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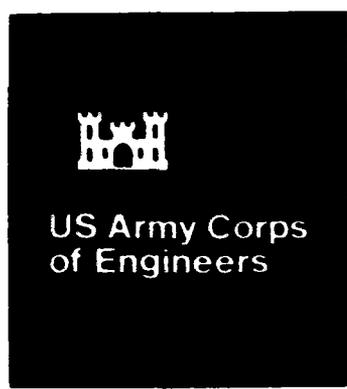
TECHNICAL REPORT REMR-CS-31

EVALUATION OF CIVIL WORKS
METAL STRUCTURES

by

Frederick H. Kisters
Frank W. Kearney

US Army Construction Engineering
Research Laboratory

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US Army Corps of Engineers
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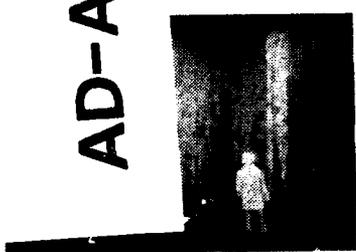
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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP   -   Lock gate.

MIDDLE   -   Lock wall.

BOTTOM   -   Inspection to measure thickness of lockwall.

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To keep civil works metal structures fully functional and safe, a thorough inspection procedure must be implemented. Engineering personnel who oversee the inspections at civil works projects can use the theory, applications, advantages, and disadvantages of each nondestructive testing (NDT) method as discussed in this report to guide the selection of an appropriate test method. Information on the elements of an NDT method that should be specified in an NDT contract are discussed. Because corrosion detection is an important part of an inspection, this process (and the equipment needed for the process) are also discussed. Case histories describe how NDT procedures can enhance inspection routines.

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PREFACE

This study was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32271, "Nondestructive Evaluation of Deteriorated Metal Structures," for which Mr. Frank Kearney was Principal Investigator. This work unit was part of the Concrete and Steel Structures Problem Area of this Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Mr. Lucian Guthrie (CECW-ED) was the Technical Monitor. Messrs. Jim Crews (CECW-OM) and Tony C. Liu (CECW-ED) served as the Overview Committee. The REMR Program Manager was Mr. William McCleese (CEWES-SC-A), US Army Engineer Waterways Experiment Station. The Problem Area Leader was Mr. Jim McDonald.

This study was conducted at the US Army Construction Engineering Research Laboratory (USACERL) under the general supervision of Dr. R. Quattrone, Chief, Engineering and Materials Division (EM). The USACERL Technical Editor was Gloria J. Wienke, Information Management Office.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degree Fahrenheit	0.55(° F-32)	degree Celsius
inches	25.4	millimetres
kips per square inch (ksi)	6,894,757.	pascals
pounds (force) per inch	175.1268	newton per metre

PART II: NONDESTRUCTIVE TESTING METHODS

6. An inspection program is necessary to ensure that structures are sound. A number of methods of checking the integrity of a structure or part without destroying it are popularly called NDT.

7. Until the late 1920's, NDT was practiced only in isolated cases and the methods used were crude and often unreliable. Critical parts were load tested, with an overload often applied. The conclusion drawn from such tests was that if a part or structure could withstand a single cycle of such a load, it would be safe enough to use in service. However, a single or static load is not always significant. Many parts in almost every type of machinery are subjected to dynamic and repeated loads (including reversed loading), and failures are sustained over time. Each applied load, or cycle, causes a small crack to progress and grow into a larger crack until at last the remaining strength of the cross section can no longer carry the applied load and the part fails. This type of progressive failure is called a fatigue failure, which can occur at stresses 30 to 40 percent lower than the tensile strength of the material from which the part is made. Designers employ experimental stress analysis, using brittle coatings or resistance strain gages to determine the optimum design for parts and structures. Nondestructive testing is used throughout parts manufacturing to make certain that the parts contain none of the defects that may result in fatigue failure. Only parts of acceptable quality are permitted to reach service, where nondestructive testing is also employed. Fatigue failures are not limited to mechanical components, but to structural members as well. Fatigue cracks may develop due to either improper design or to flaws in the material from which the part is made. However, it is possible for fatigue failures to develop in parts that have been well designed and made from adequately sound material because parts are sometimes subjected to accidental overloads not anticipated by the designer. Such overloads may be due to misuse or failure of other parts or components in the system, thus resulting in a redistribution of loads. Periodic application of nondestructive tests to parts that have been in service will discover such fatigue cracks while they are still incipient, and before they cause catastrophic failure.

8. Nondestructive testing offers assurance, in varying degrees, of the soundness of a structure or part that has been in service. Many NDT methods are used by industry today, but only a few of them can be applied to civil works projects at this time. These methods are detailed later in this chapter. Briefly they include:

   a. Visual inspection, which uses the eye, with or without a magnifier, to inspect a structure, part, or weld. This method is the least expensive and simplest inspection technique.

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b. Liquid penetrant inspection, which employs a colored liquid to detect surface cracks. Inspection kits are inexpensive, and the procedure can be performed by any person with good vision who has been instructed on the procedure and what to look for.

c. Magnetic particle inspection, which makes use of the way flaws distort a magnetic field. This method shows surface and some subsurface defects in magnetic metals. The equipment is inexpensive and the inspection procedure is easy to learn.

d. Ultrasonic inspection, which is comparable to sonar. Sound waves are reflected by discontinuities in a part or weld and produce indications on a cathode ray tube. Equipment is moderately expensive and a highly trained inspector is required to set up the inspection technique and interpret the results.

e. Radiography, which uses X or gamma radiation to photograph the interior of the part or weld. It is the most costly method, requiring a highly trained inspector to perform the inspection and interpret the radiographs. This method has the advantage of providing a permanent record of the test--the film.

9. Inspection methods often complement each other. For example, visual inspection can be used alone or with other methods. If the inspector was checking the operation of steam traps, the steam could be observed as it discharged into the atmosphere from the discharge pipe or test valve. The inspector must be able to distinguish between false steam and live steam. If a discharge pipe is not available, the trap can be inspected by listening to the sound to determine the "type" of flaw. Different steam traps make different sounds when functioning properly or improperly. By listening to the sound of the trap opening and closing using an industrial stethoscope or ultrasonic leak detector, the inspector can, with a little practice, determine the serviceability of the steam trap.

10. Other methods of nondestructive testing have been used in the past on Civil Works projects (see PART IV: CASE HISTORIES). Ultrasonic inspection has been used to inspect hinge pins on tainter gates for cracks, and to inspect welds after construction and repair. Ultrasonic thickness measurements have been used to determine the remaining thickness of lock gates or sheet piles. Magnetic particle inspection has been used to detect fatigue cracks on sector arms, and to evaluate the eye bars (attached to the gudgeon pins) on miter gates. If the bolts that hold the lifting cables fail, dye penetrant or magnetic particles could be used to evaluate the failure mode.

11. Nondestructive testing personnel are rated by the American Society of Nondestructive Testing (ASNT) at three levels of expertise; level 1 being the lowest, and level 3 being the highest. The contractor is responsible for training and certifying level 1 and 2 inspectors. Level 3 inspectors are certified by the ASNT and are required to train lower level inspectors. The contractor performing nondestructive testing must be able to verify that the inspectors are certified. Only individuals qualified for NDT level 2 or 3, or

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individuals working as NDT level 1 and supervised by an NDT level 2 or 3 inspector, may perform nondestructive testing.

12. When discussing nondestructive testing methods, it is essential that the terms used are understood and have the same meaning to all concerned. The following are some of the more common terms and definitions as applied to non-destructive inspection. It is important that they be thoroughly understood and used correctly.

a. An indication is visual evidence left as the results of a non-destructive inspection process. It may be an arrangement of magnetic particles in magnetic particle inspection, fluorescence under black lights in fluorescent penetrant inspection, colored dye markings for dye penetrant methods, a cathode ray tube reading for ultrasonic methods, or an x-ray film reading for radiographic methods. *The presence of an indication does not always denote the presence of a discontinuity.* Nonrelevant or false indications may be caused by conditions that have no bearing on the suitability of the part for its intended use. The peculiarities of the indications obtained by the various NDT methods will be discussed in detail during the study of each individual method.

b. A discontinuity is an interruption in the normal physical structure of the part. Examples of discontinuities are cracks, laps, seams, inclusions, and porosity. A discontinuity may be very fine or it may be quite large; it will generally be a definite separation or void in the metal. *A discontinuity is not always basis for rejecting a part.*

c. A defect is a discontinuity that interferes with the usefulness of a part, but *a discontinuity is not always a defect.* Whether a discontinuity is a defect is determined by the service history of the part, its stress loading, its severity, location, and proximity to other discontinuities.

Inspection Techniques

13. To evaluate a metal structure, use Table 1 to determine applicable NDT methods. If, for example, an NDT method was required to determine the quality of welds on a gate, Table 1 lists several methods that can detect defective welds. If the choice was between the two "best" methods, ultra-sonics and radiography, use Table 2 to decide which method would be better. For example, if the requirement was for a quick inspection that would not interfere with construction, ultrasonics should be selected. If, however, a permanent record is required and the inspection can be performed at night or at a distance from construction workers, radiography is a better choice, though more expensive.

Visual Inspection (VT)

14. **Application.** The most often used method to detect structural damage is simple visual observation. Visual inspection is the oldest NDT method, but its reliability depends on the ability and experience of the inspector. In looking for fatigue damage, the inspector would look carefully at the entire

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structure or part, but would conduct a detailed inspection of certain identifiable notch areas such as abrupt changes in surface contour, the toe of a weld, areas of incomplete fusion, bolt holes, surface irregularities caused by oxygen cutting, and keyways in gears, sprockets, and pulleys. A welding inspector can evaluate welds from the appearance of the weld. Visual inspection will detect undercuts, overlaps, arc strikes, underfills, crater cracks, porosities, and slag inclusions. The human eye, with the assistance of a magnifier, can see almost everything of significance on the surface of a weld, part, or structure.

15. **Theory**. Knowledge and good eyesight are the most important attributes of the inspector performing visual inspection. The Structural Welding Code (AWS D1.1) states that stress-bearing welds should be free of cracks, implying that the inspector must have good vision to spot hairline cracks. Good eyesight, lens-correctable to at least 20/40 vision in one eye, is usually a prerequisite for the visual inspector. The visual inspector should have a few tools such as mirrors, magnifying glasses, boroscopes, and flashlights.

        a. Magnifiers. Magnifiers are generally for examining a defect already found, not for locating a specific defect. A five-power (5X) magnifier is usually adequate. Figure 1 is a magnifier with an internal light source.

        b. Many magnifiers purchased at the local hardware store are not marked with the power of magnification, which should be known for report purposes. To calculate the magnification, measure the distance from the lens to the object, which is the focal length of the magnifier. Divide this number into the number 10, which is the average minimum distance of an object from the eye. If viewed nearer than 10 in., objects cannot be seen distinctly by the unaided eye. Using this formula, a lens with a focal length of 2 in. has a magnification of 5 or is said to be a five-power lens (10 divided by 2 = 5). To get the best


Figure 1. Illuminated magnifier

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possible performance from a magnifier, it should always be held as close to the eye as possible. Move the magnifier toward and away from the specimen to focus an image. The distance a magnifier can be moved toward or away from the specimen and retain a good image is called depth of field.

c. Boroscope. A boroscope is a precision optical instrument designed to enable inspection of the inside of narrow tubes, bore chambers, deep holes, and other inaccessible areas. Boroscopes are an arrangement of prisms and lenses through which light is passed with maximum efficiency. The light source located in front or ahead of the objective lens illuminates the part being examined. Boroscopes generally have fixed diameters and working lengths with optical systems designed to provide direct, right angle, retrospective, and oblique vision. Boroscopes are available in many different sizes and shapes dependent upon the type of application intended by the operator. If inspecting an area around a 180-degree corner, a flexible boroscope could be used. If the situation called for inspection with fluorescent penetrant, a boroscope using an ultraviolet light would be recommended. The basic types are illustrated in Figure 2.

(1) Angulated. Angulated boroscopes for special purpose inspection are available with fore, oblique, right angle, or retrospective visual systems. This type of boroscope consists of an objective section of varying length with fittings at the proximal end of the objective for attaching a telescope at right angles to the optical path. This permits inspection of shoulders or recesses in areas not accessible for inspection by standard boroscopes.

(2) Calibrated. Boroscopes can be provided to meet any specific inspection requirement. The external tube of the boroscope can be calibrated in inches or fractions thereof to determine the depth of insertion of the boroscope during inspection. It is also possible to provide boroscopes with calibrated reticles that may be used to determine angles in the object field or the size of objects in the field, provided the working distance is kept constant.

(3) Flexible. Flexible boroscopes can be used to examine internal areas that cannot be examined with a conventional boroscope. The flexible boroscope can be directed around curves and bends, and through gear boxes and spark plug holes. A major limitation is that it must be used in an opening 1/2 in. or larger.

16. Advantages. Visual inspection can often be done without the cost of shutting down the equipment, and it requires little training. It is a quick and very inexpensive method to determine if the part or structure conforms to specifications or codes, if it is failing, or if it has failed.

17. Disadvantages. Human factors, besides the necessary good eyesight, can influence the results of a visual inspection. Human beings are inherently different in speed and accuracy. The inspectors' tensions and emotions can also influence their judgment. Although visual inspection can often detect fatigue damage, a fatigue crack, particularly in the early stages, may be tightly closed and nearly impossible to see. (However, these types of tight

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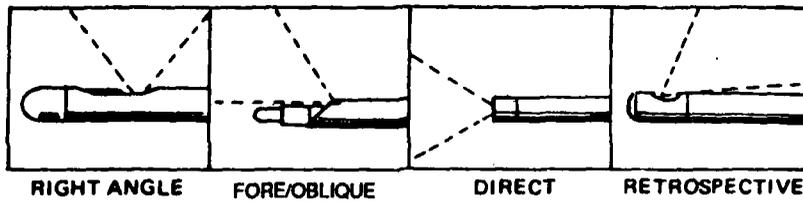
BOROSCOPE ANGLES OF VIEW
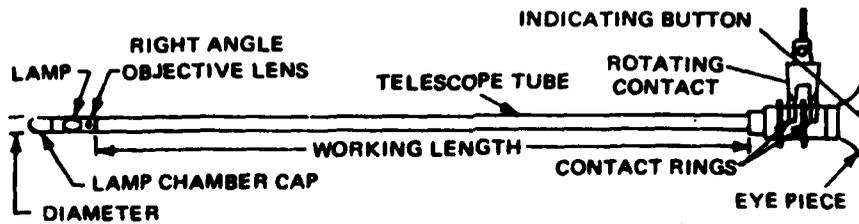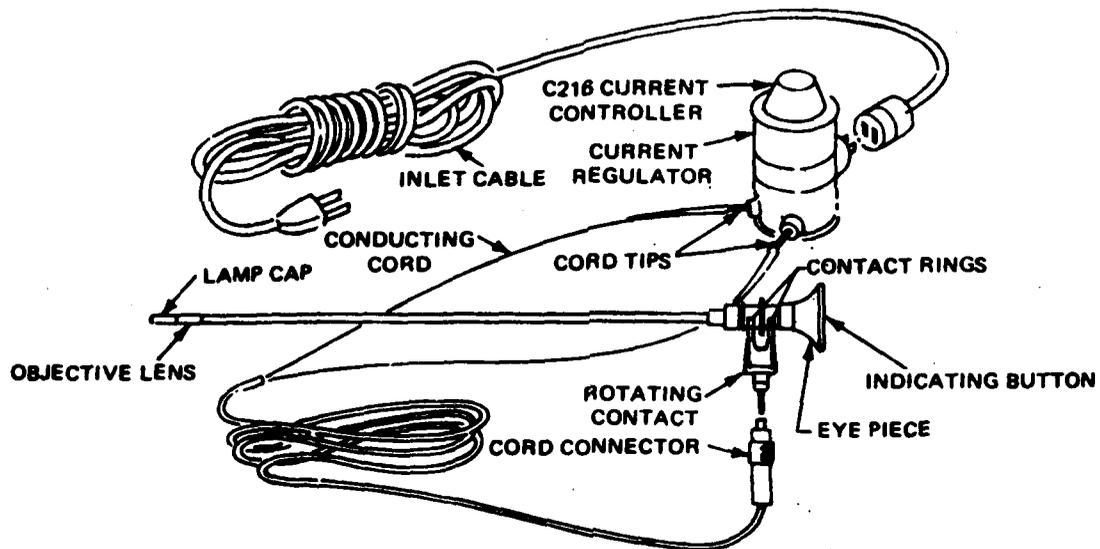
NOMENCLATURE FOR RIGHT-ANGLE BOROSCOPE

Figure 2. Optical boroscopes

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cracks can be detected and evaluated using liquid penetrant or magnetic particles.)

