its desire to examine shipboard situations
where corrosion and other inspection problems actually arise. It was felt that this early exposure to real problems and inspection needs would help direct the subsequent development of the technology. Accordingly, during the course of the Phase I research and development, we made two trips to the Puget Sound Naval Shipyard in Bremerton, Washington.

Subtask 6a. First Fact-Finding Trip

After discussions with Kirk Jenne, Naval Undersea Warfare Center (NUWC) technical project-monitor for Phase I, and Gunnar Watson the Director of the Naval Inactive Ships Maintainence Facility (NISMF) at the Puget Sound Naval Shipyards (PSNS), Building 550, 2450 Wycoff Way, Bremerton, WA 98314-5250 (Telephone: 360-476-3551)-- it was decided that a fact-finding trip to the shipyard should be arranged. Permission was granted on June 18, 1997 for a trip on July 8, 1997. The purpose of this trip (and future trips to Bremerton) was:

1) To assess real corrosion problems by visually inspecting shipboard examples of actual corrosion 2) To discuss these matters with knowledgeable personnel at the Bremerton facility 3) To eventually test equipment built under this project in a shipboard-setting on actual corrosion 4) To hold a formal demonstration (near the end of the Phase I program) of the new inspection technology for interested Navy personnel from both the Bremerton facility and the Naval Undersea Warfare Center--Rhode Island (e.g., Kirk Jenne) 5) After successfully demonstrating the feasibility of the new inspection technology, to determine the characteristics of a field-hardened system. This will be accomplished by surveying the opinions of potential end-users such

as NISMF personnel. This information will be used to design the final field-hardened system prior to production of commercially available systems.

PRi personnel in attendance were: G. L. Fitzpatrick and R. L. Skaugset. PRi personnel met with Harry Ehlert and several other persons from the Quality Assurance department of NISMF. We first discussed the magneto-optic imaging technology in a conference- room setting and then were given a brief tour of the battleship Missouri. Areas where corrosion under paint is a common problem were pointed out and discussed. The bulk of the inspection problems we observed involved steel components. However, we also stepped aboard an adjacent frigate that had a considerable amount of aluminum superstructure.

While the trip was informative, it soon became clear that the problems of the Naval Inactive Ships Maintenance Facility are less pressing and diverse than those of the Active Ship Maintenance Facilities. Accordingly, we began planning to visit the Quality Assurance Facilities associated with Active Ships at Bremerton (Code 135.1).

Subtask 6b. Demonstrations and Discussion at the PSNS in Bremerton, Washington.

On January 16, 1998 PRi personnel met with personnel of the PSNS (Code 135.1). The purpose of this visit was to acquaint Navy-personnel at the PSNS with the Navy-developed MOI-based technology and also demonstrate a working laboratory-prototype. A second purpose was to determine what the inspection applications at the PSNS are, and determine to what extent the technology in question can address these areas in addition to the original Phase I applications associated with corrosion or cracking under paint or other protective coatings.

In attendance were PSNS (Code 135.1) personnel: Valerie Baur (Branch Head of Technical Support Section), Kenton E. Donn (Quality Assurance Specialist), Bill Robbins (Test Examiner Level III), Ron Rude (Instructor), Mark Ranstrom (Instructor) and Jerry Becker (Maintenance Mechanic). PRi personnel in attendance were: Gerald L. Fitzpatrick (Senior Research Scientist) and Richard L. Skaugset (Senior Engineer).

PRi personnel demonstrated the instrument (illustrated in Figure 1a in the attached ASNT preprint—see Appendix B) in a conference-room setting. We explained how the system works (technical papers on the MOI-technology were also sent PSNS Code 135.1 personnel in advance of the meeting). We demonstrated how the system detects cracks of any in-plane orientation, and we further demonstrated the ability of the system to accommodate non-flat surfaces such as pipes. We discussed how this technology might eventually replace conventional MPI for certain inspections. After the demonstrations, PRi personnel were given a tour of the facility by Valerie Baur, K. E. Donn and several other PSNS personnel. Three inspection applications were identified that we believe the current technology can successfully address in a short time. These are:

a) Inspection of steel propulsion shafts. Currently these shafts undergo 100% examination using conventional MPI—a hand-held magnetic-yoke and conventional (dry) magnetic-particle dispersal methods. Shafts are typically 33 inches in diameter and are usually covered by a fiberglass layer for corrosion protection. While MPI cannot be done with this protective coating in place, it is typically removed because of degradation and at that time MPI is done. The inspection procedure involves a coordinate grid ("mesh" size estimated to be 8 inches by 8 inches), which is first drawn by hand on the exposed propulsion shaft. A conventional (horseshoe-type) magnetic-yoke is then used in the standard way to search for cracks (1/16 inch or longer) in each of the grid "squares."

The simple geometry of this part (cylinder) makes it an ideal candidate for inspection using our MOI-based hardware (see Figure 14 above). Basically, all that we would have to do is machine yoke "shoes" to accommodate the surface of the propulsion shaft. Inspection designed to test the system against MPI or other techniques could then proceed.

b) Air-flask and air-tank inspections. We observed 18-inch diameter air-flasks that are also inspected by MPI. This geometry also lends itself naturally to MOI-based inspections. We did not observe the air tanks, but if their geometry is well-behaved (cylindrical) they too could be inspected using MOI-based technology.

c) Corrosion under copper-nickel sleeve. Because the MOI-technology is insensitive to liftoff, or more correctly, liftoff can be compensated for by building a yoke with larger pole-area, it should be possible to detect certain kinds of defects below protective layers. We were told that in some cases 5/16 inch-thick copper-nickel is used as a protective coating on steel propulsion shafts. We were asked (by Scott Roberts) if we could detect corrosion in the steel under this protective layer. As our experience with MOI-based inspections in a project for the Department of Energy have shown, it is possible to detect cracks under layers of stainless steel up to 1/8 inch thick (see attached ASNT paper Figure 7). Depending on the amount and type of corrosion (e.g., "pitting") this experience suggests that there are reasons for thinking that the MOI-based technology (in some form) could make contribution to inspection of this kind as well.

d) Weld inspections. Under the right conditions MOI-based inspection technology should be able to inspect some welds. Basically, yoke "shoes" with a "tunnel" to accommodate the raised weld would have to be machined for each weld type. This will limit applications to similar welds--the most important parameter being weld width. For flush or ground welds the weld inspection would be much easier, since only the surface shape, which contains the weld would have to be accommodated by yoke "shoes."

Task 7. Reporting (as planned).

PRi will prepare and distribute a Phase I final report and any interim-reports that may be required by the contract. As part of the reporting process, PRi will also prepare journal articles and make presentations at technical meetings, as deemed appropriate by PRi.

As performed: As part of the reporting process PRi prepared and distributed three interim progress-reports in addition to this Phase I final report. As part of the same reporting process, PRi also prepared journal-articles, made a presentation at a technical meeting, and gave demonstrations of the Navy-developed technology to Navy (see Task 6b above) and other personnel. Specifically:

PRi presented a paper at the fall meeting of the American Society of Nondestructive Testing (ASNT) held in Pittsburgh, Pennsylvania in October of 1997. We also prepared and submitted an *invited* paper for a special ASNT publication: *Nondestructive Evaluation of Infrastructure*. Our paper (see Appendix B) is titled: "New Methods for Inspecting Steel Components Using Real-Time Magneto-optic Imaging," by G. L. Fitzpatrick, R. L. Skaugset et., al.. The U. S. Navy's support for the work described in this paper is acknowledged at the end of the paper. This paper is scheduled to appear in print sometime in 1998.

4.0 Relationship with Future Research or Research and Development

a) At the end of the Phase I program we are in possession of a portable, battery-operated laboratory/field demonstration instrument (a non-deliverable), which is capable of inspecting steel for surface-corrosion and other defects such as cracks. As part of the Phase I deliverables (see Appendix A) we have also completed designs for a commercial system that would be capable of inspecting both steel and aluminum. This instrument will be designed to be operated by relatively-inexperienced shipboard personnel.

b) Experiments with this system have demonstrated that, in principle, the overall approach is both technically-feasible and practical.

Given these accomplishments, the stage is now set for the Phase II work where the laboratory/field demonstration system will be converted (using the commercial designs referred to in a) above, into a field-hardened system in preparation for Phase III commercialization and production.

As described under Task 6b above, one of the highlights of the Phase I program was a second visit to the Puget Sound Naval Shipyard (PSNS) in Bremerton, Washington, near the end of the Phase I. The previous visit was to the inactive-ships facility. The latest visit was to the Nondestructive Test Division Technical Support Branch (Code 135.1) of the active-ships division. As we reported above (see Task 6b) we observed opportunities for numerous potential inspection applications that can be addressed by the current Navy-developed technology. The inspection opportunities we observed are generally such a good match for the Navy-developed technology, that we are recommending that a collaborative effort (in Phase II) be established--wherein the PSNS Code 135.1 facility in Bremerton would provide PRi access to non-classified inspection applications in return for information transfer on PRi-developed technology (and training on how to use the technology to address inspections of interest to the U. S. Navy) and the delivery, in Phase II, of a system for evaluation at the PSNS Code 135.1 facility.

The purpose of the collaboration will be to prove the technology in those inspections deemed to be most important to the Navy and, in particular, to Code 135.1 personnel. Eventually, this process would be directed toward the development of inspection procedures for replacing some of the existing inspection techniques (e.g., magnetic particle inspection or MPI) with magneto-optic imaging technology or MOI-based technology. Because we believe the new technology can very effectively address the Navy's inspection applications (e.g., ultimately save time and money in inspections and make inspections easier to perform and more reliable) we are prepared to submit a Phase II proposal.

PRi understands that Phase II proposals will be by "invitation" only, and will be awarded based on funding-availability and Phase I performance. PRi is prepared to submit a Phase II proposal to the Navy and we believe the Navy will agree that our Phase I progress has been exemplary, warranting Navy support for a Phase II effort. Accordingly, PRi would like to suggest that the principal investigator (Gerald L. Fitzpatrick) travel to Newport, Rhode Island for the purpose of demonstrating the new Navy-developed inspection technology to NUWC personnel. At that time PRi would also like to discuss prospects for Phase II funding.

5.0 Potential Post Applications

Physical Research, Inc. (PRi) is a small business formed in 1980. The first ten years focused on scientific and engineering research problems, primarily in response to government solicitations. In response to changing economic and budgeting events, PRi redirected its business base to concentrate efforts on developing technical products for commercial markets. In 1990, PRI Instrumentation, Inc. (PRI) was established as a close affiliate of PRi for the purpose of investing in the production, marketing, and sales of the first serious company-commercialization effort, the MOI. To date PRI has invested $3,000,000 to develop, produce and promote this new technology.