18. **Inspection Techniques.** The inspector must be knowledgeable and have good vision to make the inspection valid. The inspector must also be familiar with the required accept-reject criteria or specifications and codes. Armed with a magnifying glass, ruler, marker, and perhaps a camera, the inspector can perform the job satisfactorily. Visual inspection can be performed at any time, as a spot check, or periodically.

Liquid Penetrant Inspection (PT)

19. **Application.** Liquid penetrant testing (PT) is a method for detecting discontinuities that are open to the surface of the part or structure. Penetrants can be used on almost any nonporous material: ferrous and nonferrous metallic materials (especially brass, aluminum, and austenitic stainless steel), plastics, and ceramics. However, ferrous materials are usually inspected using magnetic particle inspection. Penetrants can detect discontinuities and defects such as surface cracks and porosity, holes, leaks, or other imperfections with a high degree of accuracy.

20. **Theory.** The fundamental theory of all penetrant inspection is the ability of a highly penetrating liquid to seep or be drawn by capillary action into any discontinuity in the material. The degree to which this occurs depends on how thoroughly surface dirt, rust, corrosion, grease, paint, or any other coating on the part have been removed.

21. **Advantages.** Visible dye penetrant is available in a small, self-contained kit and requires no special materials or equipment such as water, electricity, black lights, or darkened areas. However, visible dye penetrant is less sensitive than fluorescent penetrant. Penetrant testing is appreciably less expensive than either ultrasonics or radiography and penetrants are not affected by the geometry of the part. Penetrant inspection can be accomplished quickly, easily, and costs less per foot of weld inspected than any other nondestructive method except visual inspection.

22. **Disadvantages.** Most important, penetrant inspection is only applicable for defects that are open to the surface. Limitations of using penetrant inspection might include the size, shape, and finish of the part and when using fluorescent penetrants, the availability of a suitable darkened area for black light inspection. Penetrant procedures usually require a clean, relatively smooth surface, although some "as-welded" surfaces can be inspected. Grinding can smear the surface and close the surface openings of defects. The method's efficiency depends on the inspector's ability to recognize and evaluate the visual indications of flaws.

23. **Inspection Technique.** ASTM Standard E 165-80 describes the procedures of Method A, fluorescent penetrant inspection and Method B, visible penetrant inspection. Each method describes three types of procedures giving

a step-by-step sequence of inspection. With this combination of penetrants and developers, almost any inspection problem can be resolved, provided that the discontinuity or defect is open to the surface. The major steps in fluorescent penetrant inspection are illustrated in Figure 3.

24. Either the visible (DPT) or fluorescent (FPT) dye penetrant method can be used between a series of stringer welds or on a completed weld. There are three types of penetrant: water washable, post emulsifying, and solvent removable. Intermixing these penetrant materials is not permitted. Inspection procedures depend on the specific type of penetrant and the method used; therefore, only a general approach is outlined in this manual. Portable penetrant kits used on site are shown in Figures 4 and 5.

25. The surface must be clean and dry. The discontinuity must be free of oil, water, or other contaminants so that the void is open and the penetrant can enter. The method of cleaning the weld area is an important part of the test procedure.

26. The penetrant is applied to the surface by spraying or brushing. The inspector must allow enough time for the penetrant to enter all discontinuities. A minimum time of 10 minutes at a temperature of 37 to 125° F is recommended. The smaller the defect or the higher the sensitivity required, the longer the penetration time must be.

27. Excess penetrant can be removed from the surface by wiping with an absorbent cloth, either dry or moistened with a solvent. Removing the surface penetrant by spraying with solvents gives a clean surface; however, penetrant can be washed out of defects if the spraying is not done very carefully. Therefore, this technique is not recommended.

THE PENETRANT CAN SEEP ONLY INTO FLAWS WHICH REACH THE SURFACE

WHEN DEVELOPER DRIES IT DRAWS PENETRANT OUT OF CRACK ONTO SURFACE ON EACH SIDE OF IT, INCREASING THE SIZE OF THE INDICATION

EXPERIENCE IS NEEDED TO JUDGE EXTENT OF FLAW
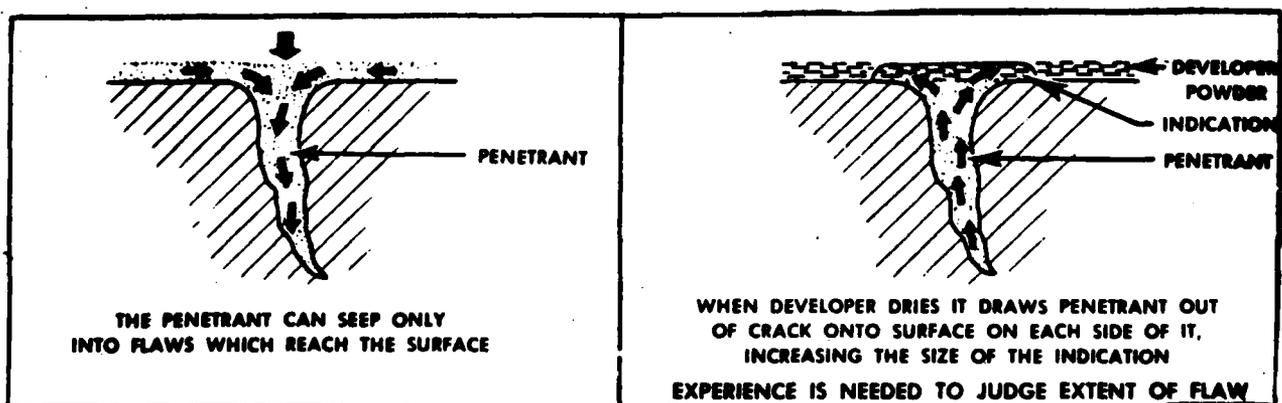
Figure 3. Major steps of fluorescent penetrant inspection
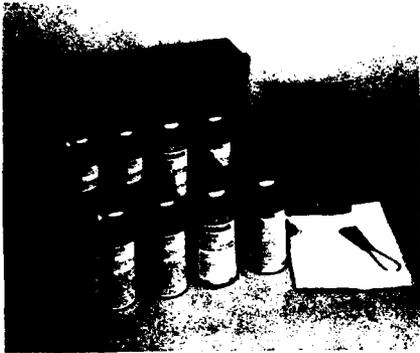
Figure 4. A typical visible
dye penetrant inspection kit

Figure 5. A typical fluorescent
dye penetrant inspection kit

28. The developer should be applied carefully to a dry surface so it does not produce a coat so thick that indications are masked. The developer acts as a blotter to draw the penetrant to the surface, where it can be seen with the naked eye or viewed under an ultraviolet light (in fluorescent penetrant inspection). The developer must be applied as soon as possible after removing the surface penetrant. The time between application of the developer and interpretation should be controlled (see following paragraphs). The true size and type of defect are difficult to appraise if the dye diffuses too much in the developer. The recommended practice is to watch the surface during the application of the developer in order to see certain indications that might tend to bleed out quickly.

29. Interpretation must be done within a specified time. A specification might indicate, for example, that interpretation must be done no sooner than 7 minutes and no later than 30 minutes after applying the developer.

30. Most acceptance standards specify similar time limits for cracks and linear indications, rounded indications of a specific size and quantity, and number of indications in a given area.

31. The shape of the penetrant indication, its size, intensity, and amount of spreading give useful information regarding a discontinuity. A fine crack will give a faint indication, but a wide or deep crack having more penetrant available can form a larger indication that will spread rapidly. The intensity and spread of the indication gives information about the size and depth of the discontinuity.

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Magnetic Particle Inspection (MT)

32. **Application**. Magnetic particle inspection is a nondestructive method of detecting cracks, seams, inclusions, segregations, porosity, lack of fusion, and similar flaws in ferromagnetic materials such as steels and some stainless steel alloys. This inspection method can detect discontinuities that may be too fine to be seen with the naked eye. It can also detect some subsurface defects, depending on the depth of flaw and type of inspection current used. This method is ideal for inspecting crane hooks, sheave blocks, and ferrous metals susceptible to fatigue cracking from vibration.

33. **Theory**. When a part is magnetized, a flux field is established in the part. If the part has a discontinuity on the surface or near the surface, the flux field will be distorted and cause a flux leakage at the surface. The break in the flux field will create poles that will hold magnetic particles so an inspector can visually evaluate the indication. Figure 6 illustrates the leakage that occurs in a magnetized specimen.

34. The ease with which a magnetic flux can be created in a material is known as its permeability. The property of a magnetic material to keep or retain a magnetic field after the magnetizing current is removed is called its retentivity. A metal object that loses most of its magnetism as soon as the magnetizing current is removed has low retentivity. Usually a magnetized metal that has high permeability has low retentivity, and conversely, a metal with low permeability has high retentivity. Construction steels generally have low retentivity.

35. The current used to induce a magnetic field in the part or structure may be dc, ac, or half-wave rectified (pulsating dc) current. If only surface defects such as fatigue cracks are to be inspected, ac current is often used. Direct current is used for detecting subsurface discontinuities, and half-wave rectified current is used to achieve maximum sensitivity. The pulsating field of half-wave rectified current increases the inspection
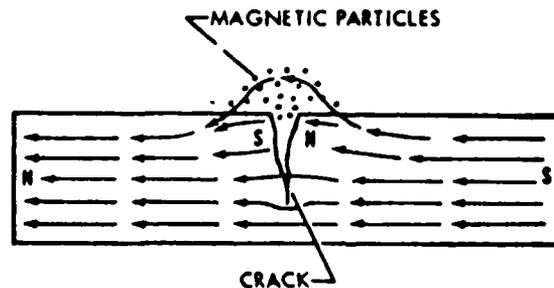

Figure 6. Crack in bar magnet attracting magnetic particles

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particle mobility and enables the particles to line up more readily in a weak leakage field, which is needed in the inspection of welds.

36. The magnetic particles used to make the defect visible may be applied to the weld either as a dry powder or as a suspension in a light oil. The dry powder is sprinkled or dusted on from a container and the wet solution is sprayed on, usually from an aerosol can. The inspection particles are carefully selected iron oxide particles of a specific size, shape, magnetic permeability, and retentivity. The particles can be gray, red, or black for contrast, or have a fluorescent coating for viewing with an ultraviolet light.

37. One method of applying the particles after magnetizing the part or structure is called the "residual method." The procedure is to apply the magnetic particles some time after the magnetic field has been removed. The residual magnetism orients the particles having high retentivity (high carbon or alloy steels). Most construction steels, however, have low retentivity and will not hold a magnetic field strong enough for this method. The recommended method for construction steel is the "continuous method"; magnetizing is done at the same time the inspection particles are applied.

38. Current can be introduced into the part or structure through prods, clamps, or a coil. When inspecting welds, prods or clamps are usually used to produce circular magnetization. A magnetic field can also be induced on a part or structure by wrapping a coil around it and sending a current through the coil. This method is called longitudinal magnetization. These two methods, circular and longitudinal, produce magnetic fields in different directions, thereby permitting the inspector to examine a metal in any or all directions when looking for specific defects. Figure 7 illustrates circular magnetism and Figure 8 illustrates longitudinal magnetism.

39. Advantages. Magnetic particle inspection can be used on any magnetic material and is rapid, inexpensive, and reliable when used by trained inspectors. Magnetic particle inspection can also be performed under water by divers.

40. Disadvantages. Magnetic particle inspection applies only to magnetic materials. It is not suited for very small, deep-seated defects. The deeper the defect is, the larger it must be to be detected. Subsurface defects are easier to find when they have a crack-like shape, such as lack of fusion in welds. Welds with rough surfaces may present difficulties.

41. The weld surface usually does not require grinding or smoothing before testing. However, if the edges of the weld are undercut or if the bead surface is extremely rough, the weld should be ground smooth and the edges blended into the base metal surface before magnetic particle inspection. The surface should be cleaned of all grease, oil, loose rust, or water because such materials interfere with the particle movement.
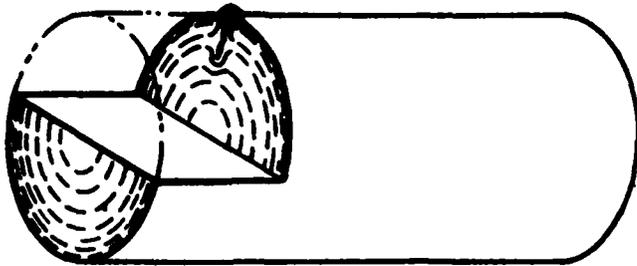
Flux leakage at
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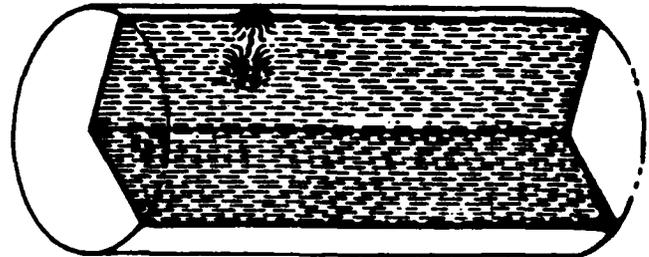
Flux leakage at
longitudinal discontinuity

TEST PART

CURRENT
APPLIED
AT ENDS

MAGNETIC LINES
OF FORCE

CURRENT
CARRING COIL

MAGNETIC LINES
OF FORCE

LONGITUDINAL DEFECT
INDICATED BEST

BEST   GOOD   FAIR   POOR

TRANSVERSE DEFECTS
INDICATED BEST

POOR   FAIR   GOOD   BEST
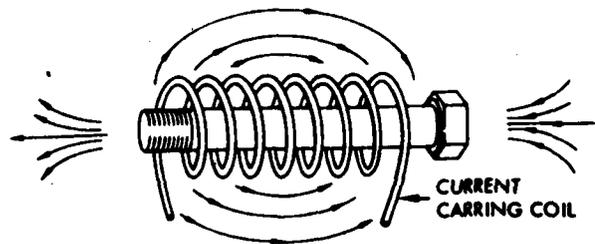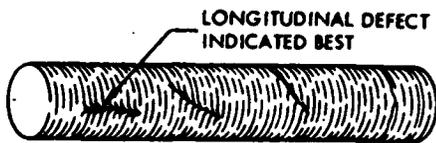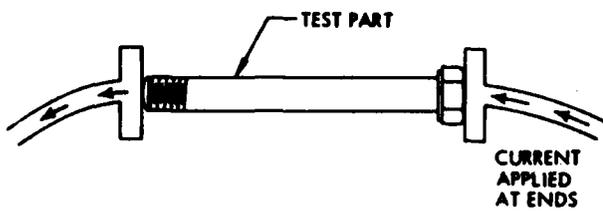
Figure 7.   Circular magnetism

Figure 8.   Longitudinal magnetism

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42. The "prod method" of weld inspection is widely used. Portable prod-type electrical contacts are pressed against the surface of the material next to the weld, as shown in Figure 9. The prods should not be spaced more than 8 in. apart. A shorter prod spacing with a minimum of 3 in. may be used to increase sensitivity. When the prods are positioned and the magnetic particle powders applied, the operator turns the current on. The current is turned off before the prods are removed in order to prevent arcing. At least two separate examinations should be done for each area. The prods are repositioned so that the lines of flux from the second examination are approximately perpendicular to the lines of flux from the first examination. Contact clamps can sometimes be used instead of prods.

43. The weld must be examined immediately. Surface defects appear as sharp indications, while subsurface indications are broad, diffuse patterns.

44. Written acceptance standards are based on the object's intended use. Standards vary, but most specify similar limits for possible defects.