The original development of the MOI technology was begun under SBIR sponsorship. The Aloha Airlines accident in 1988 focused national attention on the aging aircraft fleet and the need to develop rapid and reliable nondestructive inspection instruments. Accordingly, the MOI's capabilities were focused on the aircraft market. Under PRI sponsorship a commercially-viable instrument was developed, produced and marketed to both the military and commercial sectors. In addition, investments of personnel and equipment were made by major aircraft manufacturers such as Boeing, McDonnell Douglas, Lockheed and Cessna to test and develop procedures for use of the MOI on their aircraft. Commercial carriers such as Alaska Airlines and American Airlines worked with both the manufacturers and the FAA to implement those procedures in existing maintenance practices. Sandia National Laboratories, through their AANC facilities, and Northwestern University Transportation Lab validated use of the instrument by technical and economic studies. Customers who use this instrument report that inspections are more reliable and labor hours are dramatically cut for the manufacturer/FAA required inspections. Teamwork and cooperation between the government, the military, and the commercial airlines facilitated the MOI's rapid integration into the marketplace.

Although the MOI has received a number of awards for excellence and has been highly-touted by many in the aviation industry, current and projected sales indicate that the aircraft market is extremely limited. Real commercial success requires a much wider market. The inspection of ferromagnetic materials (e.g., steel) such as those commonly encountered in ships, in the nuclear, petrochemical and oil industries, presents an opportunity for wider use and significant financial return. Further improvement/development of the MOI for these applications is needed to secure its place as a new economically-viable product.

Commercialization of the Phase I laboratory/field demonstration system (in Phase II and Phase III), will follow the same successful pattern as the commercialization of MOI technology within the aircraft industry. The demonstrated success of the MOI in the inspection of ferromagnetic materials should have an additional natural expansion from the Navy applications to other similar industries, which have a need to inspect areas for surface-corrosion and cracking in ferromagnetic materials. These are both numerous and occur worldwide. The commercial potential for this version of the MOI is immediate and extensive.

PRI has already made a significant investment in commercializing the MOI in more conventional aerospace applications. It welcomes the opportunity to add the new MOI model to its product line. This new, improved MOI fills the industry need for new inspection equipment, and PRI is committed to bringing it to market as it has on previous SBIR-supported improvements.

Once the Phase II research is successfully completed, the product will be distributed to beta-testers (e.g., the U. S. Navy and others) and its form finalized in response to their market-feedback. A marketable business plan for investors will be prepared at this time. Moreover, PRI will continue its demonstrated commitment to implementing the most recent technological-advances and to commercializing this new technology.

6.0 CONCLUSIONS

This Phase I final report describes developments in magneto-optic imaging that make possible practical real-time imaging of surface corrosion under protective coatings in both steel and aluminum. The technology is sufficiently versatile that it can also be applied to the detection of cracks in these same materials.

We are now in possession of portable, battery-operated laboratory/field demonstration instrument, which is capable of inspecting steel for surface-corrosion and other defects such as cracks. As part of the Phase I deliverables (see Appendix A) we have also completed preliminary designs for a *commercial* system that would be capable of inspecting both steel and aluminum. This instrument is designed to be operated by relatively-inexperienced shipboard personnel.

Experiments with this system in the laboratory have demonstrated that, in principle, the overall approach is both technically-feasible and practical. Given these accomplishments, the stage is now set for the Phase II work where the laboratory/field demonstration system will be converted (using the commercial designs referred to above), into a field-hardened system in preparation for Phase III commercialization and production.

The inspection opportunities we observed on a recent visit to the Nondestructive Test Division Technical Support Branch (Code 135.1) of the Puget Sound Naval Shipyard active-ships division, are generally such a good match for the present Navy-developed technology, that we are recommending that a collaborative effort (in Phase II) be established--wherein the PSNS Code 135.1 facility would provide PRi access to non-classified inspection applications in return for information transfer on PRi-developed technology (and training on how to use the technology to address inspections of interest to the U. S. Navy) and the delivery, in Phase II, of a system for evaluation at the PSNS Code 135.1 facility.

The purpose of the collaboration will be to prove the technology in those inspections deemed to be most important to the Navy and, in particular, to Code 135.1 personnel. Eventually, this process would be directed toward the development of inspection procedures for replacing some of the existing inspection techniques (e.g., magnetic particle inspection or MPI) with magneto-optic imaging technology or MOI-based technology. Because we believe the new technology can very effectively address the Navy's inspection applications (e.g., ultimately save time and money in inspections and make inspections easier to perform and more reliable) we are prepared to submit a Phase II proposal outlining, in detail, such a comprehensive program.

7.0 ACKNOWLEDGEMENTS

This work was supported in part by the following small-business innovation-research (SBIR) projects:

The United States Navy (Contract No. N66604-M-3560) titled "Detection of Corrosion Under Paint Using Magneto-Optic Imaging;" The Department of Energy (Grant No. DE-FGO3-95ER82051) titled "Rotating In-Plane Magnetization and Magneto-Optic Imaging of Cracks in Thick-Section Steel Under Stainless-Steel Cladding"; and the United States Air Force (Contract No. F33657-96-C-2000) titled "ENSIP Inspection of Engine Components Using MOI Technology."

The authors have also benefited from numerous discussions with potential end-users of the technology. These include, among others, Valerie Baur (PSNS), Kevin Bailey (Westinghouse), Jerry Fulin (Tenneco Energy Services) and Brent Hart (American Steel Pipe). We also thank John Wozniak (De Young Manufacturing) for helpful technical advice regarding the design of magnetic yokes and coils.

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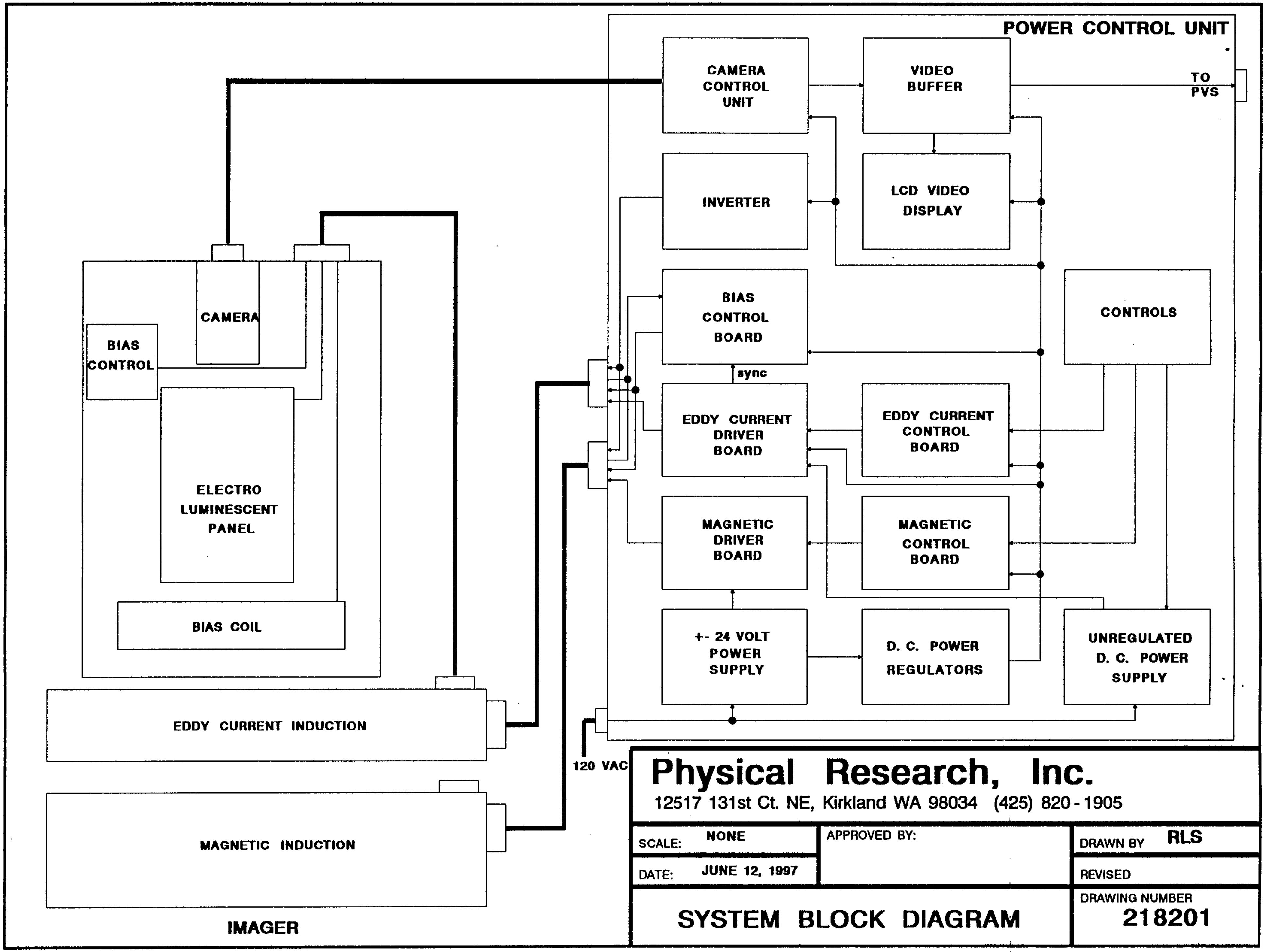
9.0 Appendix A System Design-Drawings



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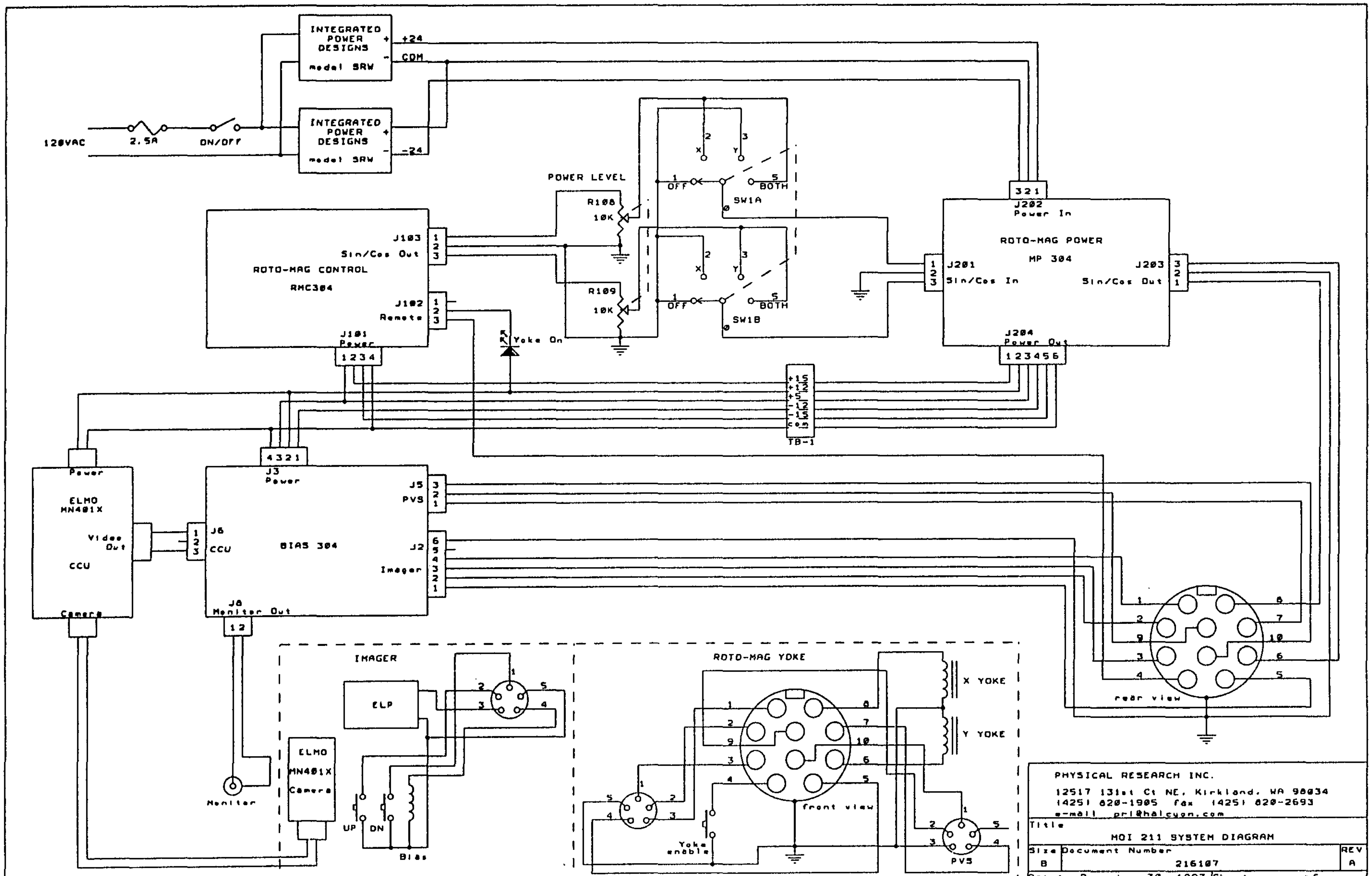
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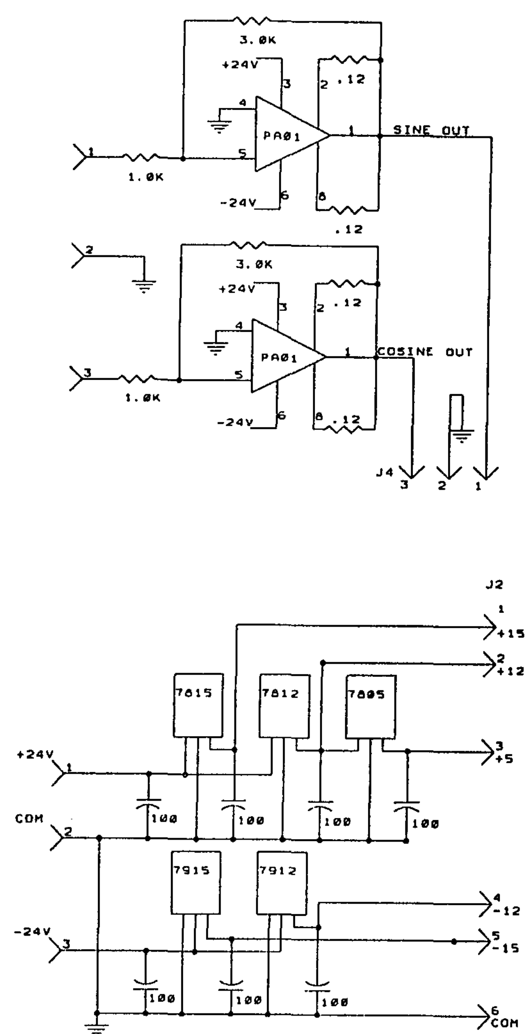

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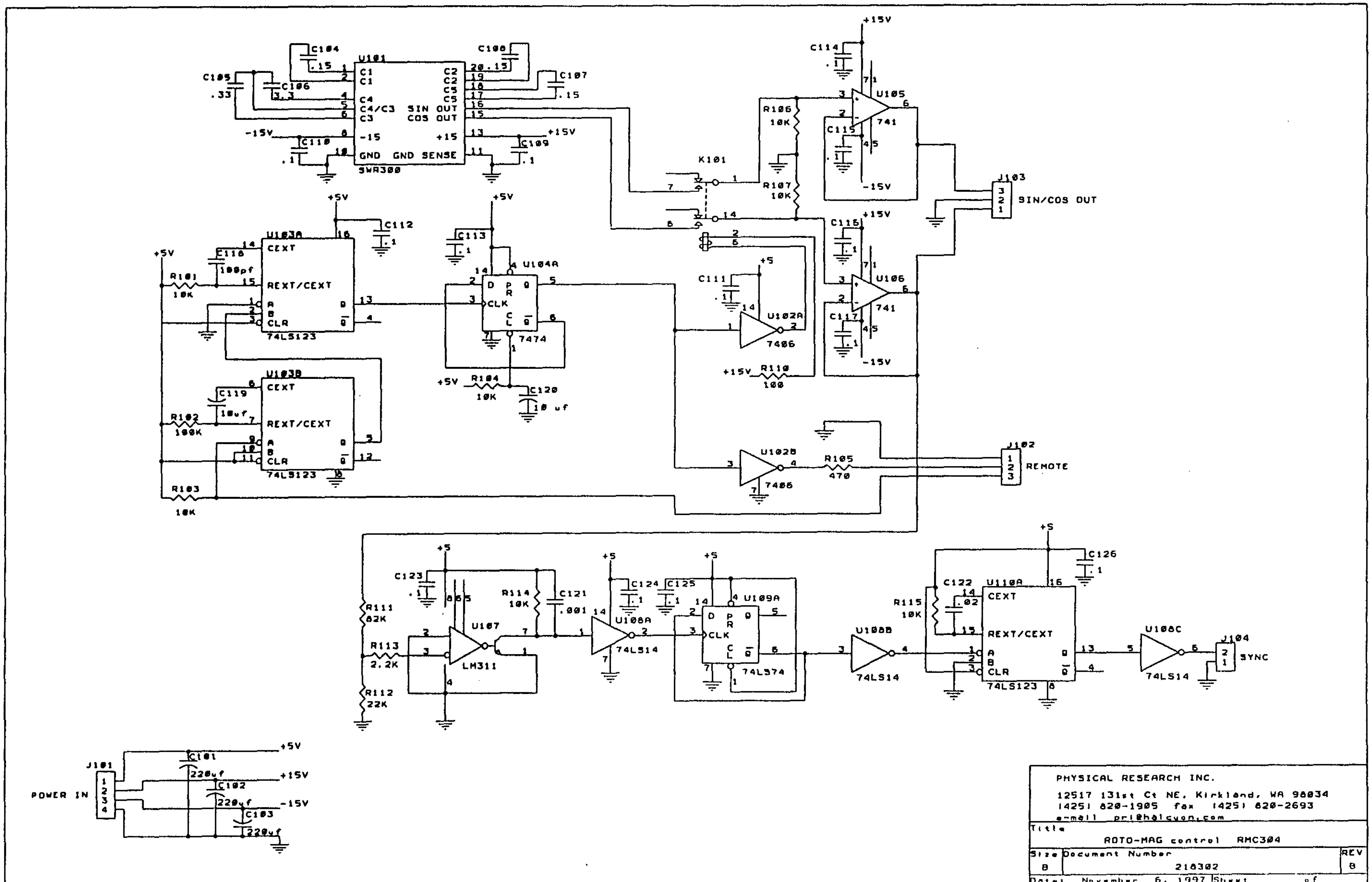

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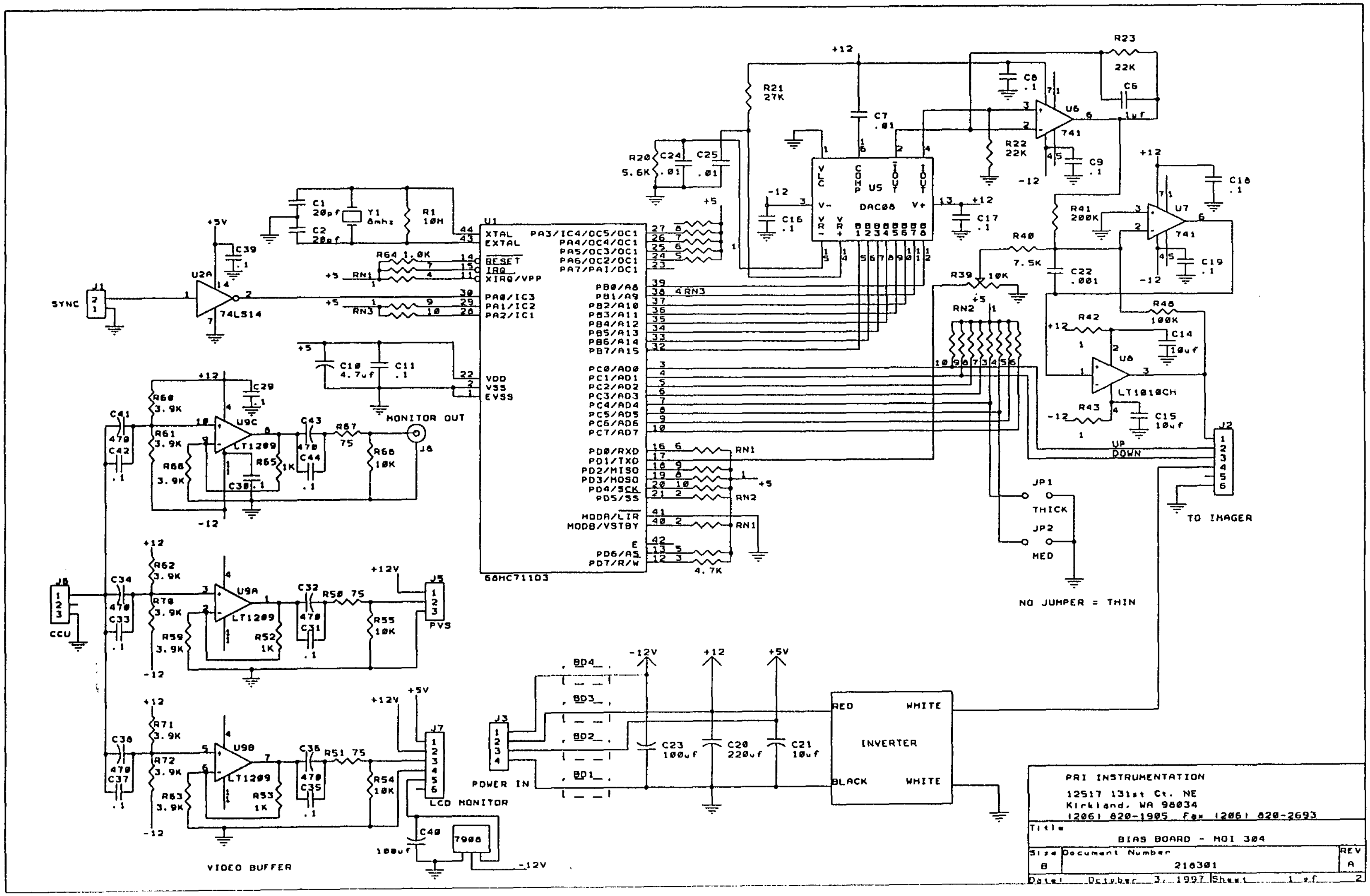

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9.0 Appendix B. ASNT Preprint.