45. Subsurface discontinuities or defects produce rather fuzzy magnetic particle patterns. They tend to appear rather wide and less sharply outlined and the particles do not adhere as well as they do to a surface defect. Defects close to the surface and those that are quite deep and sharp usually are cause for rejecting a part, especially if they lie perpendicular to the lines of stress in a part. Great care must be taken in interpreting the various types of defects because of the possibility of either over- or under-emphasizing their danger.
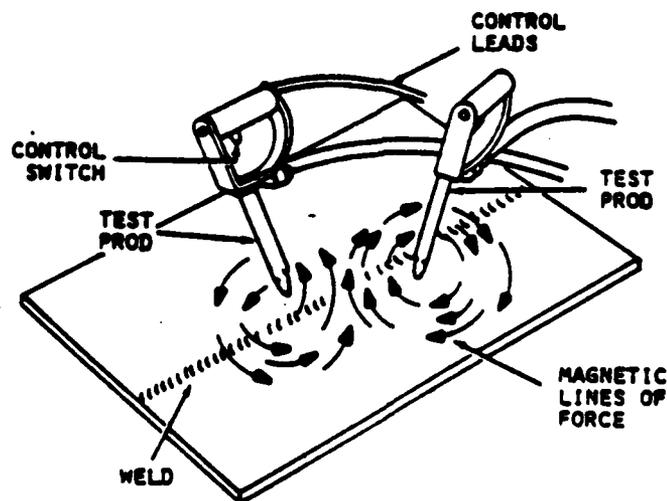
Figure 9. Magnetic field created around a weld as
current is passed between two test prods

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46. Surface defects are by far the most significant defects encountered in magnetic particle inspection. They are most easily located by this method. They are also much more dangerous than any other type of defect. Stresses are usually highest at the surface and any break in the surface constitutes a point of stress concentration that increases as the crack propagates. Because cracks are sharp, they increase stress more than most subsurface defects. The indication produced by all surface cracks is a sharp distinct outline of the defect. Defects that fall into this category are reason for rejection.

47. The correct interpretation of indicated discontinuities is extremely important. The principal distinguishing features of indications are shape, buildup, width, and sharpness of outlines. These characteristics, in general, are valuable in determining the defect's severity. However, careful observation of the character of the magnetic particle should always be included when completely evaluating the significance of an indication. The most readily distinguished discontinuities include fatigue cracks, heat-treat cracks, shrink cracks in welds and casting, and grinding cracks. The indications are distinguished by buildup of magnetic particles to a discernible height, and a well-defined sharp, thin pattern.

48. Where and why these discontinuities occur are listed below.

   a. Fatigue cracks are found in parts that have been in service. They are usually in the high-stress areas of the part, or where a stress concentration exists for some reason. It is important to recognize that even a very small fatigue crack indicates that failure of the part is in progress.

   b. Heat-treat cracks only occur on heat-treated parts and are usually located in or adjacent to abrupt changes in section, such as sharp corners and holes. They often show no relation to service stresses.

   c. Cracks in welded joints or castings that have not been heat-treated are often the result of shrinkage.

   d. Grinding cracks can only occur on surfaces that were ground and can be distinguished from other cracks because they are related to the direction of grinding and are not necessarily associated with areas of stress concentration.

   e. Indications of subsurface inclusions are usually broad and fuzzy. They are seldom continuous or of even width and density throughout their length.

   f. The magnetic particle test will sometimes reveal design features or other significant characteristics of a part. For example, when sufficient flux field strength exists, keyways, holes, or other abrupt changes of cross section will normally give a magnetic particle pattern. These discontinuities are not significant and the magnetic particle patterns resulting from them are commonly referred to as irrelevant indications. Cold worked areas may show indications by reason of a change in the magnetic properties of the metal at the point of working.

49. After evaluating the indications, demagnetization may be required. Structural steels usually have poor retentivity (will not hold an induced magnetic field), so if there is no retained magnetic field, demagnetization is

not required. If the part being inspected has a chemical composition or mechanical properties that cause high retentivity (will hold an induced magnetic field), demagnetization should be considered. The intended use of the part will be the deciding factor whether to demagnetize or not. For example, magnetism causes metallic particles to adhere to the surface of moving parts, which would cause undue wear and would be a reason to demagnetize. Magnetic fields can be detected by field indicators or a compass. These methods only show relative values, not true measurements of field strength.

Ultrasonic Inspection (UT)

50. **Application**. Ultrasonic inspection is a rapid, efficient, nondestructive method of detecting, locating, and measuring defects in weldments and/or base materials. Ultrasonic inspection is gradually replacing radiography to inspect welds during construction and maintenance because it is faster, cheaper, and safer. Ultrasonic sounds occur at a frequency too high to be audible. Human beings can hear sound vibrations between 16 and 16,000 hertz (Hz). The ultrasonic range starts at 18,000 Hz but is usually stated as beginning at 20,000 Hz. Ultrasonic flaw detection is usually in the range of 1 to 5 megahertz (MHz).

51. **Theory**. Ultrasonics makes use of low energy, high frequency mechanical vibrations or sound waves. These sound waves are directed into the material by a handheld device called a transducer or search unit. The transducer's function is to convert the electrical pulses generated by the ultrasonic inspection unit into sound vibrations. This is done by a piezoelectric element mounted in the end of the transducer which is placed in contact with the material being tested. The sound vibrations travel into the test object and are reflected from geometric boundaries or from other boundaries such as those formed by cracks, lack of fusion, slag inclusions, porosity, etc. Many of the sound vibrations are scattered and absorbed by the material; however, some of the vibrations will be reflected to the transducer. This received sound is converted into electrical signals by the piezoelectric element and is graphically shown on a cathode ray tube. A typical transducer or search unit is shown in Figure 10.

52. The sound vibrations emitted by the transducer or search unit must be coupled to the material being inspected by using water, oil, grease, or glycerin to exclude all air. The sound vibrations have properties similar to a beam of light. This energy or vibration will diverge from the transducer, be reflected at angles that are equal to the incident angle, and will become weaker as distance from the transducer increases.

53. Two important considerations in selecting a transducer are its diameter and operating frequency. The higher the frequency, the greater the
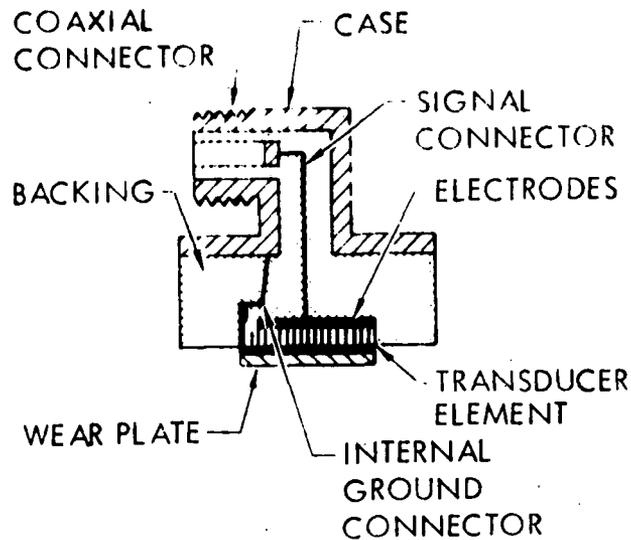
Figure 10. Contact search unit

sensitivity will be. This advantage may be offset if lower frequencies are needed to penetrate coarse-grained or very thick materials. At higher frequency and sensitivity, the penetration power decreases. Correspondingly, the lower the frequency, the greater the penetrating power but with a decrease in sensitivity. Generally, the method for determining the right frequency is to choose the lowest frequency which provides a satisfactory indication of the smallest defect to be rejected. The Structural Welding Code-Steel, D1.1-90, has specific charts and tables on ultrasonic inspection. A frequency of 2.25 MHz is recommended for weld inspection. Transducer size is determined by the scanning procedure, surface accessibility, etc. For example, small diameter transducers have a greater beam spread and thereby have less capability of pinpointing a reflecting surface. Most ultrasonic weld inspection is performed using a straight beam or angle beam transducer.

54. The straight beam transducer uses a longitudinal wave, which directs the sound into the material perpendicular to the surface. This method is used to locate subsurface defects such as laminations or porosity on material approximately 1/2 in. thick or greater, as shown in Figure 11.

55. The angle beam transducer is a straight beam transducer mounted in a plastic wedge of a specific angle. The sound wave is introduced into the material at 45, 60, or 70 degrees, depending on the material thickness. This angle beam is a shear wave that travels at approximately one-half the speed of longitudinal waves. Most weld inspection is accomplished using an angle beam transducer, as shown in Figure 12.

56. Most straight and angle beam techniques use the pulse-echo method where one transducer, or search unit, is both the transmitter and receiver of

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·WIDTH OF INSPECTION ZONE
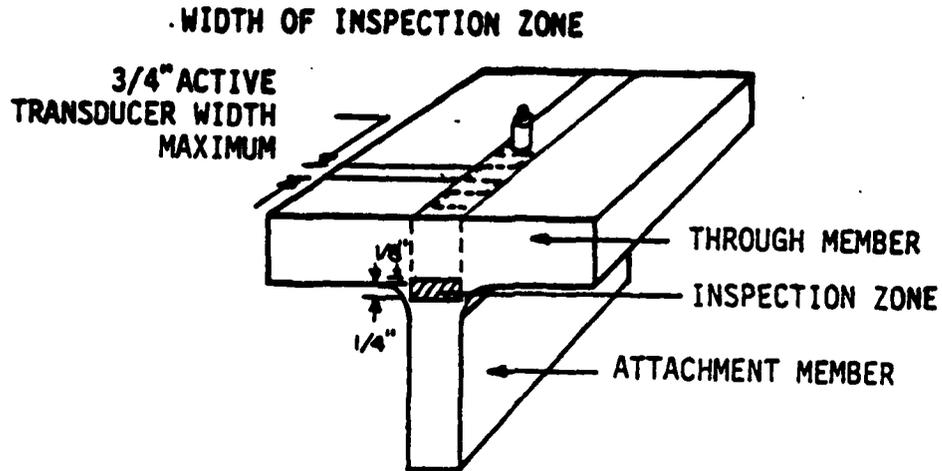
Figure 11.   Straight beam inspection technique used
in scanning a tee weld
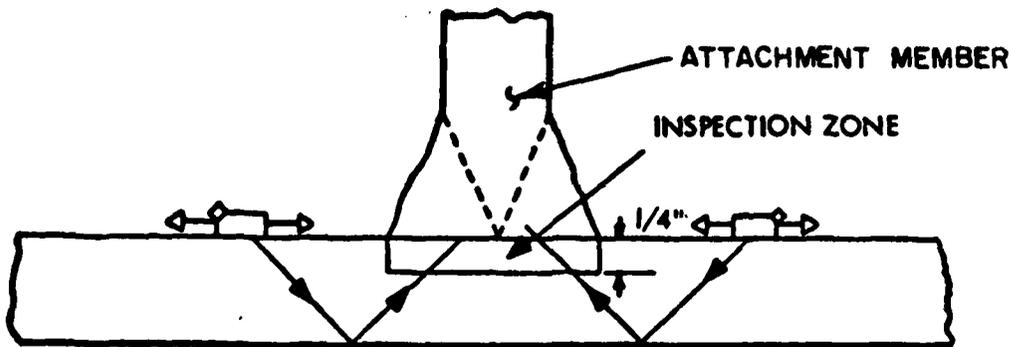
Figure 12.   Angle beam transducer

the ultrasonic sound waves. Like sonar, the transducer emits a burst of sound
waves then waits for reflected waves. The electrical signal striking the
transducer, which is usually not more than 1 microsecond in duration, makes
the transducer vibrate during the driving period. The duration of the pulse
is short, so that returning or reflected echoes from defects or boundaries
lying close to the surface will appear as separate indications, as shown in
Figure 13. Such a presentation is called an A-scan and is a "time versus
amplitude display." The relative depth and size of the discontinuity can be
estimated from the pip or pulse location on the CRT time line and its
amplitude.

57.   Some applications use a method called "through transmission" or
"pitch and catch," where the transmitting and receiving transducers are
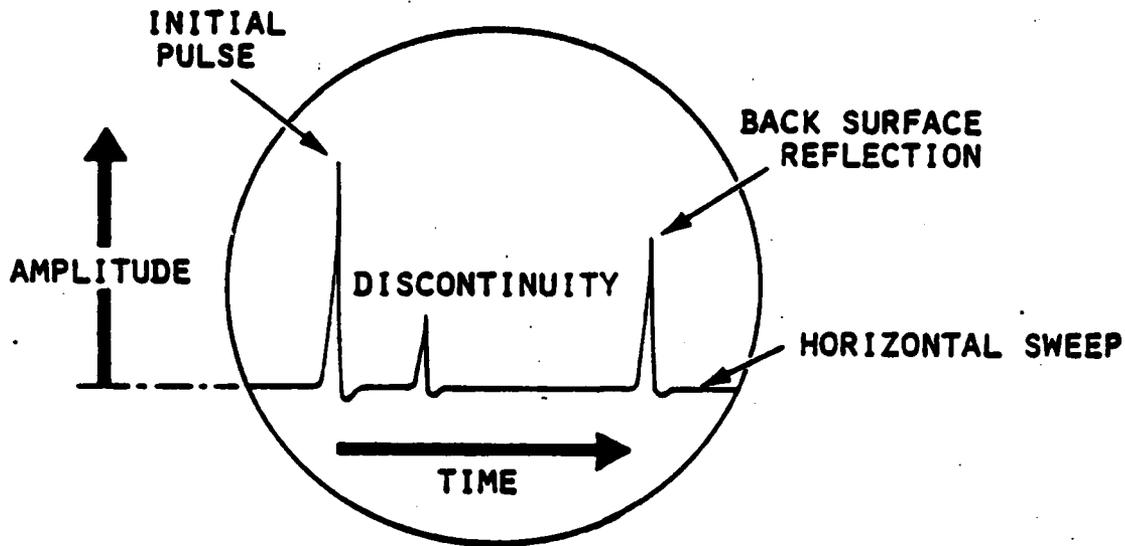
Figure 13. A-scan presentation on cathode ray tube

separate, each connected to a different cable. Using through transmission,
the transducers are geometrically aligned so that a maximum signal is trans-
mitted by one transducer and picked up by the receiving transducer. The
presence of a defect in the path of the sound will reduce this received signal
since defects would reflect or scatter the sound energy emitted by the trans-
mitting transducer. The amount of reduction in the received signal indicates
the severity of the discontinuity. This technique is difficult to use because
of the possibility of misaligning the transducers. Because it is difficult to
evaluate the defect's size using this technique, it is most frequently used in
"go/no-go" situations. However, the defect size can be determined if a stan-
dard is used to calibrate an amplitude height on the CRT. When moving the
transducer along the test piece, the loss (or gain) of reflection is indica-
tive of a defect.

58. **Advantages.** Ultrasonic inspection has many advantages over other
methods. It is fast, and the equipment is compact and portable. Unlike
radiographic inspection, it involves no time delay while film is being pro-
cessed and poses no radiation hazard to persons working in the inspection
area. Indications of flaws can be seen immediately on the CRT. Both internal
and surface flaws can be detected (though shallow surface cracks are more
easily and relia'ly detected with magnetic particles or liquid penetrant).
Since there are ɔ expendable materials, the inspection can be performed
faster and at ɔ̣r cost than radiography. Certain types of defects not
readily detected by other inspection methods can be found by ultrasonics. By
using calibrated standards and a few calculations, the inspector can classify
the indications as irrelevant, acceptable, or unacceptable. Ultrasonic

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inspection has a higher sensitivity level than does radiographic inspection. Ultrasonic inspection is more sensitive to crack detection as the material thickness increases. For radiographic inspection, the opposite is true.

59. Disadvantages. Ultrasonic inspection alone produces no permanent record showing the flaws and their locations. A high degree of operator skill and training is required to interpret the oscilloscope patterns reliably. Flaws, such as cracks, oriented parallel to the sound beam may not be detected. The surface of the material must be free from weld spatter and must be smooth enough to allow effective coupling between the transducer and the material. Surface roughness can cause scattering and absorption of the sound. Also, inspecting a rough surface creates undue wear on the surface of the transducer, causing premature failure. A viscous coupling agent such as glycerin or oil which fills surface depressions or pits, is necessary to eliminate the compressible air which prevents sound (mechanical vibrations) from entering the material from the transducer.

60. The CRT presentation of a defect can be photographed for a permanent record and the location of the flaw plotted on a blueprint of the structure. The plotting accuracy depends on the integrity of the inspector. Some ultrasonic inspection instruments are combined with loggers and printers that produce a digital printout of the flaw and location. Again, the accuracy of the flaw location on this printout depends on the inspector.

61. Inspection Techniques. ASTM E 164-81, Standard Practice for Ultra-sonic Contact Examination of Weldments, covers personnel qualification, search units, calibration, reference standards, and inspection procedures. AWS Structural Welding Code-Steel, D1.1-90, covers reference standards, testing procedures and flaw size evaluation procedures that give accept-reject limits.

62. In preparing for an ultrasonic inspection, an operator must consider certain parameters: type and size of transducer, couplant, scanning procedures, peaking techniques, frequency, pulse length, linearity of indications, distance/time relationship, and sensitivity/time relationship. Other items to be considered are specimen properties: material sound/velocity, specific acoustic impedance, part geometry, material attenuation, and noise level. Each signal peak along the scan line represents a place in time where the acoustic energy has encountered an interface or a multiple of a previously generated signal. By knowing the beam path and spread, the operator can interpret the signal and separate relevant from irrelevant indications. The operator must consider amplitude/distance response and amplitude/area response when determining flaw size. The shape and orientation of the flaw also affect the signal amplitude. In attempting to determine flaw size, an operator must watch both the flaw signal amplitude and the loss of amplitude of the back reflection.

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63. Before any inspection, the ultrasonic unit must be calibrated for sensitivity and horizontal sweep (distance); a calibration block or other recognized method must be used. Calibration of ultrasonic equipment is important in determining the exact location and approximate size of defects. A calibration block is used to standardize the different kinds of ultrasonic equipment and transducers in the field, to reproduce a specific sensitivity setting, and to give a basis for the exchange of measuring data. Various manufactured calibration blocks are referred to in the ASTM, ASME, and IIW codes and standards. Two commonly used calibration blocks are shown in Figure 14. A part with a known defect or a sample part with a hole simulating a defect can also be used, as shown in Figure 15. Locating a flaw is usually simpler than evaluating a defect.

64. The surface of the material being inspected must be free of weld spatter, rust, and any extreme roughness. A wire brushing or light sanding is usually sufficient. A rough surface creates poor transducer contact and can cause damage or premature failure of the transducer. Grease, dirt, and loose scale can cause scattering or attenuation of the sound waves. Tight layers of paint need not be removed unless the thickness exceeds 10 mils.

65. A coupling agent must be used between the search unit and the metal. The base metal is first examined for lamellar flaws using a straight beam search unit, and is then inspected using the angle beam. The search unit must be placed on the metal surface with the sound beam aimed about 90 degrees to the weld axis and manipulated laterally and longitudinally so the ultrasonic sound beam passes through all of the weld metal.

66. For welds not ground flush (Figure 16), the angle beam or shear wave technique is used. To detect longitudinal flaws, sound is directed into the weld from each side. The transducer is oscillated to the left and right with an included angle of about 30 degrees. For transverse defects, the transducer is placed on the base metal at the edge of the weld. It is then positioned so the sound beam makes about a 15-degree angle to the longitudinal axis of the weld. To scan, the search is moved along the weld edge from both sides. Scanning is done similarly for welds ground flush. However, the transducer is moved across the weld to detect longitudinal flaws. To detect transverse defects, the transducer is oscillated left and right through a 30-degree angle while continuously advancing along the top of the weld.

67. When an indication of a flaw appears on the CRT, the location and position of the transducer are recorded. By using graphs, calculators, or guides, the operator can accurately locate the position of the defect in the weld. By using applicable charts and attenuation factors, the weld discontinuity can be accepted or rejected.

68. <u>Thickness Measurement</u>. Ultrasonic inspection is specifically applicable to inspecting piping, sheet piling, or lock gates to determine

1.0 IN.

4.0 IN.

12.0 IN.

IIW-2 BLOCK

1.0 IN.

3.0 IN.

0

0

30° 45° 60°

70° 60°

MINIATURE ANGLE BEAM BLOCK
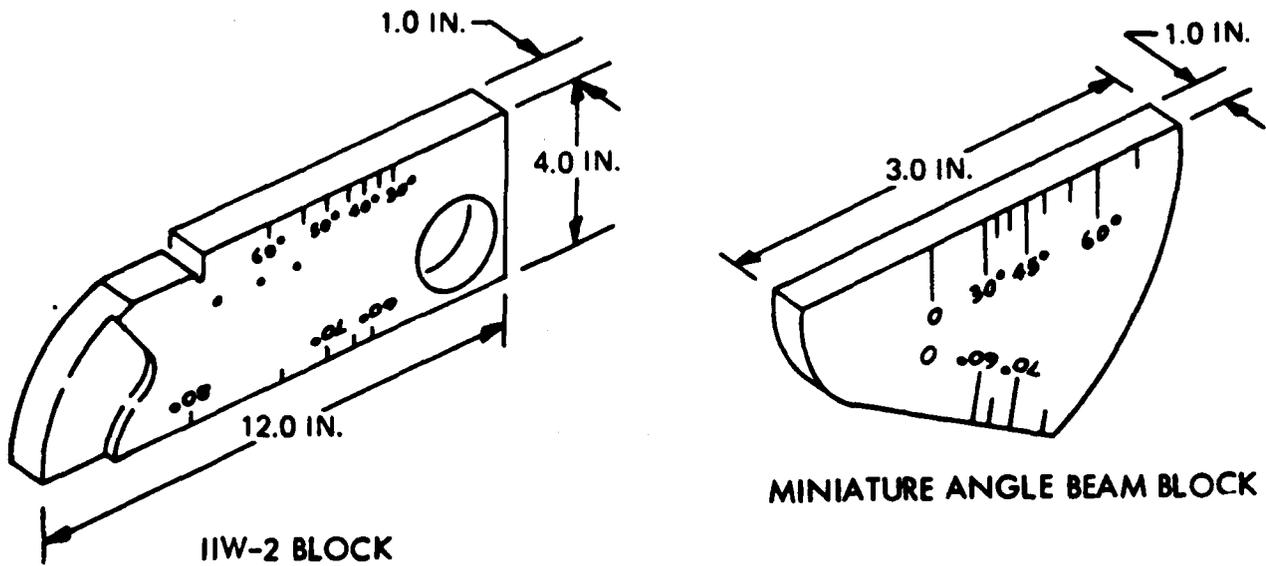
Figure 14.   Ultrasonic calibration blocks

SEARCH UNIT

BOLT

SAWED
SLIT
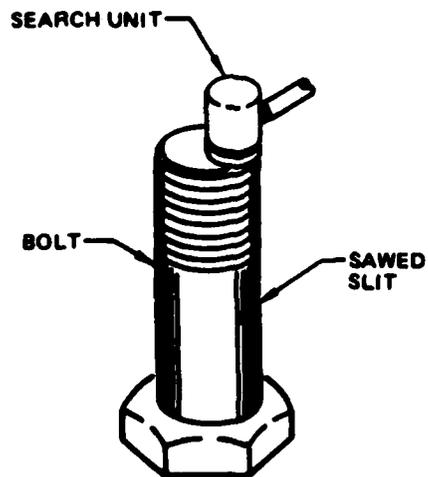
Figure 15.   Reference standard for inspection of a bolt

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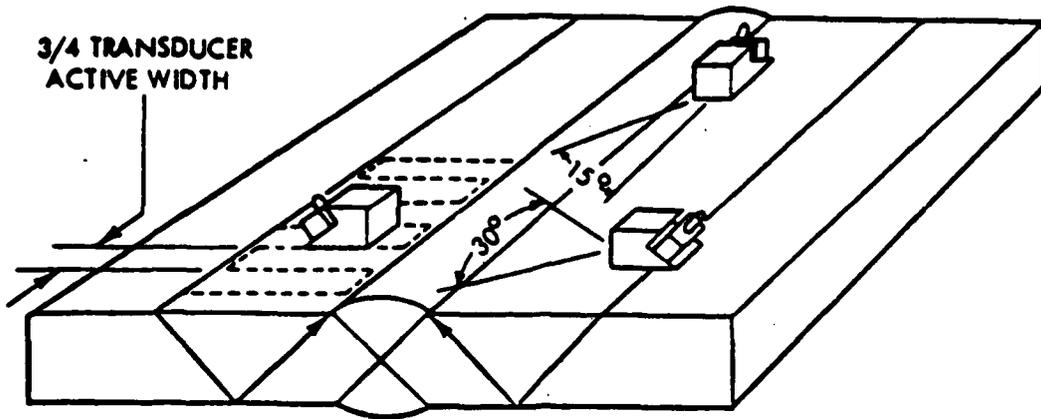
SCANNING PROCEDURES FOR WELDS NOT GROUND FLUSH
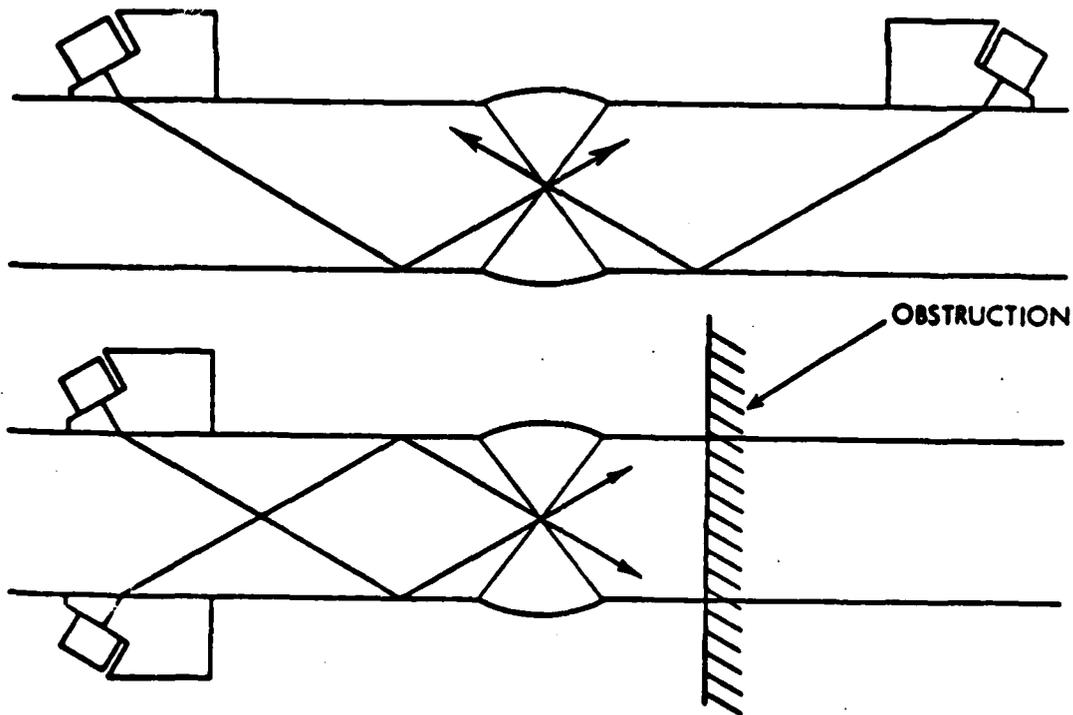
Figure 16.   Scanning procedures for welds not ground flush

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material thickness. The inspector can easily determine how much material has corroded or eroded by subtracting the current metal thickness from the thickness at the time of construction. For example, if the sheet piling was 0.375 in. thick when it was installed and the ultrasonic unit indicates that the present thickness is 0.125 in., the material has corroded or eroded 0.250 in. With this information, the corrosion engineer can determine the material's corrosion rate and can approximate the material's remaining service life.

69. Ultrasonic Leak Detection. Many methods available to detect vacuum or pressure leaks use Freon or helium as tracer gases. These systems require the gas from the leak to be drawn into an instrument and analyzed. This type of sensing instrument is generally limited to a single or limited number of gas types. Unless the work area is virtually free of the gas from a located leak, the ambient gas may give false indications or mask the true location of another leak.

70. Because the ultrasonic leak detector doesn't use a tracer gas, it is not limited to a single gas type and does not need a gas-free work area. Gas molecules escaping from a container, line, fitting, or hose under pressure create ultrasonic sound energy. The molecules of gases escaping under similar conditions will generate similar sounds. The intensity of the sound is a function of the size of the leak as well as the pressure differential across the effective leak orifice. The sonic energy from a pressure leak creates a sound in the frequency range between 35,000 and 45,000 cycles per second. The frequency depends on leak rate.

71. The sound frequencies are above the human range of hearing and are classified as ultrasonic. Certain characteristics of these frequencies make them ideal for inspecting pressure and vacuum leaks. Since they are outside the range of the majority of machine and work area noise, background sounds do not interfere with testing. Also, the short wavelength of these frequencies permits ultrasonic detection equipment to easily pick out the sound from a leak and pinpoint the source.

72. The ultrasonic leak detector is really a "translator detector." A microphone on the instrument detects the ultrasonic sounds and translates them into sounds within the audible range so the operator can hear the leak as the familiar "hiss." Ultrasonic equipment comes in a variety of sizes and with a variety of accessories. Most equipment is battery powered and handheld, the size of a small portable radio. The inspection procedure is simple. The operator holds the probe, or instrument, and scans the piping, hoses, or other possible leak sources in the same way that a flashlight would be directed to illuminate the suspected source locations. Since the response is acoustical, it is not necessary for the probe to actually "sense" or absorb gas from the leak. The operator can wear headphones to eliminate any audible background

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noise that could cause distraction. The ultrasonic leak detector is not affected by wind or background noise.

73. Some ultrasonic leak detectors also have a "contact probe" that the operator can place on a valve. The operator can watch a meter for visual indications or listen with headphones for specific sounds generated by a leak. By moving from spot to spot over the surface and evaluating the sounds produced, the operator can easily and quickly locate leaks. Suspected cavitation of a pump can be detected. Spots of excessive frictional wear on a component can also be detected. For example, normal valves under pressure are quiet when closed. Leaking valves produce the sounds of fluid rushing through a restricted passage, which the leak detector picks up. The ultrasonic leak detector has been used by industry to detect malfunctioning steam traps, arcing in electrical transformers and components, and to locate failing bearings on pumps and motors.

Radiographic Inspection (RT)

74. **Application**. Radiographic inspection is a nondestructive testing method that provides a permanent film record of the internal condition of a material, such as a weld or casting. Some of the weld defects that can be recorded on a film are: porosity, slag inclusions, cracks, lack of fusion, incomplete penetration, burn through, inclusions, undercutting, and surface irregularities. Radiography is useful in detecting corrosion, cracks, wear, and misalignment in areas that are inaccessible by visual or other inspection methods. However, the defect in the part must be properly oriented in relation to the primary beam of radiation. For example, radiographic inspection will not reveal laminations. Although radiography has earned a reputation as a reliable test method, it cannot detect tight surface cracks as readily as the liquid penetrant method. Also, in radiography, the film must be placed on the side of the object opposite the radiation source. If the opposite side of a part, or a weld is inaccessible, some other inspection method (ultrasonics or magnetic particle inspection) must be used. ASTM Standard E94-84a, Radiographic Testing, covers radiographic quality levels, radiographic film, use of filters, backscatter protection, use of screens, exposure calculations or charts, technique files, penetrameters, film processing, viewing radiographs, and storing processed radiographs. Only certain aspects are listed here that might be of specific concern to the practicing engineer.

75. **Theory**. In radiographing a structure or part, the film, screens, and exposure time depend on the part being filmed and are determined by the engineer. The radiation source is positioned with the proper source-to-film distance. Penetrameter and identification numbers are placed on the part being radiographed. The film is then exposed, developed, dried, and interpreted. Some of the radiation that penetrates the specimen is scattered or absorbed, but a small amount of radiation reaches the film to expose it. If

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the specimen is a uniform thickness, the processed radiograph will be a uniform shade of darkness and the specimen will be outlined. If the specimen has recesses, cutouts, or voids, more radiation reaches the film and creates darker areas (Figure 17). The dark areas create a contrast with other shades of darkness on the radiograph, allowing the film interpreter to evaluate the interior of the specimen.