This paper presents work supported, in part, by the U. S. Navy under the present Phase I project. The paper will be published sometime in 1998 in an American Society of Nondestructive Testing (ASNT) Special Topics Volume titled: "Nondestructive Evaluation of Infrastructure."

NEW METHODS FOR INSPECTING STEEL COMPONENTS USING REAL-TIME MAGNETO-OPTIC IMAGING

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ABSTRACT. This paper describes recent developments in magneto-optic imaging that make possible practical real-time flux-leakage imaging of cracks in steel (e.g., steel plate, pipe). Specifically, a new method for producing rotating in-plane magnetization in steel parts was developed and combined with real-time magneto-optic imaging. Small, relatively light-weight self-contained inspection systems suitable for field applications have been produced. Typically, these systems consist of a compact two-channel power-supply for "driving" novel surface-conforming "quadrature" magnetic-yokes, a hand-held imaging probe that "nests" inside the quadrature yoke, and a charge-coupled device (CCD) camera-display system that provides real-time image monitoring and/or recording. Magneto-optic images of cracks or machined notches in steel pipes, steel plate, and cracks in steel under protective coatings such as paint or stainless-steel cladding, are illustrated. The potential for replacing some magnetic-particle based inspections with the new magneto-optic imaging technology is briefly discussed.

Key Words: flux leakage, magnetic particle inspection, magnetic yokes, magneto optics, nondestructive inspection

INTRODUCTION AND BACKGROUND

Magneto-optic/eddy-current imaging (MOI) technology is revolutionizing the nondestructive inspection (NDI) of aging aircraft systems [1,2]. By combining magneto-optic imaging methods with novel eddy-current excitation methods, MOI makes possible realistic real-time eddy-current images in nonferromagnetic materials ranging from aluminum to titanium (see Appendix A). These images can be viewed by the inspector using a head-mounted personal viewing system and/or images may be recorded and processed for future use. Current applications of MOI range from the inspection of aluminum lap-joints for cracks and sub-layer corrosion (in aircraft), to the inspection of jet-engine parts (for cracks) made of materials such as titanium. In its current commercially-available form, MOI has proven to be a reliable in-service inspection tool. It has been approved—and is currently in widespread use—for the inspection of Boeing, Douglas and Lockheed commercial aircraft. The U.S. Air Force, NASA and other domestic, and foreign, organizations are also successfully applying this form of the technology. However, applications of MOI to ferromagnetic materials such as steel have seen only limited success in the past due, in part, to the difficulty of properly magnetizing steel parts [3-5].

The purpose of this paper is to describe recent developments in magneto-optic imaging that make possible practical, real-time flux-leakage imaging of cracks in steel (e.g., steel plate or pipe) without the requirement of conventional (cumbersome) magnetizing methods (see Figure 1). This was accomplished by first developing a method for producing rotating in-plane magnetization in steel parts and then combining this capability with real-time magneto-optic imaging [6-8]. In particular, these improvements were accomplished by providing magnetic-excitation yokes to the outside of imagers of reduced size. By contrast, in commercially-available MOI systems, the eddy-current excitation mechanism resides *inside* the MOI-imager housing. This results in a housing that is sometimes larger than necessary for many applications. By placing the magnetic excitation device *outside* the imager, smaller light-weight systems capable of inspecting in confined spaces, and adapting to curved surfaces, are possible.

By applying the foregoing innovations, small, relatively light-weight, self-contained inspection systems for steel suitable for field applications, have been developed (see Figure 1). Typically, such an inspection system consists of a compact two-channel power-supply for "driving" novel surface-conforming "quadrature" magnetic-yokes, a hand-held imaging probe that "nests" inside the yoke, and a CCD camera-display system. Real-time, magneto-optic images of cracks or other defects in steel including images of cracks under protective "coatings" such as paint or stainless-steel cladding, are possible with these systems. This capability is a significant advantage over conventional magnetic particle inspections (MPI) where surface coatings present a major problem [9].

TECHNICAL PROBLEMS THAT HAD TO BE OVERCOME

To achieve a practical magneto-optic imaging system for steel a number of basic problems had to be overcome. The following discussion outlines these problems and their solutions.

The Problem of Stray Flux

The magneto-optic sensors used in these imaging systems exhibit a property called uniaxial magnetic-anisotropy (see Appendix A). Loosely speaking, this means that the sensor only responds to those magnetic fields that are directed *perpendicular* to the plane of the sensor. Flux-leakage fields due to flaws fall in this category, since these fields "leak" out of the part in the vicinity of flaws, i.e., they have components perpendicular to the surface of the part. However, if for any reason the part being inspected also has retained magnetic-field unrelated to material flaws, and if this retained magnetic-field is also *perpendicular* to the surface of the part it will tend to overwhelm the relatively weak magnetic-fields from the flaw, making flaw detection by magneto-optic methods difficult or impossible.

Because it is difficult to magnetize steel parts, without such undesirable magnetic-field components using conventional methods of magnetization, new methods of magnetization had to be developed to take advantage of the potential provided by magneto-optic imaging. In particular, when using magneto-optic sensors, it is necessary to control both the temporal and spatial properties of the magnetic fields being applied to the part. Ideally, these applied magnetic-fields should be in the plane of the part at the location of the flaw, thereby, eliminating or significantly reducing the unwanted normal-component magnetic fields. Moreover, the orientation of the fields as a function of time should change because of the unknown crack-orientation. The solution to both of these "problems" was to develop special magnetic-yokes that not only force the magnetic flux to remain essentially in-plane, but also force the flux to *rotate* in the plane of the part [6-8].

In-Plane Magnetization

Four basic technical difficulties had to be addressed and solved to achieve a practical magneto-optic imaging system for steel. First, because eddy-current inspection methods are generally inappropriate for the inspection of ferromagnetic materials such as steel, some non eddy-current method of excitation such as magnetic yokes, current-carrying coils or contact electrodes, had to be used to make magneto-optic images of flaws in these materials. Second, because conventional magnetizing devices such as yokes are usually heavy and cumbersome, the motivation for employing magneto-optic imaging (using such devices) as a replacement for MPI is, thereby, considerably diminished [9]. Third, even if conventional magnetization-methods were *not* cumbersome, the irregular (non-flat) shape of many steel parts makes it difficult, or impossible, to induce the required in-plane magnetic fields with such devices. And without in-plane magnetic fields, magneto-optic sensors are likely to be overwhelmed by stray magnetic-flux having nothing to do with material flaws (see previous section). Fourth, and finally, because crack orientation is generally unknown, conventional inspection methods require special procedures for finding cracks (see the discussion on MPI below, Appendix B and [9]). How can the foregoing technical difficulties be overcome in a practical way? An examination of familiar MPI procedures provides useful insights, which will eventually lead to an answer that addresses *all* four of the problems outlined above.

The general procedures for detecting cracks in conventional flux-leakage type inspections such as MPI are well known (see Appendix B and [9]). Surface-breaking cracks in ferromagnetic materials such as steel are best detected when the magnetization direction in the part being inspected is *perpendicular* to the (unknown) crack direction. In general, cracks will *not* be detected when the magnetization is *parallel* to the crack direction. For example, the inspection procedure for MPI calls for performing *two* inspections with the magnetizing yoke oriented ninety-degrees relative to the orientation of the yoke in the first of the two inspections.

These facts imply that a better way to inspect steel samples using a flux-leakage method such as magneto-optic imaging might be to have the magnetic field responsible for magnetizing the part continuously *rotate* in the plane of the part while the magneto-optic imaging is occurring. Clearly, such rotating in-plane magnetic fields would eliminate the MPI-requirement to physically rotate a yoke when performing inspections. Moreover, if rotating in-plane magnetization can be achieved, by definition, the magneto-optic sensor should *not* be overcome by stray magnetic flux, since flux is being forced into the plane of the part.

APPARATUS

In this section, a detailed description of specific items of hardware for achieving practical in-plane magnetization and combining this with magneto-optic imaging systems is given.

Quadrature Magnetic-Yokes

As described in the previous section, rotating in-plane magnetic fields would seem to be ideal for magneto-optic imaging. But how are such fields to be established in a practical way? The drawings presented in Figures 2 and 3, together with the supporting discussions regarding magnetic circuits given in Appendix C and [6-8], provide an explanation of how a quadrature magnetic-yoke achieves this goal.

Note that because these yokes are closed "loops", as illustrated in Figures 2 and 3, the flux from one pair of coils, electrically connected in series, passes through some of the *same* yoke material as the magnetic flux from a second pair of coils, also connected in series. However, as long as the combined magnetic-flux does not saturate the yoke material, flux from the two pairs of coils will pass through the yoke material, essentially, without interaction. This fact insures that a single, compact quadrature magnetic-yoke will act as if it were two separate two-pole magnetic-yokes combined.

The flux return-path for each pair of yoke poles in a quadrature magnetic-yoke is through the material being inspected. Note that if one pair of coils is driven by a sinusoidal potential, $V_o \mathbf{sin} (\omega t)$, while at the same time the second pair of coils is driven by a potential 90 degrees out-of-phase with respect to the first, i.e., $V_o \mathbf{cos} (\omega t)$, the magnetic field in the part will, necessarily, rotate [6-8]. This rotation should produce excellent quality magneto-optic flux-leakage type images. In particular, under these conditions out-of-plane magnetic anomalies associated with flaws should be imaged by simply adjusting the magnetic-field bias applied to the magneto-optic sensor to produce the best image (see Appendix A and Ref. [2]).

Yoke Shoes

If the surface of the part being inspected is essentially flat, a quadrature magnetic-yoke having flat in-plane poles will suffice to link the magnetic flux efficiently to the part. However, such a yoke cannot link magnetic-flux efficiently to a curved surface owing to air gaps (see Appendix C for a discussion of magnetic circuits).

To efficiently link magnetic-flux to steel parts having surfaces that are not flat, quadrature magnetic-yokes can either be machined to accommodate these surfaces, or they can have removable "shoes" that accommodate these surfaces. Because yokes are generally heavier and more bulky than such shoes, and because it is much easier to machine shoes made from a continuous piece of high-permeability steel, than it is to machine yokes made of discontinuous silicon-steel sheet—it makes good sense to have a single quadrature magnetic-yoke and a selection of relatively light-weight shoes designed to accommodate curved surfaces. Accordingly, we have developed yoke-shoe combinations similar to those illustrated in Figure 4 and 5. Experiments on the flux-producing characteristics of these modified yokes demonstrate that this is a practical solution to the problem of inspecting non-flat steel surfaces.