76. The radiation source can be either x-rays or gamma rays. X-ray machines are available in a wide range of sizes and voltage ratings. The voltages needed depend on the thickness and composition of the metal to be radiographed and are in the kilovoltage range. Gamma sources have more penetrating power than x-ray sources. Gamma radiography (Figure 18) is frequently used in construction because no external power is required, the equipment is portable, and confined spaces can be inspected because of the small source size.
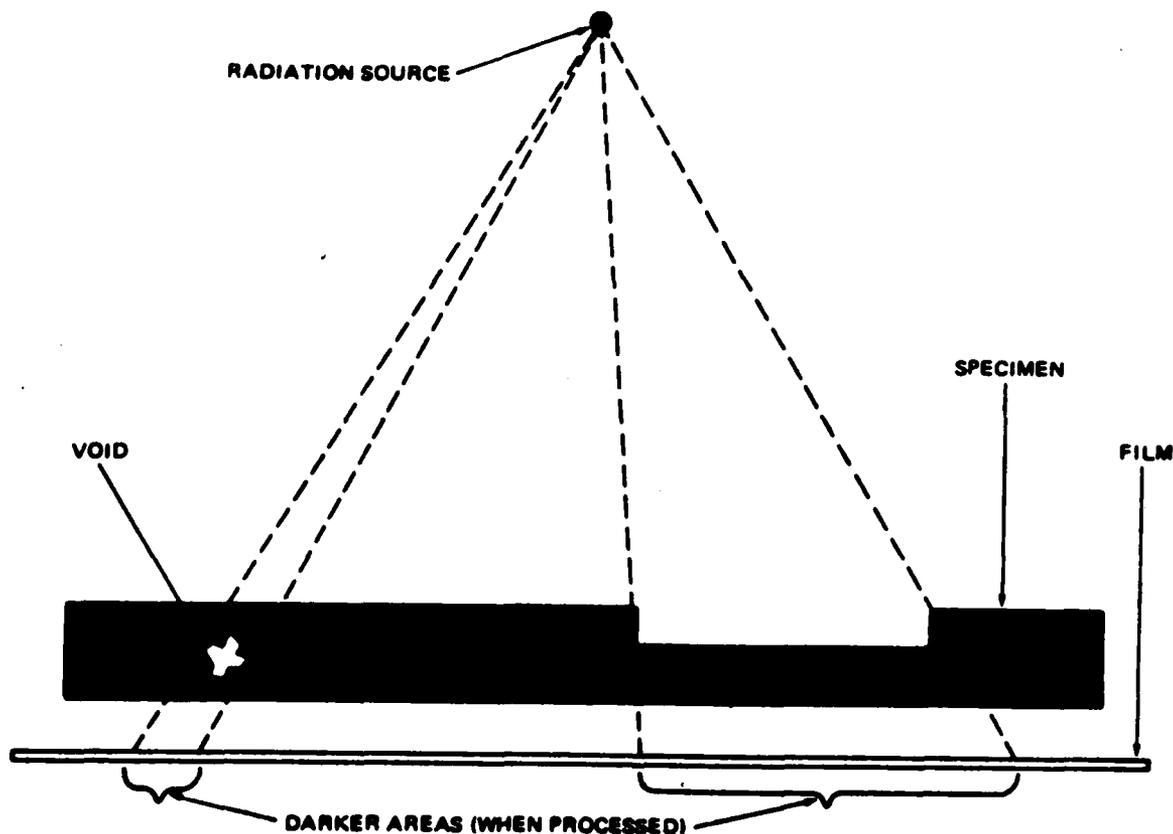
Figure 17. Basic radiographic process showing differential absorption
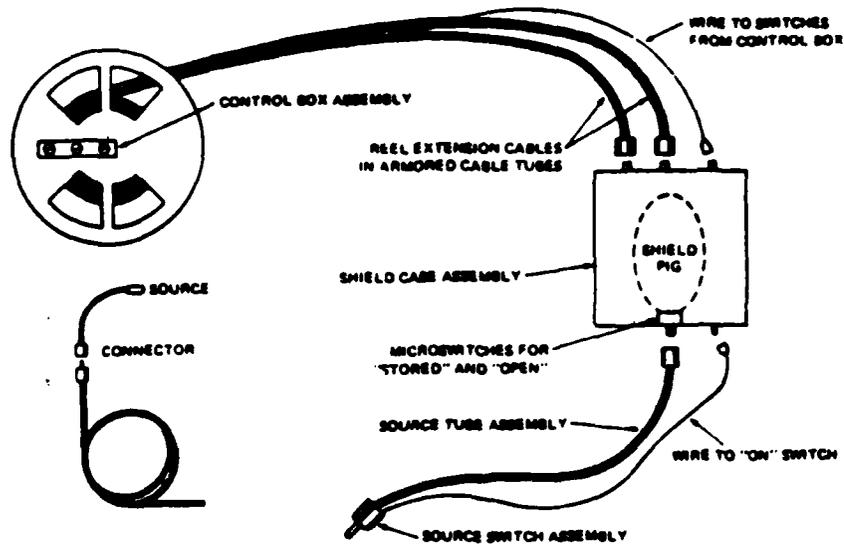
DIAGRAM OF TYPICAL ISOTOPE CAMERA
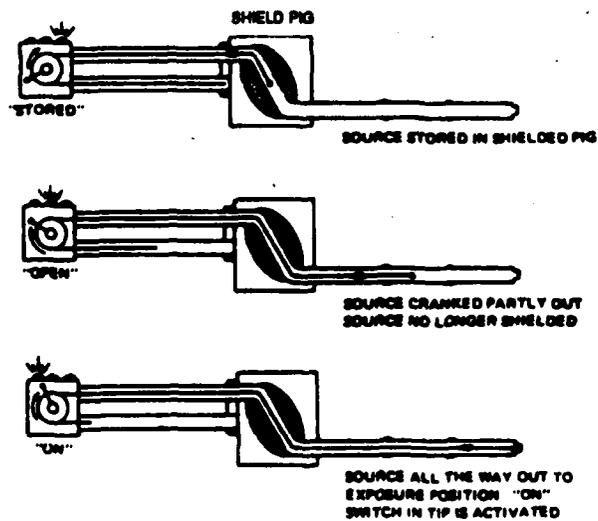
OPERATION OF TYPICAL ISOTOPE CAMERA

Figure 18. Typical arrangements for gamma radiography

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77. The proper radiographic film must be selected to produce the desired image sharpness with the best contrast and the least exposure time. Selecting the film to be used depends on several factors: the thickness and composition of the item to be radiographed, the exposure time desired, the radiation source, and the voltage range of the source unit. Generally, as film speed increases, quality decreases. Images on the film are formed by multitudes of microscopic silver crystals called grains. The grain size determines the fineness of detail that can be perceived on a film. Fast films have a large grain and poor resolution, while slow films have fine grain and good resolution.

78. When an x-ray or gamma ray beam strikes a film, less than one percent of the energy is absorbed. Since the formation of the radiographic image is primarily governed by the absorbed radiation, more than 99 percent of the available energy in a beam performs no useful photographic work. Obviously, any means to more fully use this energy, without complicating the technical procedure, is highly desirable. Lead screens placed in the film holder can intensify and filter some scattered radiation. The intensifying action is due to the emission of electrons from the surface of the lead when radiation impinges on the screen and by the action of the secondary x-rays produced by the lead. The electrons in turn cause a photochemical reaction in the film. The intensifying screens are placed in close contact with each side of the film. The lead screens also absorb the low energy scattered radiation from the part being radiographed, giving a sharper radiograph. Figure 19 illustrates a typical x-ray set up.

79. Penetrameters (Figure 20) are placed on the object to be radiographed to determine the quality of the radiograph. ASTM Standard E 142-86, Controlling Quality of Radiographic Testing, describes penetrameter composition, thickness and hole size, radiographic quality levels, placement of penetrameters, location of markers, identification of the radiograph, image quality, and maintenance of records.

80. Penetrameters are fabricated of a thin strip of metal of the same (or radiographically similar) composition and of approximately the same density as the object being radiographed. The penetrameters are identified with lead alloy numbers at one end indicating the thickness of the material being radiographed. Lead letters are located on the other end of the penetrameter indicating the composition of the penetrameter.

81. The three holes in the penetrameter are used to demonstrate detail sensitivity. The holes are artificial flaws of specific dimensions and are usually expressed in the thickness of the penetrameter. For example, a 1T hole has a diameter equal to the penetrameter thickness while a 2T hole would have a diameter twice the penetrameter thickness. The penetrameter and its

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holes show clearly in the radiograph. The quality level required for radiography on Corps of Engineers projects should be at least 2 percent.

82. Film processing equipment can be either manual or automatic. Processing systems should contain separate tanks for developing, short stop or washing, fixing, and final washing. Film driers must not cause processing defects.

83. A densitometer or a density strip is placed on the film during test shots to make sure film density requirements have been met. Density, a measure of the degree of blackness, is a function of exposure time and intensity of the radiation to which the film is subjected. The radiographer controls these variables.

84. **Advantages**. Radiography permits the inspection of parts without major disassembly, and the inspection of opaque objects such as welds. The radiograph provides a permanent record. Isotope radiography is used more than x-radiography because of the higher penetrating power and portability. Isotopes also require no power source or maintenance and are lightweight.
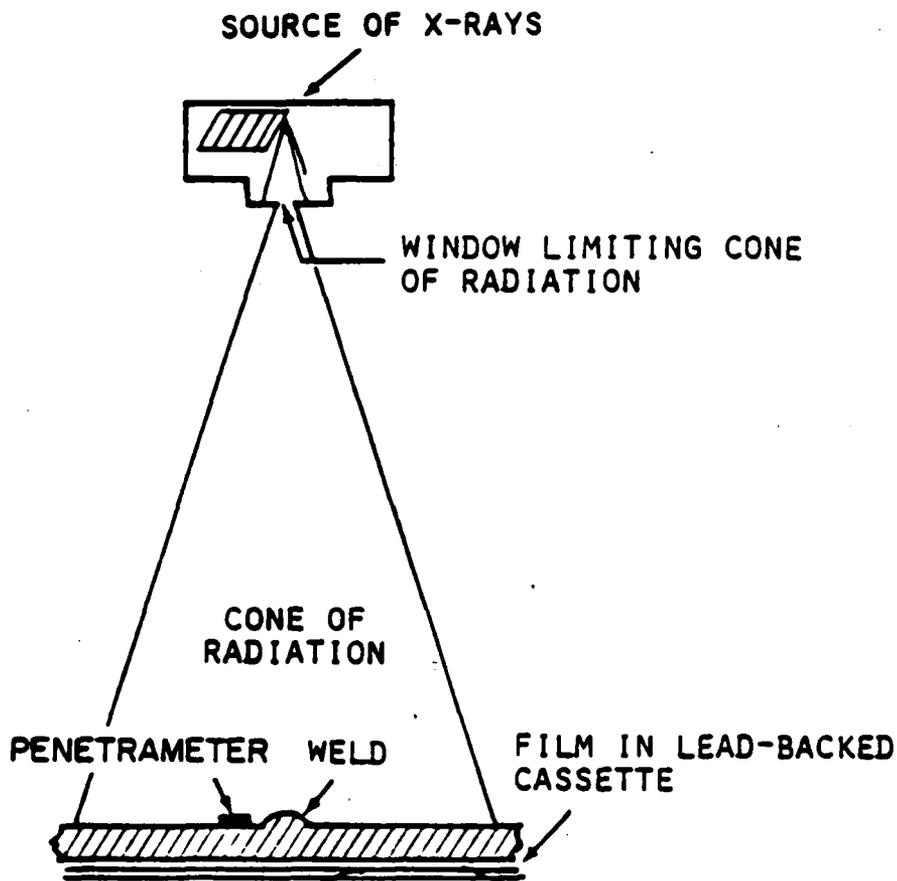
Figure 19. Radiographic setup

ALL DIMENSIONS IN INCHES
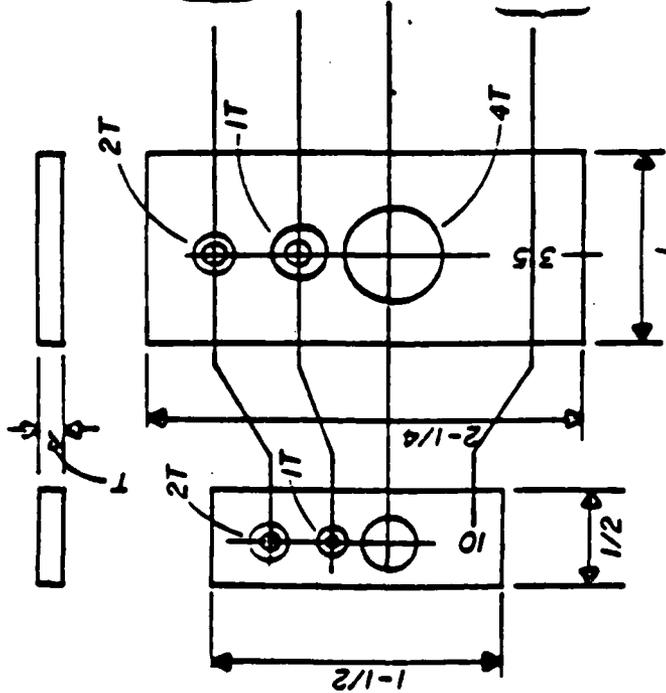
T = THICKNESS OF THE PENETRAMETER (LESS THAN 2% OF TEST SAMPLE THICKNESS)

DIAMETER = 2T BUT NOT LESS THAN 0.020"

DIAMETER = 1T BUT NOT LESS THAN 0.010"

DIAMETER = 4T BUT NOT LESS THAN 0.040"

IDENTIFICATION NUMBER SHOWING MINIMUM THICKNESS ON WHICH THE PENETRAMETER MAY BE USED. NUMBER MUST SHOW IN RADIOGRAPH.

ALL HOLES SHALL BE TRUE AND NORMAL TO THE SURFACE AND NOT CHAMFERED.

PENETRAMETERS SHALL BE MADE OF MATERIAL BEING TESTED.

PENETRAMETER THICKNESSES EXCEEDING 2-1/2

PENETRAMETER FOR THICKNESS NOT GREATER THAN 2-1/2

2T

1T

4T

2T

1T

10

2-1/4

1

1/2

1-1/2

Figure 20.   Details of penetrameters

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85. Disadvantages. Due to the hazardous nature of radiation, all personnel must be cleared from the area when using x-ray or gamma ray equipment. Personnel must be trained to operate the equipment. The initial radiographic set up is expensive. Related equipment and a darkroom must be provided to develop the film. There is a delay in reviewing inspection results due to the time required to process the film.

86. Inspection Techniques. The procedure described below substantially conforms to ASTM E 94, ASTM E 142, and AWS D1.1.

87. The operator measures the thickness of the material to be radiographed to determine the exposure time and selects the radiographic film from Class 1 or 2 film groups. The film must have the ability to show the required penetrameter holes. The operator then positions the radiation source so it is in the optimum position to record any defect present, and so all space on the film is used. Penetrameters, numbers, and indicating markers must be placed on the part. Shims must be placed under the penetrameter if required. The film holders must be placed tightly against the part being radiographed. The radiographic operator must use radiation detection devices, including survey meters, film badges, and dosimeters.

88. The films must be processed so that the radiographs have no processing defects such as stains, streaks, spots, fogging, scratches, crimps, or finger marks.

89. The required density range of the film depends on what specification or code is being used; however, a range of 1.8 to 3.0 would be acceptable to most codes. Commercial fluorescent lights are satisfactory for making radiographs with a density of approximately 1.8 to 2.3, but a high-intensity light with a control to adjust light levels from dim to bright is usually used to interpret radiographic film. (If a specific range of densities is called for, the contractor must have a densitometer on hand to confirm the film density.)

90. Before evaluating the radiograph for discontinuities or defects, the penetrameter should be located. An acceptable radiograph will show a sharp outline of the penetrameter and the required hole size will be visible. When interpreting radiographs, the interpreter should be in a darkened area with no lights that could reflect on the viewer.

91. ASTM Standard E 390-75, Reference Radiographs for Steel Fusion Welds, and the Structural Welding Code-Steel, D1.1-90, can be used as references to interpret the radiographs.

Eddy Current Inspection (ET)

92. Application. Eddy current inspection is a versatile inspection method based on the principles of electromagnetic induction. This method can be used to detect surface, or near surface cracks in most metals. It can also be used to identify metals and separate alloys of the same metal. Eddy

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current inspection is used to a large extent by the aircraft industry on nonferrous metals to detect cracks and heat or fire damage. Inspecting ferrous metals is more difficult because of changes in a metal's permeability caused by welded areas and heat affected zones. Inspection units now entering the market can differentiate between a crack and any material or permeability change. Eddy current inspection has been used under water as a substitute for magnetic particle inspection on off-shore oil platforms. Eddy currents will penetrate rust, plating, and paint (up to 2 mm thick), allowing the underlying metal to be inspected for cracks. Since many physical and mechanical pro-perties of a metal are directly related to electrical conductivity, eddy current instruments can be used to measure a metal's hardness, alloy propor-tions, thermal conductivity, strength, and heat treatment condition.

93. <u>Theory</u>. In a piece of metal, the atoms are arranged in an orderly or near orderly lattice structure. By colliding with the atoms of the metal lattice and with foreign atoms present, some of the current electrons are scattered in all directions, like billiard balls, and give up part of their energy to the lattice atoms, energy which then appears as resistive heat (Figure 21). An eddy current is the directional flow of the free electrons in a conductor under the influence of an electromagnetic field. Each electron has its own field which is extremely weak. When a magnetic flux field is induced into a conductor, the field will force the electron into a path perpendicular to the magnetic flux field. When a series of these electrons travel in the same direction, the flux field of each combines to form a secondary field about the eddy currents (Figure 22).

O – Metal atoms
● – Foreign atoms
► – Electron paths
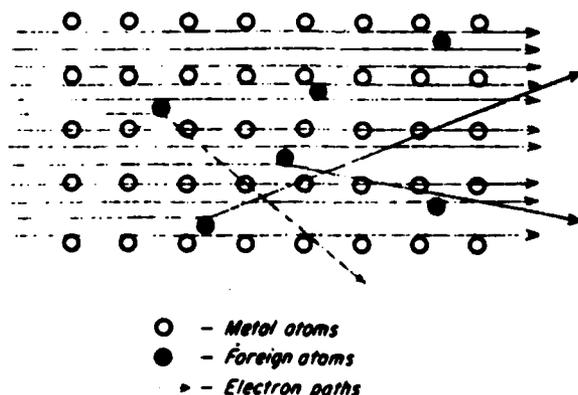
Figure 21. Scattering of eddy current electrons

PRIMARY ELECTRO-
MAGNETIC FIELD

COIL

CONDUCTOR

EDDY CURRENT
PATHS

SECONDARY
FIELD CREATED
BY EDDY CURRENT
IN TEST OBJECT.
SECONDARY FIELD
OPPOSES PRIMARY
FIELD.

EDDY CURRENT
STRENGTH
DECREASES
WITH DEPTH
OF PENETRATION

EDDY CURRENT PATHS
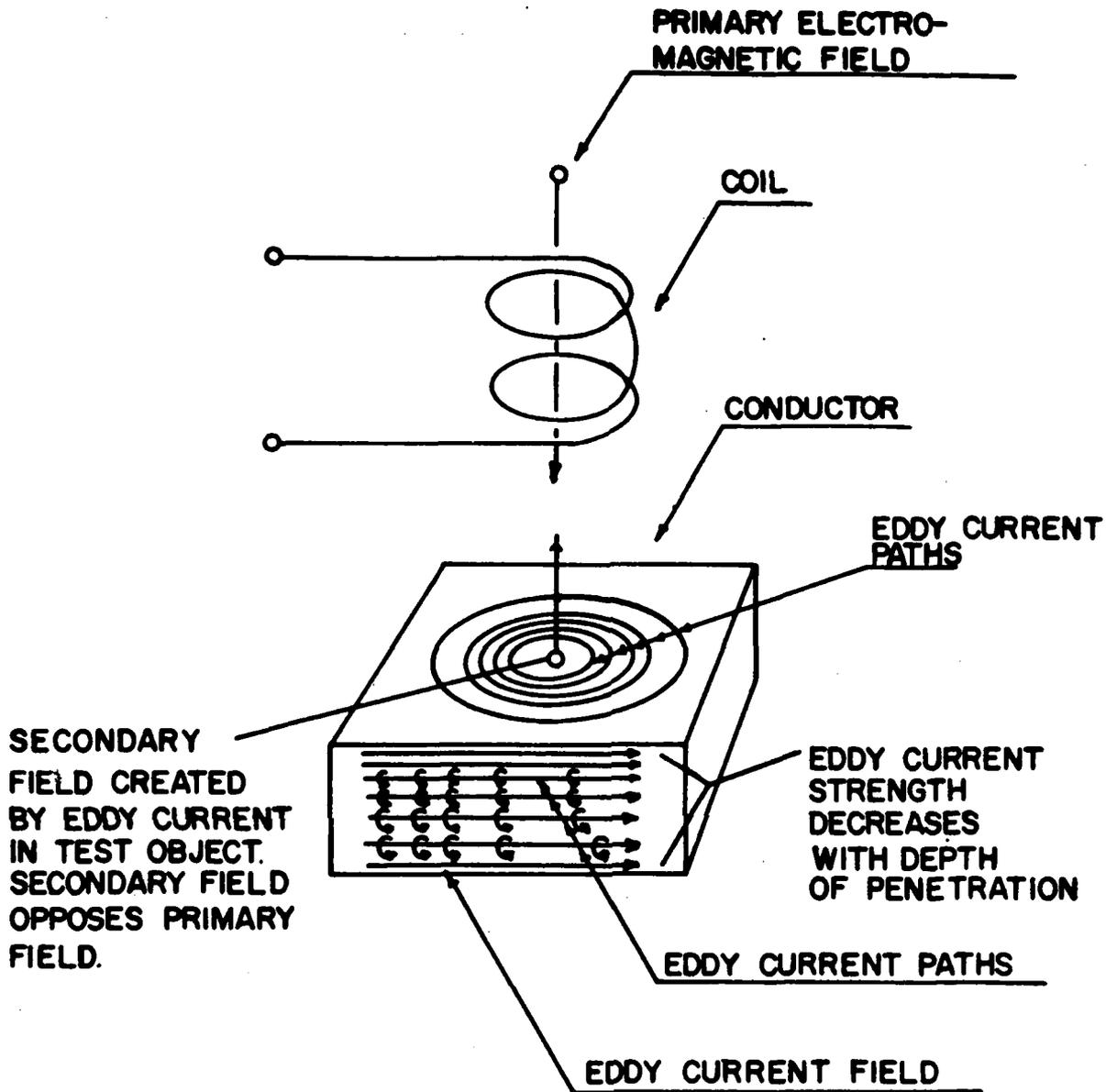
EDDY CURRENT FIELD

Figure 22.   Eddy currents produced in a conductor by a
varying electromagnetic field

94.   This induced flow of electrons produces an eddy current field of
sufficient strength to oppose the primary field produced by the probe.   The
degree or amount of opposition is determined by the electrical conductivity,
permeability, mass, and structural condition (homogeneity) of the conductor.

95.   Opposition to the primary field is electronically detected by the
eddy current instrument as an impedance change (resistance and inductance) in
the coil producing the primary field.   This impedance change is usually
referred to as coil impedance.

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96. Electrical resistivity is a consequence of the collisions between current electrons of any kind and the atoms of the lattice. The appearance of energy in the form of resistive heat diminishes the energy and changes the time phase of the ratio field. These two independent effects are measured by the equipment and translated into information about the test piece. A perfectly orderly lattice cannot scatter electrons; hence it has zero resistivity. The electrical resistivity of metals arises from deviations from a perfect lattice caused by thermal motion of the atoms and from lattice imperfections such as dislocations and impurity atoms. That portion of the resistivity which is not due to thermal vibrations in the lattice, or which does not vanish as the temperature approaches absolute zero, is called the residual resistivity. If the atoms of a metal are arranged in a perfectly orderly lattice, the current electrons will not scatter, therefore, it would have zero resistivity.

97. The depth that the eddy currents penetrate is controlled by the frequency. High frequencies will produce the highest sensitivity in detecting small surface flaws. As frequency decreases, sensitivity also decreases, but the penetration of the eddy currents increases. If subsurface flaws are to be detected, a lower frequency is used. The range of frequencies is from 200 Hz to 6 MHz, with the lower frequencies used primarily to inspect ferromagnetic metals.

98. The wire coil used to create the primary electromagnetic field can be any size. For example, it could be small enough to be mounted in a probe the size of a pencil. The probe is then placed on a calibration sample with the same electrical and magnetic properties as the test block, and a bridge circuitry similar to that used to monitor electrical resistance strain gauges, is balanced. The probe is then placed on the test object and moved over the test area. Very small changes in the coil impedance will unbalance the bridge circuit and are indicated on a meter, audible alarm, oscilloscope, computer, or other suitable device.

99. Advantages. Many physical and electrical properties can be detected with eddy currents if the instrument is balanced on a reference object. Properties related to conductivity (hardness, alloy composition, thermal conductivity, strength, and heat treatment condition) allow eddy current testing to be used in many applications.

100. Disadvantages. Hardness, strength, chemical and alloy composition, internal stress, and work hardening will alter the conductivity of a part. Therefore, a material's conductivity (or resistivity) will not provide a conclusive test for any one property unless all other properties are known and are constant. Because the penetration of eddy currents into an object, even at low frequencies, is only a few thousandths of an inch, the applications are limited.

Contract Specifications

101.   The civil works engineer who prepares a contract for NDT should be familiar with the various test methods and the advantages, disadvantages, and limitations of each method.   Courses teaching the fundamentals of these tests are available (see Part IV).

102.   The engineer needs to identify specific items that the contractor must comply with in performing the inspection.   The first items to be "called out" should be the requirements and qualifications of the test equipment and testing personnel.   The next item should be the extent of the examination. Indicate the methods of testing, the welds and/or parts to be tested, and the position of the welds and/or parts to be tested.   The contract should indicate that a visual inspection should be conducted before any other tests.   The next call-out should specify the test operating methods.   For example, this category should include the dwell time for penetrant testing, the transducer sizes, frequencies, and use of couplant for ultrasonic testing, and the film density, source-to-subject distance, and the location of penetrameters for radiographic testing.

103.   Other call-out items depend on the spcified test method, but should define the acceptance standards.   For example, the contract should state that any process or activity that obscures portions of a weld will render the radiograph unacceptable.

104.   Items discussed in this section are examples.   Other call-out items are discussed in the sources listed in Table 3 which should be referred to when preparing an NDT contract.

PART III: CORROSION EVALUATION

105.   Corrosion evaluation methods should be used periodically to determine corrosion areas, mechanisms, and rates. Soil resistivity measurements and structure-to-electrolyte potentials are required to determine the corrosion mechanism and the probable rate of corrosion. The corrosion of a metal such as steel is a natural process that is concentrated at anodic areas. The basic reactions responsible for underground corrosion are galvanic and electrolytic. Galvanic corrosion is caused by the potential difference between the anodic and cathodic areas randomly distributed on the metal surface. In civil works structures, galvanic corrosion frequently occurs because of the proximity of dissimilar metals that form a galvanic cell. An example of this is a stainless steel guide or track adjacent to structural steel. In galvanic corrosion, the corrosion of the metal generates the corrosion current. In electrolytic corrosion (often called stray current corrosion) a dc current from an outside source is responsible for corrosion. Refer to TM 5-811-7, Electrical Design, Cathodic Protection, for information on soil resistivity and soil-to-electrolyte measurements, equipment used in inspection surveys, and cathodic protection used on locks and underground lines. The National Association of Corrosion Engineer (NACE) Standard RP-01-69, Control of External Corrosion on Underground or Submerged Metallic Piping Systems, lists the accepted criteria for corrosion control.

Resistivity Measurements

106.   Electrical resistivity tests combined with a knowledge of the texture, aeration, and alkalinity or acidity of the types of soil in an area, present the most accurate method of predicting corrosivity. Low resistivity areas are more corrosive than high resistivity areas. When designing a cathodic protection system, the resistance values of the soil around underground or underwater structures is necessary to locate anode groundbeds and provide information on current distribution. This information is also used to design electrical grounding systems.

107.   Soil resistivity in corrosion work is measured in ohm-centimeter (ohm-cm). Field measurements are taken using the Wenner Four-pin Method. In this method, four steel pins or rods are pushed into the ground in a straight, equally spaced line. By forcing a known dc current to flow through the two outer pins and measuring the voltage drop across the two inner pins, the resistance of the soil can be obtained using Ohm's Law. In a congested area, buried utilities can produce interference. To minimize this problem, the pins must be placed perpendicular to an underground pipeline. Figure 23 illustrates the Wenner Four-pin Method.
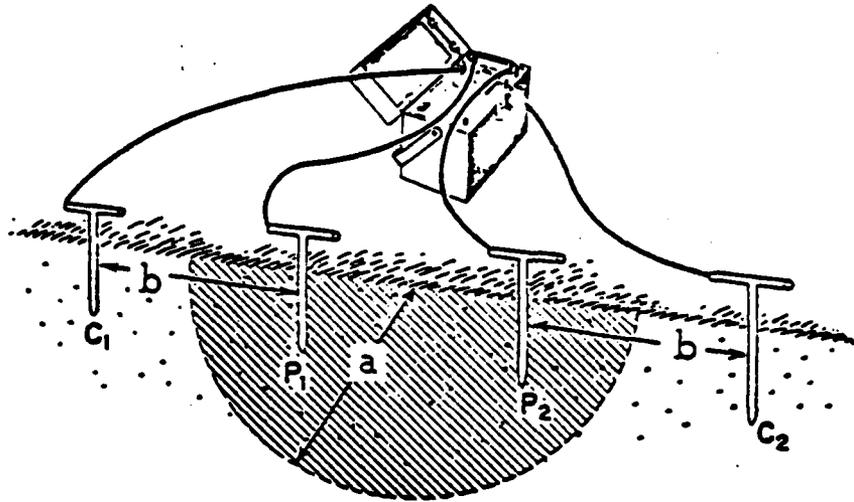
Figure 23. Four-pin resistivity equipment

108. The measurement of electrical resistivity and its relation the corrosivity are:

    a. Values. Resistivities are measured in ohm-centimeter (ohm-cm) and may be classified roughly as follows:

Ohm-cm	Value
Up to 1,000	Very low
1,000 to 3,000	Low
3,000 to 10,000	Medium
10,000 to 30,000	High
Over 30,000	Very high

    b. Relative corrosivity. Low resistivity soils are corrosive because their high conductivity allows an easy path for the flow of current from the anodic areas to the cathodic areas of a structure. The alkaline soils of the West are low in resistivity because of their large content of soluble salts and, therefore, are considered corrosive. A low resistivity coupled with an alkaline pH is an indication of a highly corrosive soil. In such soils there is a direct correlation between resistivity and corrosivity. In the past, medium and high resistivity soils were not considered particularly corrosive; however, much corrosion has been found in high resistivity soil areas. Consequently, a change in resistivity between different soils in contact with different parts of a structure is a much more accurate indication of corrosivity in medium and high resistivity soils than an absolute resistivity value.

Structure-to-Electrolyte Potentials

109. Structure-to-electrolyte potential surveys are performed to analyze corrosion activity along an existing lock structure, retaining wall,

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or underground pipeline. A structure-to-electrolyte potential measurement can be a structure-to-soil or a structure-to-water measurement. Structure-to-electrolyte measurements are used to evaluate the adequacy of a cathodic protection system, and to qualify the effects of galvanic attack or stray-current corrosion.

110. A survey is conducted using a high resistance voltmeter connected between the structure under investigation and a reference electrode. The reference electrode most commonly used is a saturated copper-copper sulfate (Cu-CuSO$_4$) half cell. The reference electrode is connected to the positive terminal of the multimeter and the structure or pipe is connected to the negative terminal.

111. Each of the four inspection methods for metal structures located in soil or water is based on a specific criterion that has advantages and disadvantages.

112. The first criterion is: a negative voltage of at least -0.85 volt to a copper-copper sulfate reference electrode taken with the protective current applied. Although this is the most convenient criterion for field use and yields results that are easy to interpret, it is best suited for use on coated structures where the reference electrode position and soil or water IR drop are not critical. It is well suited for use in areas of stray dc currents and where other cathodic protection systems may interfere.

113. The procedure and evaluation of a structure-to-water potential survey is very similar to the structure-to-soil survey except that the half-cell electrode is placed in the water next to the lock or wall surface when the readings are made. The negative connector of the meter is attached to the structure being inspected. The electrode is raised or lowered to different heights in the water at the same location, then moved along the metal surface at selected distances. This survey gives a direct indication of the corrosivity. A potential requirement for cathodic protection is a negative (cathodic) potential of at least -0.85 volt as measured between the structure and a copper-copper sulfate reference electrode in contact with the electrolyte. A potential which is less than -0.85 volt is assumed to be corrosive, with the corrosivity increasing as the negative value decreases (becomes more positive).

114. In accordance with TM 5-811-7, the current density required to shift the potential indicates the structure's surface condition. A structure that has a good paint coating will require a very low current density, for example, 0.05 milliampere per square foot. An uncoated structure would require high current density of approximately 10 milliamperes per square foot. The average current density required for cathodic protection is 2 milliamperes

per square foot of "bare" area. The amount of current required for complete cathodic protection can be determined by one of the following methods:

    a. An actual test on the existing structure using a temporary cathodic protection setup,

    b. A theoretical calculation based on coating efficiency,

    c. An estimate of current requirements based on field experience.

     115. The second criterion is: a negative voltage shift of at least 300 millivolts resulting from the application of the protective current taken with the current applied. This criterion requires a comparison of off and on readings and, therefore, is less convenient for field use and also makes the results more difficult to interpret. This difficulty results from the fact that the total change in potential includes IR drops as well as polarization effects. This criterion is most often used on bare structures. Because IR drops are more significant on bare structures, considerable experience is often required to judge the effectiveness of protection as indicated by this criterion. It is not suited for use in areas of stray dc currents.

     116. The third criterion is: a negative (cathodic) polarization shift of at least 100 millivolts. This criterion eliminates the instant-off potential relative to the copper-copper sulfate electrode of at least -0.85 volt (discussed below). The -0.85 volt instant-off criterion is similar to the 100 millivolt polarization shift.