EXPERIMENTAL RESULTS—MOI IMAGES

By combining small magneto-optic imagers with quadrature magnetic-yokes fitted with special surface-conforming shoes, a system similar to the one illustrated in Figure 1 results. Typical images obtained with this system are illustrated in Figures 6 and 7. In Figure 6 the advantages of employing rotating in-plane magnetic fields are clearly demonstrated, and in Figure 7 a dramatic example of the capability of imaging flaws through protective-coatings such as stainless-steel cladding is demonstrated. In Figure 7, a fatigue crack was successfully imaged through 0.120-inches of liftoff. The fact that images can be made through relatively thick protective-coatings is a very promising characteristic of the new technology.

FUTURE DIRECTIONS

The technology described in this paper was originally intended to improve the NDI of thick-section steel nuclear-reactor pressure vessels. While it holds great promise for this purpose, we believe that the technology will also find many other applications wherever the NDI of steel is required (e.g., chemical reaction vessels, steel parts in jet engines, steam turbine blade-roots). Accordingly, we will continue to develop and improve the technology by optimizing quadrature magnetic-yokes, magneto-optic imagers and power supplies. In that regard, consider again the images illustrated in Figure 7.

Variations in liftoff for the same yoke show steady degradation in image quality with increasing liftoff. However, by increasing the surface area of the yoke poles, the reluctance of the magnetic circuit can be significantly reduced (see Appendix C). This will have the effect of increasing the magnetic flux linked to the part, thereby, improving the image that would result at the same liftoff but for a smaller yoke-pole area. To put it in other words, because the reluctance of the magnetic circuit is directly proportional to the liftoff distance, and inversely proportional to the pole area, the reluctance can be kept constant by increasing the area of the poles while increasing the liftoff. Consequently, doubling the liftoff and the pole area simultaneously, should result in images that look the same as images made at half the liftoff and half the pole area. Figure 7 illustrates how images are degraded with liftoff for *constant* pole-area. Figure 8 illustrates a prototype magneto-optic imager that is designed to image flaws through thick protective coatings such as stainless-steel cladding. Note the relatively large yoke in Figure 8 relative to the yokes illustrated in Figures 1.

Even though the emphasis in this paper was on developing devices for producing rotating in-plane magnetization in steel, the ability to place the magnetic yoke outside the imager, as illustrated in Figures 1 and 5, has implications for magneto-optic eddy-current imaging in materials such as aluminum. Just as it is possible to place the magnetic yoke outside a small imager, it is also possible to place an eddy-current excitation-mechanism outside an imager (see Figure 9). This means that it should be possible to attach interchangeable excitation devices to the same imager housing—making possible the inspection of steel or aluminum using the *same* magneto-optic imaging system with different external excitation devices. Work in progress is devoted to making this idea a practical reality.

CONCLUSIONS

The main objective of this work was to explore and develop a novel approach to magneto-optic imaging of cracks in steel parts that are generally not flat. This was accomplished by providing a method to induce rotating in-plane magnetization in the part and then employ magneto-optic imaging to form dynamic flux-leakage images of material flaws. From the foregoing technical discussion and experimental results, it is clear that the new inspection technology can accommodate both flat and convex curved-surfaces, including surfaces with relatively thick protective-coatings (e.g., stainless-steel reactor pressure-vessel cladding). Moreover, because the in-plane magnetization rotates, all cracks can be imaged without regard to their orientation. Finally, because the reluctance of a magnetic circuit can be decreased by increasing the cross-sectional area through which magnetic-flux passes, it should be possible to compensate for liftoff due to cladding or other protective coatings by simply increasing the "footprint" area of the quadrature magnetic-yoke poles.

MOI as a Replacement for Some Magnetic Particle Inspections

While conventional magnetizing yokes and current-carrying conductors are commonly used for magnetic-particle inspections, this equipment is cumbersome and tends to inhibit the use of the MOI on steel (see Appendix B). However, with the self-contained systems described in this paper—consisting of an MOI-imager of reduced size and a self-contained means of magnetizing parts, the foregoing limitations have been significantly minimized. Hence, flux-leakage imaging by magneto-optic methods could be superior to MPI for some applications.

The field-sensing method is very different in these two technologies. Unlike the case of magnetic particles "sliding" across a surface toward regions of increasing magnetic-field strength, magneto-optic sensors possess magnetic domains that expand or contract in response to the presence of magnetic fields, thereby, producing images of magnetic anomalies associated with surface or near-surface cracks a (see Appendix A and Refs. [2, 10-12]). The controlled motion of domain walls within the magneto-optic sensor, rather than the relatively uncontrolled motion of particles sliding along a sometimes rough-surface, constitutes a major difference between these techniques. The result is that magneto-optic flux-leakage images are inherently much less effected by surface coatings such as paint or cladding that result in liftoff. The foregoing successes of magneto-optic imaging suggest that these new imaging techniques may be capable of replacing MPI in many important situations.

ACKNOWLEDGEMENTS

This work was supported in part by the following small-business innovation-research (SBIR) projects: The Department of Energy (Grant No. DE-FGO3-95ER82051) titled "Rotating In-Plane Magnetization and Magneto-Optic Imaging of Cracks in Thick-Section Steel Under Stainless-Steel Cladding"; The United States Navy (Contract No. N66604-M-3560) titled "Detection of Corrosion Under Paint Using Magneto-Optic Imaging," and the United States Air Force (Contract No. F33657-96-C-2000) titled "ENSIP Inspection of Engine Components Using MOI Technology."

The authors have also benefited from numerous discussions with potential end-users of the technology. These include, among others, Kevin Bailey (Westinghouse), Jerry Fulin and Brent Hart (American Steel Pipe). We also thank John Wozniak (De Young Manufacturing) for helpful technical advice regarding the design of magnetic yokes and coils.

APPENDIX A. MAGNETO-OPTIC IMAGING TECHNICAL BACKGROUND

By combining magneto-optic imaging and eddy current excitation in an unconventional manner, it is now possible to obtain real-time, eddy current images of fatigue cracks and areas of hidden corrosion in structures such as the aluminum fuselage of an aging aircraft [1, 2]. This existing technology-base was the starting point for the present effort and will now be described briefly.

The magneto-optic sensors consist of a thin film of bismuth-doped iron garnet, namely, $(Bi,Tm)_3(Fe,Ga)_5O_{12}$ grown on a three-inch diameter, 0.020 inch-thick substrate of gadolinium-gallium-garnet (GGG) [10-12]. These films exhibit three physical properties that are crucial for a practical magneto-optic imaging device. First, they exhibit an important property called uniaxial magnetic-anisotropy. That is, they have an "easy" axis of magnetization normal to the sensor surface and a "hard" axis of magnetization in the plane of the sensor. Second, if the magnetic fields along the easy axis of magnetization are removed, the magneto-optic film will retain most of its established magnetization, i.e., it has an effective "memory." Third, these films possess a large specific Faraday rotation, θ_f, up to 30,000 degrees/cm of thickness, which makes it possible to directly view the images.

If normally incident, linearly-polarized light is transmitted through such a magneto-optic sensor, the plane of polarization of the light will be rotated by an angle called the Faraday rotation, which is $\theta \propto \theta_f\ \mathbf{k} \bullet \mathbf{M}$, where **k** is the wave vector of the incident light, and **M** is the local time-dependent magnetization along the easy-axis of magnetization. Because the angle between **k** and **M** completely determines the sign of the scalar product **k•M**, the sense of the Faraday rotation (relative to **M**) for a given state of magnetization **M** does *not* depend on the sign of **k**, i.e., the *direction* the light is being propagated through the sensor. Thus, the Faraday rotation relative to **M** will be *doubled* if the light is first transmitted through, and then reflected back through the sensor again, thereby, enhancing sensitivity.

By properly viewing this reflected light through an analyzer, the local state of magnetization of any region in the sensor can be seen as a high-contrast dark or light area, depending only on the direction of the magnetization **M** and the setting of the analyzer. This is the basic property that allows the sensor to create images of the normal-component magnetic fields associated with any source of magnetic fields such as eddy currents or, in the present case, magnetic leakage-fields from ferromagnetic parts.

APPENDIX B. MAGNETIC PARTICLE TECHNIQUES

Magnetic particle inspection (MPI) is a well established method of inspecting ferromagnetic materials for cracks and inclusions [9]. The method relies on the fact that magnetic particles, which act like small magnetic-dipoles, are always attracted toward regions of increased magnetic-flux. Thus when magnetic particles are distributed over the surface of a ferromagnetic part, and an alternating magnetic field is introduced into the part via magnetic-yokes, contact electrodes etc., the region of strong flux-leakage, associated with a surface-breaking crack or inclusion, will drag the magnetic particles across the surface (or pull them from an aerosol or liquid stream) toward the flaw location. Under ideal conditions this process results in excellent flaw-indications. However, if paint greater than about 0.003-inches thick, or other thin coatings such as electroplated nickel are present, sensitivity is greatly reduced and particle indications are often degraded. Two studies sponsored by the Electric Power Research Institute, namely, RP 2904-1 and RP 2904-2, demonstrated that the detection of small cracks (e.g., ¼ -inch long) is significantly degraded using MPI when coating thickness exceeds 0.005 inches.

APPENDIX C. MAGNETIC CIRCUITRY (GENERAL BACKGROUND)

As described in the text, we employ special quadrature magnetic-yokes to achieve rotating in-plane magnetization. And, since quadrature magnetic-yokes, which are magnetically-"shorted" to the part being inspected, represent magnetic circuits, it is important to have a general understanding of the basic principles involved in such circuits and the terminology commonly used in describing them.

There is a close analogy between magnetic circuits and electric circuits. In particular, the familiar Ohm's law, namely, $\mathbf{V}_{emf} = \mathbf{I}\,\mathbf{R}$ for electric circuits containing an electromotive force or potential drop $\mathbf{V}_{emf}$, an electrical resistance **R** and an electric current **I**, can be cast in an analogous form [13] for magnetic circuits, namely, $\mathbf{V}_{mmf} = \mathbf{\Phi}\,\mathfrak{R}$. In this formula, $\mathbf{V}_{mmf}$ is the magnetomotive force that "drives" magnetic flux $\mathbf{\Phi}$ through the magnetic material, constituting the magnetic circuit, against the reluctance $\mathfrak{R}$. Clearly, $\mathbf{V}_{mmf}$ is the analog of electromotive force that "drives" current **I** through an electrical conductor against the electrical resistance **R**. Hence, reluctance $\mathfrak{R}$ is the analog of electrical resistance **R**, and magnetic flux $\mathbf{\Phi}$ is the analog of electric current **I**.

Because magnetic flux $\mathbf{\Phi}$ is typically driven through a magnetic circuit by a current-carrying, hence flux-producing, coil that links the magnetic circuit, the magnetomotive force is given, in this case, by the simple expression $\mathbf{V}_{mmf} = n\,i$, where n is the number of turns on the coil carrying current i and linking the magnetic circuit.