     117. The fourth criterion is: an instant-off potential relative to copper-copper sulfate electrode of at least -0.85 volt. This criterion is similar to the 100 millivolt polarization shift. Using the -0.85 volt instant-off criterion eliminates the problem of considering IR drops. The field measurements are less difficult, and the results are easier to interpret. It is most appropriate for coated structures.

Stray Current Corrosion

     118. Stray current corrosion on underground or submerged metallic structures differs from other types of corrosion because the electric current is an externally generated direct current originating from sources that are remote to the affected structure. Stray currents may be encountered in any area where direct current is generated or where dc equipment is operated, and in areas where one or both terminals of such equipment are purposely or accidentally grounded. As a result of grounding, part or all of the circuit return current will flow through the earth or water. Water has less resistance than soil and the current will travel quite large distances before returning to its source.

     119. Cathodic protection current is a dc source. Current leaves the anode, travels through the electrolyte and enters the structure giving that

area "protection." The current then returns to the source through the struc-
ture to complete the circuit. This returning current may leave the structure
at any point where a path of least resistance occurs. Corrosion will occur
where the current leaves a metallic structure.

120. If the underwater or underground metallic structure could be
coated by a perfect coating, no current would accumulate on the surface of the
structure. Since all coatings have some defects, stray currents can enter a
structure through a coating defect and leave by a coating defect. When cur-
rent enters through a defect in the coating, the structure is not harmed.
Because coating defects are small, the discharging current is concentrated at
small areas resulting in rapid corrosion of the structure.

121. The stray current corrosion areas can be determined by a corrosion
engineer and are usually remedied by bonding or adding anodes at critical
points.

122. On hydraulic structures, the current strays excessively when the
anodes are remote from the cathode. Stray currents often travel through
reinforcing bars in concrete. The fact that the stray current is taking a
different path and is not available to protect the structure is not the major
problem. Corrosion of the reinforcing bars can result in cracking and spall-
ing of concrete causing an expensive repair problem.

Corrosion Rate Instruments

123. Using an instrument to continuously and instantaneously record the
corrosion rate allows direct measurement without having to expose a specimen
for a long time. The method is based on small current and potential
measurement. The corrosion rate meter takes advantage of an empirical
relationship between the $\Delta E/\Delta I$ ratio and the instantaneous corrosion rates.
The $\Delta E/\Delta I$ ratio (termed polarization resistance) is measured by applying very
small currents to an electrode and measuring its change in potential.

124. The most common corrosion rate instruments use a three-electrode
system in which the reference electrode is composed of the same metal as the
test electrode (structure under investigation). The corrosion rate meter will
measure the actual rate of corrosion and produce direct mils-per-year (mpy)
readings. These readings can be recorded on a strip chart recorder; this
automatic system requires little supervision.

Specific Applications of NDT Paint Inspection

125. An inspector with field experience and proper equipment can inspect any painted surface efficiently and effectively. Several good references are available to help the inspector. Pictorial Standards of Coatings Defects (published by the Federation of Societies, Adelphia, PA 19107), for example, is a compilation of several ASTM standards for visual ratings of paint performance or conditions. This information can help the inspector analyze failures or rate surface conditions such as blistering, cracking, flaking, mildew, and rusting. ASTM D 3276-80, Recommended Guide for Paint Inspectors, is also a good reference for the inspector.

126. The inspector may use a wet film gage, a viscosity/consistency cup, and a dry film thickness gage. The first two would be used during paint application. The last would be used at any time after the paint has dried. The dry film thickness gages can be either nondestructive or destructive. The nondestructive gages are used to measure films on metallic substrates and the destructive to measure films on both metallic and nonmetallic surfaces.

    a. Nondestructive gages. The most popular nondestructive gages use magnetic principles to make measurements. With this type of gage, it is important to know the condition of the substrate, as the gage will measure all nonmagnetic materials, including underlying rust and mil scale, as coating thickness. Nondestructive gages for use on nonferrous metallic substrates are also available. Their use is documented in: ASTM D 1400-81, Method for Nondestructive Measurement of Dry Film Thickness of Nonconductive Coatings Applied to a Nonferrous Metal Base, ASTM E 376-69, Recommended Practice for Measuring Coating Thickness by Magnetic-Field or Eddy Current (Electromagnetic) Test Methods, and ASTM G 12-83, Method for Nondestructive Measurement of Film Thickness of Pipeline Coatings on Steel.

    b. Destructive gages. The most common gage of this type is called the Tooke Gage. This device cuts into the film to make a measurement. It has the advantage of being able to measure thicknesses of individual coats, intercoat contaminants, or voids that the nondestructive gages don't detect. Follow the manufacturer's instructions on the use of this gage.

    c. Holiday detector. A holiday detector is an electrical device designed to locate holidays (pinholes, voids, and thin spots) in coatings. Holidays are not easily seen by the naked eye. These detectors can be used when a relatively high electrical resistance coating is applied to the surface of a low electrical resistance material. The coatings may include thin films such as vinyls, epoxies, polyethylenes and thicker coatings such as hot applied coal tar, asphalt, and heavy plastic materials.

127. The holiday detector uses a dc pulse generated by the detector. A negative lead is connected to the metal or concrete structure and the positive lead is the handheld electrode or wand that is passed next to or on the coating. When electrical contact is made, a spark discharge is created. A

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peak or crest reading voltmeter has the ability to hold the dc pulse for
evaluation.

128. Holiday detectors are either low voltage or high voltage. Low
voltage units operate at less than 100 volts of dc (Vdc) and are designed for
use on thin film coatings (less than 10 mils) but are also effective on films
up to 20 mils if a wetting agent is used. The high voltage units operate at
voltages from 900 Vdc to 20,000 Vdc and use a coil or brush as the electrode.
These portable, battery-powered units are used on thin or thick film coatings
from 0 to 200 mils. Once the unit is calibrated, it can be used by unskilled
personnel with acceptable results. The coated surfaces that can be inspected
can be metal or concrete, damp or dry, and can be any shape from flat surfaces
to small diameter pipe. (Note: a paint test kit developed at USACERL can be
used to run several quality control/quality assurance tests on the liquid
paint onsite. It is not meant to replace laboratory testing; however, it can
be used as a screening device to show which samples definitely need laboratory
testing.)

PART IV: ECONOMIC CONSIDERATIONS OF STRUCTURAL EVALUATION METHODS

Introduction

129. Economics play an integral part in choosing an appropriate evaluation method. When an inspection is imperative for structural assurance, two or three techniques can often be used. If these techniques yield similar results (in the sense of accuracy), comparing the economics of each method is an excellent "tie-breaker." However, if one technique is better suited for the structure in question, economics should be considered secondary.

130. When an evaluation method is chosen, the next step is to decide how many measurements to take and in what locations. Rational selection of evaluation points is necessary for a cost effective study; needless and insignificant data points are a waste of time and money.

131. Along the same vein, if components of a structure are not considered critical, it may be economically wise to allow them to fail and then repair or replace them. In other words, the most cost effective procedure might be to not inspect or evaluate the component. This, of course, would only hold true when safety or structural integrity is not a concern.

132. When considering the economics involved in the maintenance of a structure, the interval between inspections is a major concern. For example, if a lock was dewatered every 20 years instead of every 10 years, a 50 percent savings in expenditures would result. There are certain periods of time during a structure's lifetime when failure is more likely to occur. These are the times when structural evaluation is most important. The famous "bathtub" curve shows that the critical times for a structure are in its early life and when it has passed its "useful life." Monetarily speaking, these would be the most appropriate times to conduct structural evaluation.

Training Requirement Costs

133. A certain amount of training is needed to conduct each NDT technique. The American Society for Nondestructive Testing requires that only individuals qualifying to NDT level 2 may perform nondestructive tests without supervision. The AWS Structural Welding Code-Steel, D1.1-90, states "all individuals providing testing services under the Code must be qualified to level 2." To be qualified to proficiency level 2, an individual must have several weeks of specialized training and several months to several years experience.

134. Due to the long training time, it would not be advantageous to train a government employee to the proficiency required for an NDT level 2. A more realistic approach would be to attend a nondestructive testing fundamentals course (similar to that sponsored by the Corps of Engineers given

by Hobart Brothers of Troy, Ohio). One 40-hour course "Welding Inspection and Quality Control" offers lectures, conferences, and practical exercise sessions on welding safety and precautions, welding symbols, welding processes, codes, operator qualifications, filler metals, and workmanship. Nondestructive testing methods including visual, dye penetrant, magnetic particle, radiographic, ultrasonic, and NDT interpretation are discussed during the course.

135. The other 40-hour course presented for Corps of Engineers personnel is the Welding Design course, which covers design considerations and proper communications of welding processes, joint designs, weldability of metals, weld size determinations, estimating weld costs, design formulas, and failure analysis.

136. After attending one of these courses, the engineer can contract the inspection project to a NDT testing laboratory and can oversee and monitor the inspection process with confidence.

Equipment Costs

137. NDT equipment is expensive. In most instances, a district or even a division could not afford the purchase. As seen in Table 4, radiography would be quickly eliminated from consideration. However, visual inspection equipment or an ultrasonic thickness instrument could be purchased by a division and used by any district. The payback on the investment would be realized quickly.

Inspection Costs

138. Commercial testing laboratories are located throughout the country and can perform almost any test on any material. Although some testing laboratories are limited by equipment or personnel, it is not difficult to locate a laboratory that can perform the test you require. Appendix B contains a list of laboratories from the annual reference issue of *Materials Evaluation*.

139. The cost of the inspection depends on a variety of factors including distance to test site, complexity of test, hazards involved, and extra equipment or expendables required. Table 5 lists the approximate cost of a nondestructive test (but does not include portal-to-portal costs). These dollar amounts (which vary across the country) are for testing laboratories in large northern cities. Table 5 indicates radiography is the most expensive testing method and is therefore usually specified for critical welds or components.

140. Nondestructive testing may seem costly, but savings resulting from reductions in downtime, machine damage, or equipment failures often pay the cost of inspection many times over.

PART V: CASE HISTORIES

141.   In this chapter, four case histories illustrate how evaluation
techniques can be used to ensure structural integrity. Each case is described
in detail and the benefits of incorporating evaluation methods are emphasized.
These cases show how the techniques can help make structural evaluations
complete and what conclusions can be drawn from their use.

Uniontown Locks and Dam, KY

142.   The Uniontown Locks and Dam, consisting of 10 tainter gates and 2
miter gates, have bolt failures on 2 of their more frequently used tainter
gates. Each gate has two rows of bolts (type 416 stainless steel) on each
side, where cables are attached to raise and lower the gate (Figures 24 and
25). Both gate numbers 8 and 10 had four bolts fail. Four other bolts were
sent for a metallurgical examination.

Examination of Bolts

143.   Circumferential cracks in the shaft and corrosion pits and longi-
tudinal cracks in the threads were noticed after the bolts were brushed and
sprayed with a dye penetrant. An optical microscopy study of these longi-
tudinal cracks showed that the steel bolts were temper embrittled. Thus,
intergranular cracks developed when the material was exposed to the aqueous
environment. These embrittled bolts failed at much lower loads than they were
designed to withstand. Once corrosion pitting began, stresses became concen-
trated and cracks formed. Embrittled type 416 stainless steel exhibits a loss
of both corrosion resistance and crack propagation resistance, but not a loss
of ductility.

Conclusions

144.   It was determined that a special heat treatment could restore the
bolts to their original (nonembrittled) form. There was nothing intrinsically
wrong with using type 416 stainless steel.

145.   Specifications for the bolt material were recommended to fall in
these ranges:

Tensile Strength:	110 ksi to 140 ksi
Hardness:	RB 95 to RB 26
Tempering Temperature:	1,100° F to 1,200° F (587° C to 642° C)

146.   As a precautionary measure, the fillet radius between the shaft
and the bolt head should be increased to reduce stress concentration.

147.   The cables attached to the 13 bolts should have uniform tension,
so each bolt carries the same load. It was observed that this was previously
not the case. The tension can be easily checked by measuring the sound pitch
of the individual cables.

Figure 24. Tainter gates at Uniontown Locks and Dam
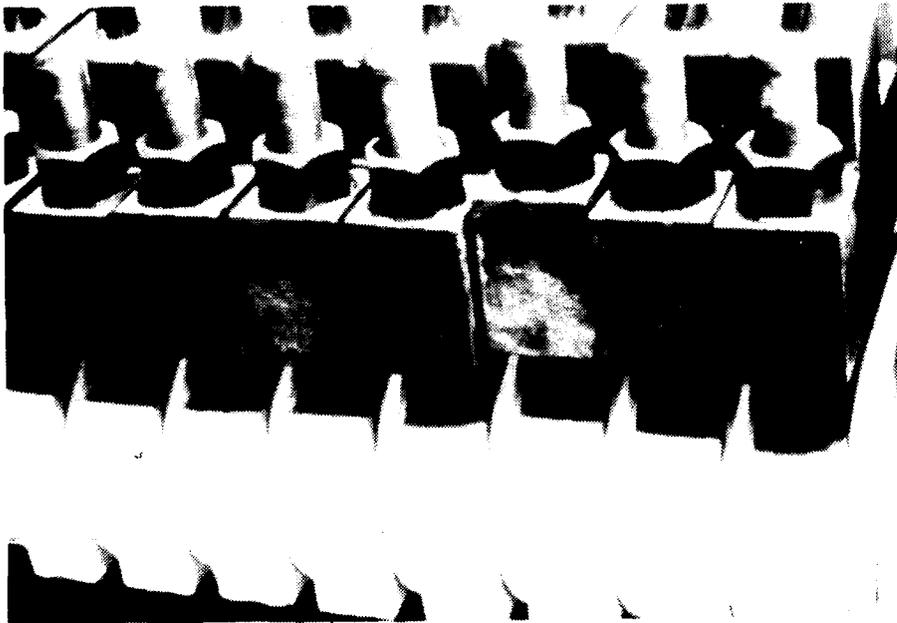
Figure 25. Bolt assembly securing lifting cables

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148. The metallurgical examination coupled with dye penetrant evalua-
tion proved worthwhile, since bolt failures would have become more prevalent
as the cyclic loading continued. The discovery of inadequate bolts at such an
early stage prevented possible costly damage to the gates, thus making this
metallurgical examination a very cost-effective study.

Point Pleasant Canal Bulkhead[*]

149. Between 1967 and 1974, various sheet pile sections were installed
at the Point Pleasant Canal in New Jersey, and in 1984 a study was completed
to determine how corrosion was affecting these sheet piles. Ultrasonic
measurements were used extensively in this survey. Velocity measurements were
taken and a soil and water analysis was completed to make this a thorough
study of the corrosion rates.

Method of Survey

150. At 10 locations (5 on each side of the canal), detailed measure-
ments were taken from the top of the bulkhead and continued down to the stone
revetment. The plate thickness was determined at 6-in. intervals, with divers
taking the underwater readings.

151. General measurements were taken in 53 locations (half on each
side), and at 1-ft intervals on the bulkhead. A representative sampling was
taken of the different types of sheetpile (Z-27, DA-27, and MA-22), all of
which were originally 3/8 in. thick.

152. Because of the relationship between corrosion and water velocity
(increased velocity increases corrosion rate), velocity measurements were
taken on both sides of the canal. With the use of a weighted buoy, a stop
watch, and a boat, measurements were recorded at each of the 10 locations used
for the detailed ultrasonic measurements. Since the water velocity changes
during the day and with respect to the tide, data was taken at various times
of the day. The maximum value of the duplicated readings was considered the
important one.

153. In the water and soil analyses, pH measurements and soil and water
resistivities were taken at each of the detailed measurement locations.

Field Results

154. The sheet pile walls were mildly corroding, being about 85 percent
of their original thickness. Corrosion patterns could be seen from the data.
The sheet walls were broken down into four areas: the sheet tops, the inter-
tidal zone, the low water zone, and the submerged and toe zone. The sheet
tops, which were in the "splash" zone, had the fastest average corrosion rate,

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[*] Conducted by Petro-Chemical Associates.

about 4.5 mpy. The low water zone had the next highest rate (3.8 mpy) while the other two zones had much lower rates, about 2 mpy.

155. The velocities in the canal were generally less than 4 ft/sec (122 cm/sec), except in two turbulent areas, where protective measures were taken or corrosion was not a problem.

156. The resistivity of the water ranged from 32 to 50 ohm-cm, which is considered a fairly corrosive environment. The soil at the mud line had values between 106 and 140 ohm-cm, which was less corrosive than the water. The pH of the soil and water was between 7.6 and 7.9, which has little influence on corrosion.