Reluctance $\mathfrak{R}$ depends on the geometry and material properties of the magnetic circuit. In particular, the reluctance of a magnetic circuit, consisting only of a closed iron-path (e.g, a toroid) is given by $\mathfrak{R}_{iron} = \mathbf{L}_{iron} / (\mu_{iron}\ \mathbf{A})$, where $\mathbf{L}_{iron}$ and **A** are, respectively, the length and cross-sectional area of the circuit, and where μ_{iron} is the magnetic permeability of the iron. Similarly, the reluctance of an air-gap in a magnetic circuit is given by the expression $\mathfrak{R}_{air} = \mathbf{L}_{air} / (\mu_{air}\ \mathbf{A})$. And, because μ_{air} is very much less than μ_{iron} , the reluctance of a magnetic circuit containing an air gap is mostly due to the reluctance of the air gap, even though $\mathbf{L}_{iron}$ is typically much larger than $\mathbf{L}_{air}$. This means that, all other things being equal, *the liftoff* $\mathbf{L}_{air}$ *between the sample to be inspected and the surface-conforming quadrature magnetic-yoke will be the single most important factor in determining the overall reluctance associated with such yokes.* Clearly, if the liftoff is too large, the reluctance will be so high that the magnetic-flux linking the part being inspected will be significantly reduced. This, in turn, would make detection of material flaws much more difficult.

Because the reluctance of the magnetic circuit is determined by the presence of air gaps anywhere in the circuit, they are to be avoided as much as possible. And, if they can't be avoided they should be minimized or compensated for if possible. For example, as a practical matter in some applications, it is necessary to employ surface-conforming shoes on the quadrature magnetic-yokes (see discussion in the text). These shoes should be machined to fit the yoke (and accommodate the shape of the part being inspected) as "tightly" as possible so as to minimize air gaps. Having done these things, it is also possible to reduce the reluctance of the magnetic circuit by increasing the area **A** of the yoke-pole "footprints." For example, when attempting to see cracks in steel through thick coatings, such as cracks under heavy paint layers or even stainless-steel cladding, it is essential that yokes with a sufficiently large footprint area be used to minimize the reluctance. This will result in the smallest possible reluctance, hence the largest possible magnetic flux in the part. And this, in turn, will maximize the magnetic anomaly associated with the flaw, thereby, making it easier to detect even through relatively thick protective coatings.

REFERENCES AND FOOTNOTES

1. The MOI has been qualified by the FAA for use by commercial airlines in the NDI of aging aircraft, and is being marketed worldwide by PRI Instrumentation, a subsidiary of Physical Research, Inc. (PRi).

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8. To see why the magnetic field inside the part rotates, note that the magnetic induction for each pair of yoke poles (**B**), in the region of the part *between* the yoke poles, is roughly proportional to the applied voltage (or current) in a given pair of coils. The total induction is then the vector-sum of the **B**-fields from each coil-pair. That is, if two sinusoidal voltages 90 degrees out-of-phase, drive each pair of coils, and if the magnetic flux from each coil-pair is simultaneously applied to two perpendicular-directions (by the quadrature magnetic-yoke) a multidirectional or *rotating* magnetic induction will be established. A simple analysis shows that along any particular in-plane direction of the part (located "inside" the quadrature magnetic-yoke), there will be a total magnetic-induction at the surface of the part of the form,

$$\mathbf{B} = \mathbf{B}_o \sin(\omega t - \Psi).$$

Thus, two different in-plane **B**-vectors will exhibit a phase difference that depends only on the angle Ψ between them. Alternatively, by writing the vector **B** as (note $B_o = |\mathbf{B}_o|$)

$$\mathbf{B} = B_o [\sin(\omega t)]\, \mathbf{j} + B_o [\cos(\omega t)]\, \mathbf{i},$$

where **i** and **j** are orthogonal unit-vectors in the plane of the part, we see that **B** can also be viewed as a **B**-vector that rotates with an angular frequency ω. We refer to this as a multidirectional, or rotating, magnetic induction.

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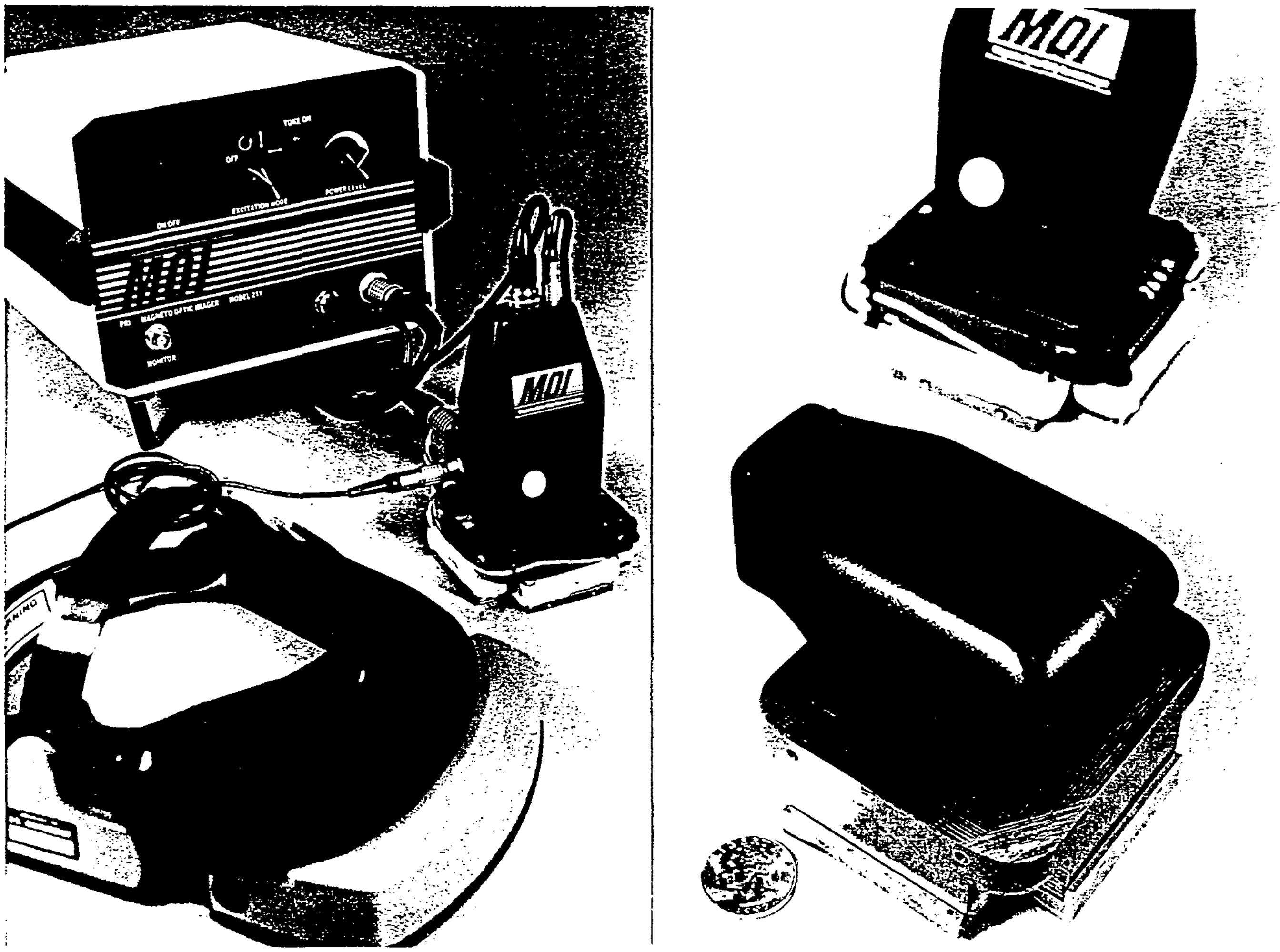


a) Assembled system

b) Two types of magneto-optic imagers

Figure 1. In a) a magneto-optic imaging system designed for the inspection of steel parts is illustrated. The system combines a magneto-optic imager of reduced size and a novel quadrature magnetic-yoke that produces rotating in-plane magnetization (right foreground). A special 60 Hz dual-channel power supply "drives" the flux-producing yoke coils (upper background). Magneto-optic images are "captured" by a CCD camera (located inside the imager) and can be displayed on a conventional monitor and/or head-mounted personal viewing system (left foreground). In b) magneto-optic imagers of two different configurations are shown "nested" in their respective quadrature magnetic-yokes. Note that the yoke-coils, shown here as being exposed, will be covered by a protective shroud in a final system. Note also that the four yoke-shoes will eventually be part of an assembly for easy attachment to the yoke poles.

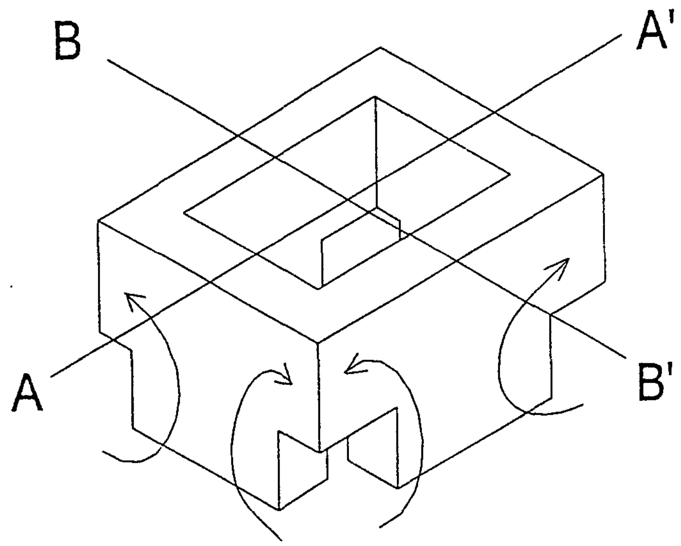


Figure 2. A four-pole quadrature magnetic-yoke (coils not shown) showing flux-paths when the yoke is magnetically "shorted" to a test piece (implicit in the drawing). Cross-sections B-B′ and A-A′ are indicated. Note that each of these cross-sections includes two, of the four, yoke-poles.

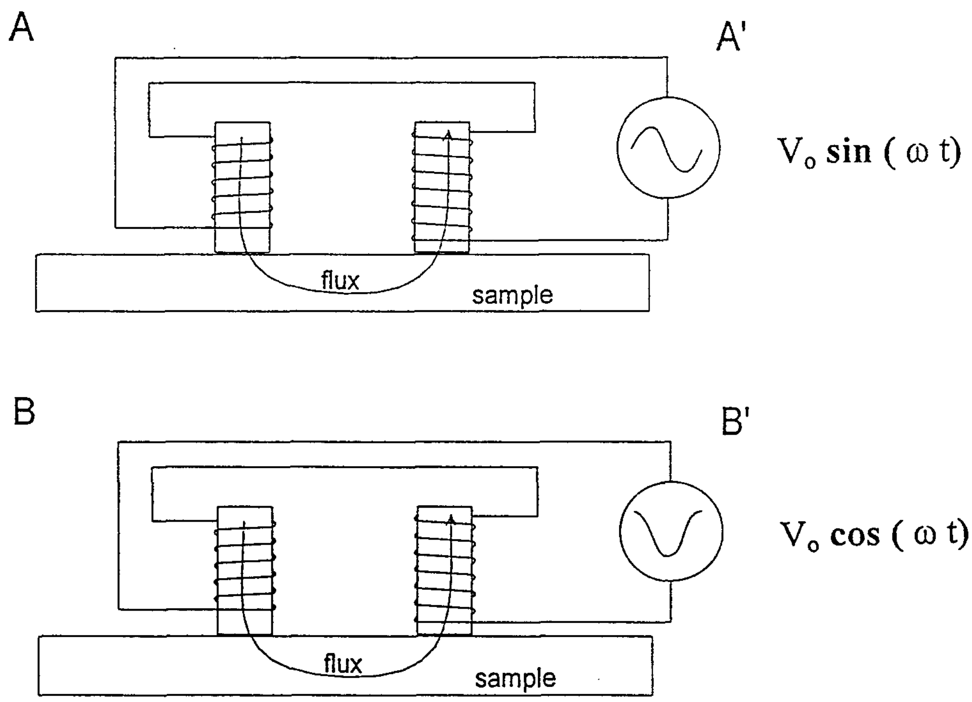
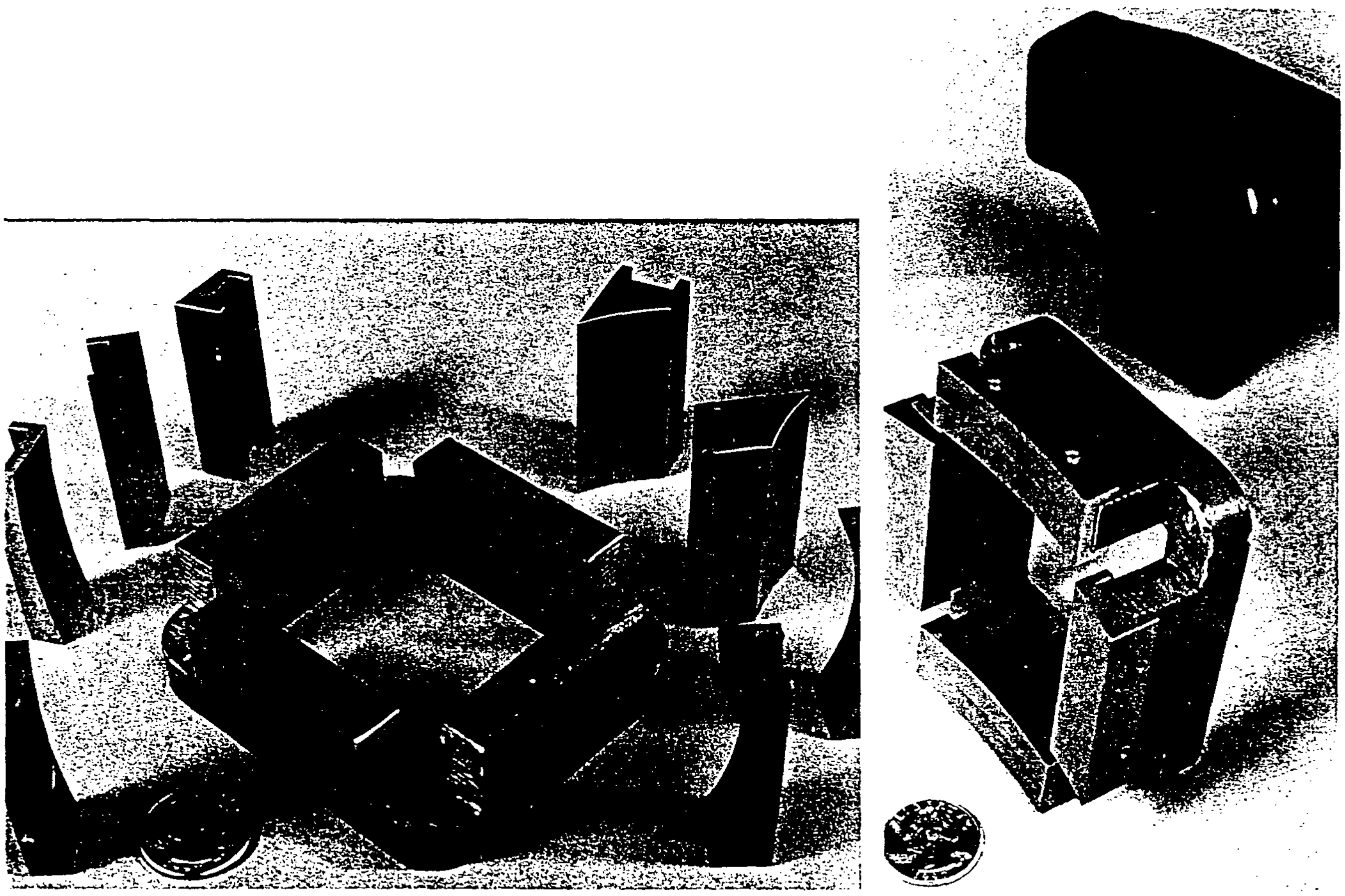


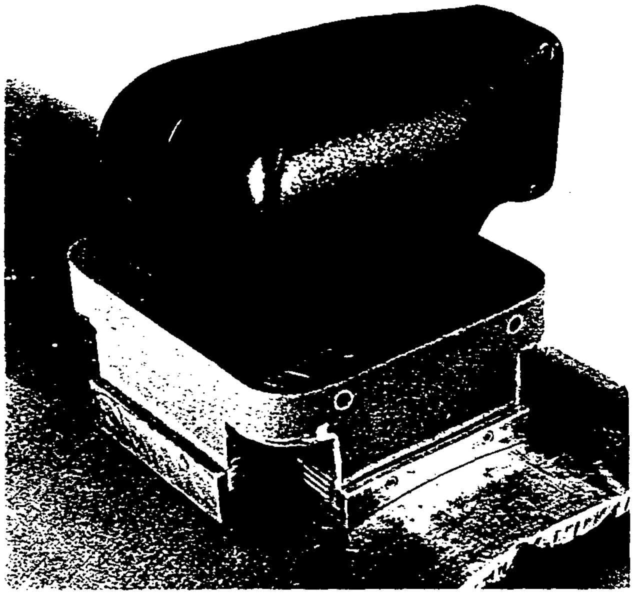
Figure 3. The flux-paths for each of the two cross-sections (through the four-pole quadrature magnetic-yoke) of Figure 2 are illustrated. Coils are connected in series and wound on the yoke-poles in such a way that the flux adds. Each coil-pair is magnetically-"shorted" to the part as shown. The complete flux-return path, for each coil-pair, is not shown, but is easily inferred from Figure 2. Each coil-pair (connected in series) is "driven" by a sinusoidal voltage at 60 Hz. Because one coil-pair is driven ninety-degrees out-of-phase with respect to the second, the flux in the part "rotates" more or less in the plane of the part.



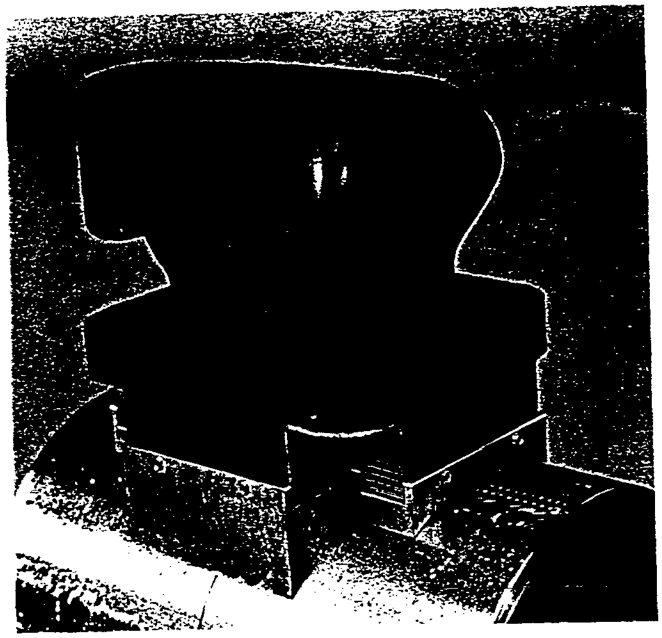
a) Yoke core and two sets of shoes

b) Attached shoes

Figure 4. Four-pole quadrature magnetic-yoke and shoes (no coils shown). In a) the four shoes to the right of the yoke (center) were machined to accommodate the outside surface of a 4.5-inch diameter pipe, while the four shoes to the left of the yoke were machined to accommodate the outside surface of a 12.75-inch diameter pipe. In b) a yoke with shoes attached is illustrated in the foreground. In the background the housing for a magneto-optic imager, which "nests" in the yoke, is pictured. Note that the four yoke-shoes will eventually be part of an assembly for easy attachment to the yoke poles.



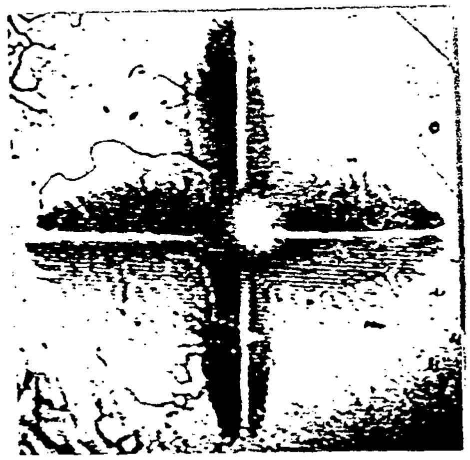
a) 12.75-inch diameter pipe



b) 4.5-inch diameter pipe

Figure 5. Shoes designed to accommodate curved surfaces. In a) the surface is a pipe segment 12.75-inches in outside diameter. And, in b) the surface is a pipe segment 4.5- inches in outside diameter. A small magneto-optic imager is shown "nested" in the yokes (coils not present on the yoke poles). The four yoke-shoes will eventually be part of a single assembly.

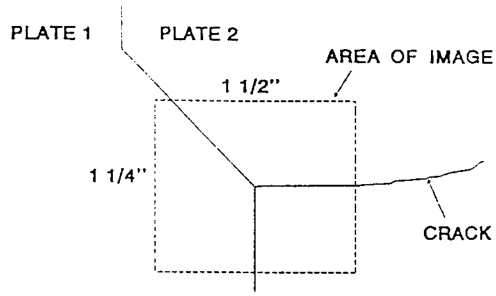
a) "up-down"



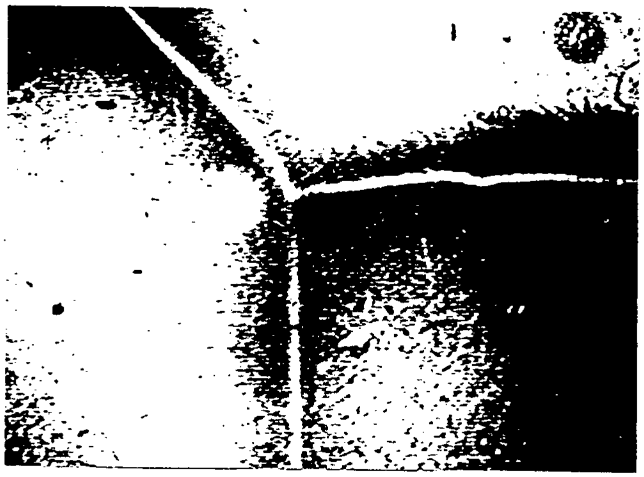
b) Rotating

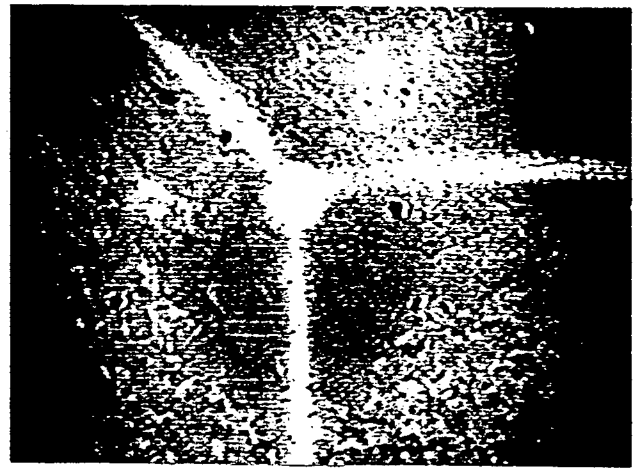
c) ¼ -inch crack

Figure 6. MOI images of 0.5-inch long machined notches in a "cross"-pattern in a flat A-36 steel plate and an MOI image of a 0.25-inch long crack in a 12.75-inch diameter pipe. In a) only the "up-down" arm of the quadrature magnetic-yoke was excited and in b) both arms of the yoke were excited (in quadrature) to produce rotating in-plane magnetization. Only half of the cross is visible in a) whereas the entire cross-pattern is visible in b). In c) an MOI image of a 0.25-inch long crack in a 12.75-inch diameter pipe is illustrated.



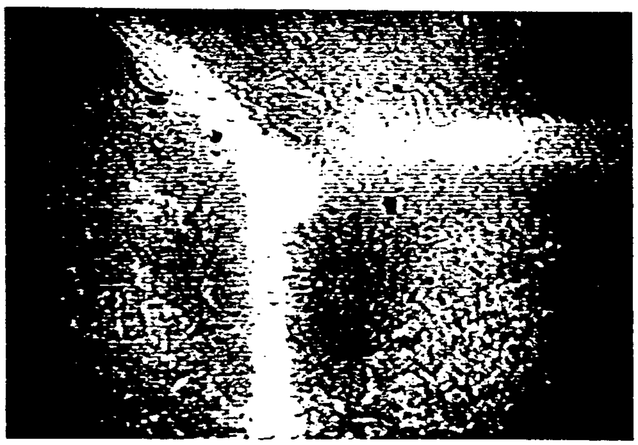
a) The test sample





b) "Zero"-liftoff

c) 0 .03-inches liftoff



d) 0.06-inches liftoff

e) 0 .120-inches liftoff

Figure 7. Magneto-optic images of the sample illustrated in a). In b) the image at "zero"-liftoff in c) at 0.030-inches liftoff in d) 0.060-inches liftoff and e) 0.120-inches liftoff. The yoke excitation-frequency was 60Hz. Liftoff was achieved by stacking cardboard spacers each 0.03 inches thick. An image of the crack nearly identical to e) was obtained through 0.125 inches of stainless-steel and was readily detected, although it was not well resolved.

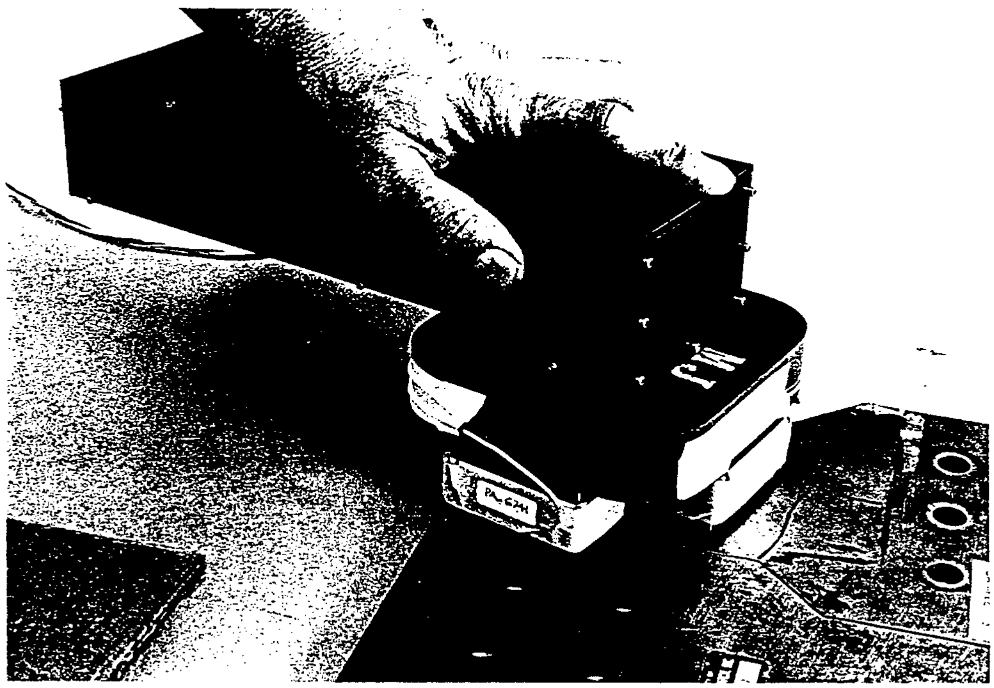


Figure 8. A laboratory-prototype imager being developed for the Department of Energy (see acknowledgments). The imager employs a relatively large quadrature magnetic-yoke to increase the magnetic flux in the part undergoing inspection. Larger yokes are required when parts are covered by thick protective-coatings such as stainless-steel cladding. The area of the yoke-poles shown here is about four times the area of the yoke poles illustrated in Figures 1 and 2. This means that the reluctance, which varies as the ratio of the liftoff, or coating thickness, to the pole area, can be made the same as that for a yoke with pole area ¼ of the larger yoke and liftoff ¼ of the larger yoke. The practical significance of this is that the magnetic-flux linking the part in these two cases is the same (see Appendix C) and magneto-optic images of cracks in the part will look the same at a liftoff of 4 units (with the larger yoke) as they do at a liftoff of 1 unit with the smaller yoke.

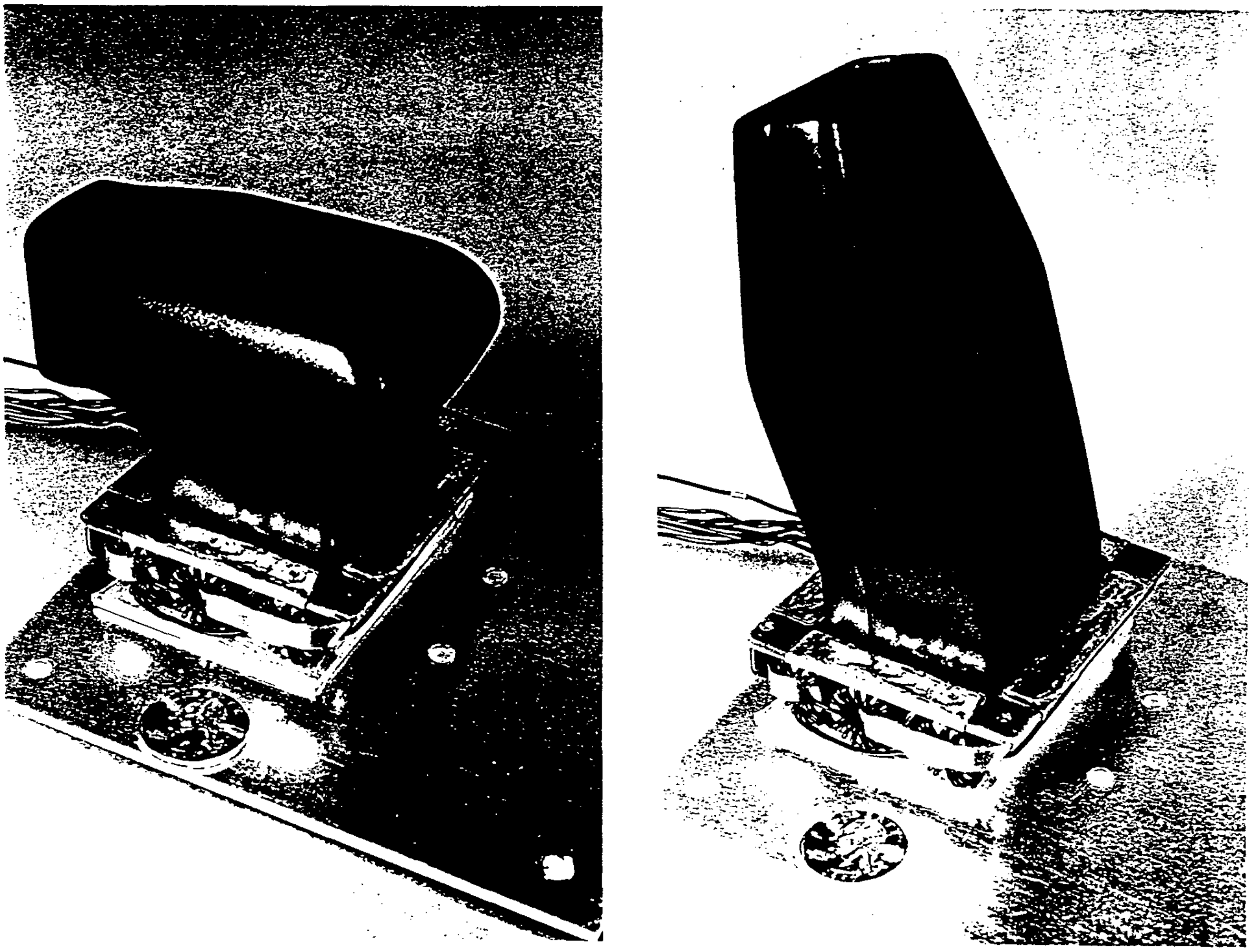


Figure 9. Imagers of reduced size having eddy-current excitation devices placed on the outside of the imager housing instead of inside (as in the currently available commercial devices) greatly reduces the size of the imager. At the same time, this innovation opens the possibility of developing interchangeable excitation devices—some for inducing rotating in-plane eddy-current excitation (for the inspection of nonferromagnetic materials such as aluminum), and some for exciting rotating in-plane magnetization—for the inspection of materials such as steel.