Conclusions

157. Based on 33 percent wear, the bulkhead would last at least 30 years, although there are places where holes would probably develop before that time. It was recommended that a coating (epoxy) be applied to all of the sheet pile, which would effectively mitigate the corrosion activity. The coating would consist of a two-part, 100 percent solid polyamide epoxy, hand applied, and no less than 125 mils thick. (An alternative coating for the sections above water would be 30 mils of coal tar epoxy).

158. A cathodic protection survey should be completed to determine a system suitable for the structure, with emphasis on protecting the structure from the bottom edge of the splash zone down to the mud line.

159. This study exemplifies how NDT methods should be used together (in this case, ultrasonic and resistivity measurements) in a manner that fully describes the possible structural deficiencies of a system in question.

Spillwater Tainter Gate Vibrations at Arkansas River Navigation Projects[*]

160. Tainter gate vibrations occurred at six locks and dams on the Arkansas River in the late 1960's. In some cases, these vibrations were severe enough to cause fatigue failures in structural members and weld connections. A thorough inspection of these gates indicated that a high percentage of the welded rib-to-girder connections were cracked or were broken loose. Most of the damage occurred on the bottom girders.

161. The structurally important members were repaired to ensure that the gates remained serviceable during the inspection. In addition, certain gate settings that tended to vibrate the gates excessively were avoided.

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[*] For additional information, refer to Engineer Technical Letter (ETL) 1110-2-117, "Spillway Tainter Gate Vibrations at Navigation Projects" (USACE, 24 March 1971).

162. Accelerometers were used to standardize the vibration measurements obtained at different sites. The accelerometers indicated the average displacement of the vibrating members in mils. The displacements were quantified in the following manner:

Average displacement range (mils)	Vibration Description
0 - 12	Negligible (normal operation)
2 - 10	Minor
10 - 20	Moderate
over 20	Severe

163. Accelerometers were an important element in this inspection, since they turned the subjective problem of vibrations into a numerical study, making it easier to find workable solutions.

164. Personal observations and measurements determined that the vibrations were caused by the following factors:

a. Gate lip design.

b. Tail water level.

c. Gate opening.

d. Gate rigidity.

e. Side seal adjustment.

f. Adjacent gate detting.

g. Gate movement.

165. A model study conducted by the US Army Waterways Experiment Station reproduced most of the tainter gate vibrations experienced at locks and dams along the Arkansas River (using a 1 to 12 scale model).

166. From these tests, several modifications were developed to decrease the vibration on the gates. Most of the modifications dealt with the design of the side and bottom seals. See ETL 1110-2-117 for a complete discussion on the modifications.

O'Brien Lock and Dam, Illinois Waterway, Chicago, IL

167. In 1977, the Chicago District of the Corps of Engineers conducted a partial dewatering and inspection of the O'Brien Lock and Dam which revealed excessive corrosion and severe pitting. In view of these findings, USACERL was asked to perform an analysis of the corrosion damage--causes and extent-- and recommend remedial measures.

168. The objective of the work was to assess the present structural condition of the lock and dam, delineate a structural quality vs. time prognosis based on predicted corrosion rates, and develop the most appropriate corrosion mitigation program.

169. The program consisted of three principal efforts: a) establishing the present condition of the structure and the appurtenances, b) quantifying

the ambient corrosion environment, and c) developing a projection of structural performance. To accomplish this, the study contained the following activities:

    <u>a</u>. Evaluation of site corrosion characteristics

       (1) field survey data analysis

       (2) inspection and analysis of test piles

       (3) corrosion environmental history

    <u>b</u>. In-situ corrosion rate measurement

       (1) installation of a continuous corrosion monitoring system

       (2) polarization current measurements

    <u>c</u>. Cathodic protection system development

       (1) design cathodic protection for land side of lock walls and guide walls

       (2) design cathodic protection for water side of lock walls and guide walls

    <u>d</u>. Structural analysis of lock walls and guide walls

       (1) life cycle determination of lock and guide walls and anchor systems

       (2) determine structural integrity of the lock and guide walls in their present state of deterioration relative to original design requirements.

170. The in-situ measurements and tests, laboratory testing, and analytical work, were conducted simultaneously. As the analytical work progressed, requirements for additional field data were realized and elements of the ongoing analysis were used to determine the most appropriate test locations and procedures.

171. Only one dewatering (in November 1979) occurred during the field investigation phase of the evaluation. Therefore, it was necessary to rely heavily on in-situ nondestructive evaluation techniques for most of the field measurements, particularly the polarization techniques. This investigation marked the first time that the Corps used a continuous and instantaneous corrosion rate measurement system. This system was used to determine if any cyclical changes in the corrosivity of the water flowing in the lock occurred.

172. Since most of the available design information applied to new construction and did not consider corrosion damage, it was necessary to develop a specialized analysis for this structure. The analysis was general enough, however, for use in other similar structures.

Field Tests

173. The ambient corrosive conditions had changed during the 20-year existence of the structure, thus changing the corrosion rate from year to year. On the water side of the structure, the water quality changed as environmental protection procedures were implemented. Meanwhile, on the land

side, runoff from a landfill operation in the vicinity of the project became a variable electrolyte.

174. Fortunately, at the time of construction, the North Central Division Engineering personnel had the foresight to place a series of H-beam piles adjacent to the lock structures. The piles were to be pulled at 20-year intervals to provide an indication of corrosion damage. These piles gave corrosion indications at various depths for the backfill pattern used. As expected, the corrosion pits were very severe in the region of coarse gravel backfill. Corrosion pits were caused by a crevice type corrosion between the web and large stones. Analysis of this corrosion pattern served as a valuable guideline for the ultrasonic measurements made of the lock walls during the dewatering inspection.

175. Another parameter affecting the corrosion rate on the land side of the structure was the soil resistivity. Several soil resistivity measurements were made adjacent to the lock wall and the guide walls.

176. A unique continuous and instantaneous corrosion rate recording instrument was placed in the water to determine cyclic (seasonal) variation in water conductivity. This device provided an indirect corrosion current reading (or corrosion rate measurement) by taking advantage of the fact that there is a measurable relationship between the direct corrosion current and the effect of an externally applied current on a metal surface. Analysis of the data obtained over a period of approximately 1 year indicated no extreme variations in the corrosivity of the water. Current requirements and IR drop tests were also performed to assist in cathodic protection design polarization. Tubercles of corrosion that were removed during the dewatering in 1979 were also analyzed.

Structural Analysis: Scope and Basis

177. The purpose of this analysis was to estimate how long the sheet pile structural systems of the lock walls, the guide walls, and the dam would function satisfactorily without major repairs. The analysis would also provide a basis for developing corrosion mitigation procedures. The length of service depends on rates of corrosion at critical places, but the stress analysis concentrates on the minimum allowable thickness of sheet piles. The life of a sheet pile was defined as the time in which corrosion will reduce the thickness of the pile to its minimum allowable value.

Failure Mode Analysis

178. **Interlocks**. Hoop tension in the walls of a cellular cofferdam may damage the sheet piling, either by rupturing the webs or by pulling the claws apart. Before a failure could occur, there would be considerable elongation of the shanks, as illustrated in Figure 26. Usually the shanks must bend before the claws part. The bending causes the bulbs to pull on the hooks.

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The hooks must also bend before the claws part. This behavior is illustrated in Figure 27.

179. <u>Lock Walls and the Dam</u>. The lock walls and the dam are cellular cofferdams formed from interlocked S-28 sheet piles that are driven into clay and hard glacial till. At a junction of a cross wall with the cylindrical walls, there is a V-shaped pile. The other sheet piles are flat.

180. A cellular cofferdam may fail in several ways. One way would be general heaving or tilting of the whole structure. Since heaving had not occurred in the past, and is not aggravated by corrosion, this possibility is remote. Sliding in the interlocks was also dismissed as a possible failure mode due to the fact that it has not occurred in the past and corrosion deposits decrease the chance of sliding. The cell walls carry considerable horizontal tension. If corrosion proceeds too far, this tension will cause the cells to burst. Since hoop tension is transmitted to the V-piles at the junctions between the cylindrical walls and the cross walls, horizontal tension is developed in the cross walls.

181. Because of the pressure of the backfill, the land wall of the lock carries greater shear than the river wall. The greatest shear occurs at the
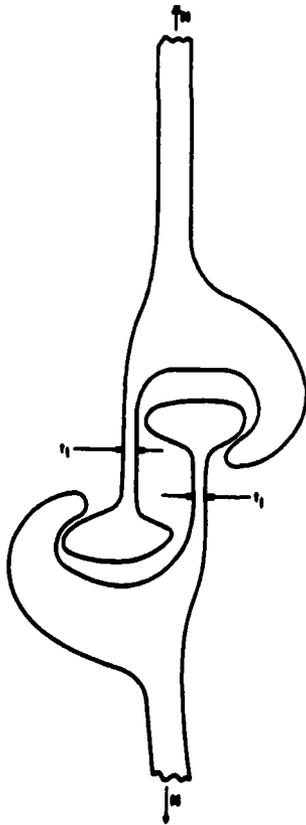

Figure 26. Elongation of the shanks   Figure 27. Bending of the shanks
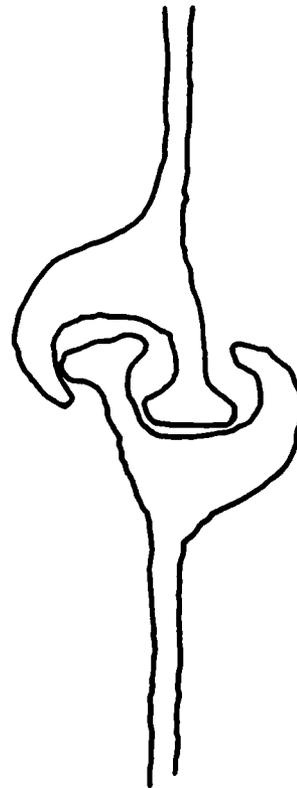
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bottom of the lock chamber. This shear flow was calculated to be 1,774 lb/in. under normal conditions. In a dewatered state, the sheer flow was 2,335 lb/in. At a V-pile junction, half of the shear flow passes into each of the connecting cylindrical walls. Consequently, the shear flow in the cross wall is twice that in either of the cylindrical walls at the junction.

182. It is important to consider the hoop tension in a cell of the land wall. Analysis for a dewatered condition yields a maximum tension of 5,127 lb/in.

183. Using this value, the maximum shear in the cross wall can be determined, and it is also at its maximum (3,382 lb/in.) for the dewatered condition. These results are on the high side because shear carried by the fill in a cell has been neglected. However, they indicate that the point of highest stress in the lock wall is in a cross wall, near its junction with the cylindrical walls on the chamber side of the land wall at the bottom of the chamber.

184. Because the maximum shear is known (and by setting the ultimate shearing stress at 30 ksi), the minimum allowable thickness of a web in the cross wall is t = 3,382/30,000 = 0.11 in. Since the initial thickness is 0.375 in., severe corrosion can develop before the cross walls are in danger of failure. The maximum tension in the claws of the sheet piles has been determined to be about 5,100 lb/in.

185. The hoop tension in cells of the river walls and the dam cells can be determined in the same manner, with the resulting hoop tension being 3,719 lb/in. (again, the dewatered condition being the largest). Because there is negligible transverse shear, this is also the maximum principal stress.

186. Guide Walls. A guide wall is essentially a corrugated plate formed by interlocking Z-shaped sheet piles and is regarded as a flat orthotropic plate.

187. A beam analysis was performed on the wall and a maximum bending moment was obtained. This bending moment was used to determine the stresses in the sheet piling. Even if corrosion was severe, it would be unlikely that the stresses would rupture the piles. An interactive process was used to determine the thickness of the sheet piles at which crumpling would occur.

188. Wales consisting of two rolled channels back-to-back, are connected by buried tie rods to a buried sheet-pile wall located at some distance behind the guide wall. Failure modes for these were analyzed, and considered inconsequential. Lastly, corrosion failure limits for the downstream guide wall were calculated.

Deep Well Anode System for Guide Walls and Dam

189.   To mitigate corrosion and increase the expected operational life of the O'Brien Lock and Dam, a deep anode cathodic protection groundbed was employed. A deep anode groundbed is defined as one or more anodes installed vertically at a depth of 50 ft or more, in a drilled hole, to supply cathodic protection. An important advantage of the deep anode system is that the anodes can be removed and replaced, for any reason, at a minimum cost.

190.   An analysis of the geology near the dam indicated the deep anode groundbed would need to be approximately 600 ft deep, with the anodes placed in the bottom 120 ft. In this space, approximately 12 center tapped graphite anodes would be placed. The maximum current output for 12 anodes would be about 36 amps. It was estimated that four 600-ft deep groundbeds can be completely designed, installed, energized, and post installation testing conducted for $240,000.

Conclusion and Recommendations

191.   It was determined that the allowable amount of corrosion at any point in the lock walls, the dam, and the guide walls was about 0.25 in. of thickness. Corrosion in excess of 0.25 in. could cause serious damage.

192.   In the lock walls, the point of highest stress was in a cross wall of the land wall of the lock, near its junction with the cylindrical walls on the chamber side, at the bottom of the chamber. This cross wall's thickness may be reduced to 0.11 in. before a shear rupture may occur. Since the initial thickness is 0.375 in., this reduction corresponds to 0.26 in. This result was probably conservative since the shear carried by the fill in the cells was neglected.

193.   As a round figure, 0.20 in. of thickness can be deteriorated without any structural problems. To translate this detailed knowledge of the rates of corrosion at critical places in the lock, measurements were taken during the dewatering of the lock chamber in 1979 which indicated that the mean thickness of the webs of the sheet piles in the cofferdam was 0.348 in. Initially, the thickness of these webs was nominally 0.375 in., and the reduction of thickness occurred over 21 years. The standard deviation was 0.008 in.

194.   Through a statistical analysis, it was determined that at worst the webs would deteriorate at a rate of 0.0024 in. per year; having 83 years of total life. This conclusion holds also for the claws of the interlocks in the walls of the cofferdam, if the shanks and the hooks in the claws corrode at the same rate as the webs. However, rates of crevice corrosion of claw parts were not as well known as the rates of corrosion of the webs. Studies of corrosion rates of the claws were indicated.

195.   Observations made during dewatering of the lock applied only to the cylindrical walls. Observations of the corrosion of the cross walls at

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the bottom of the basin were not possible. Inspection of the guide wall and tie rods was advisable, since they were the parts most likely to fail. Also, some underwater measurements of sheet pile corrosion in the guide walls near the bottom of the river were desirable.

196. The worst corrosion found was in the test pile interlock shown in Figure 26. In 21 years it has lost about 0.125 in. of its thickness. This sample suggested that some repairs may be needed in regions of high corrosion in 21 years. Uncertainty in projecting the life of the structure arose primarily because some places that were inaccessible for inspection, such as the lower parts of the cross walls in the cofferdams, might have been corroding faster than observations of exposed parts would lead one to expect.

197. On the basis of the analyses, field measurements, and mechanical properties tests, the conclusion was that corrosion damage had not caused the structure to be unsafe or unserviceable, nor were these conditions imminent. Further, the geometry of the sheet pile structures and the types of corrosion mechanisms involved indicated that cathodic protection could be successfully used to prevent additional corrosion damage. Effectively, this corrosion mitigation method would stabilize the structure in the present acceptable condition. A cathodic protection system ideally suited for the O'Brien project was developed (Kearney 1986).

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Table 1

Defects in Metal Structures That Can Be Detected

Using Nondestructive Testing

General Defect	Specific Defect	Use NDT Method
Surface defects in gear boxes, recessed or inaccessible area, interior of piping, valves, cylinders	Fatigue cracks in gears, shafts, structural members	Visual (VT) (Boroscope)
Surface defects in structural, mechanical, hydraulic components, welds	Fatigue cracks in structural members, gears, shafts, and welds for porosity	Penetrant (PT)
Surface and some subsurface defects in structural and mechanical components	Fatigue cracks in structural members, gears, pumps, shafts, heat cracks, weld defects such as undercut, lack of fusion	Magnetic Particle (MT)
Surface and subsurface cracks in structural members, welds, castings, forgings	Fatigue cracks, weld defects such as lack of penetration, lack of fusion, inclusions, porosity, delaminations, lack of bond, corrosion	Ultrasonic (UT)
Loss of thickness on sheet piling, gate skin, pipes, tanks	Corrosion, wear	Ultrasonic – Thickness Measurement
Leaking vacuum or pressure system	Leaking valves, tanks, steam traps, piping systems, check valves	Ultrasonic Leak Detection
Surface and subsurface defects in welds, castings, and forgings. Defects located in the interior of pipes, tanks, and inaccessible areas	Fatigue cracks, internal defects such as pitting and corrosion. Weld defects such as lack of penetration, lack of fusion, inclusions, porosity	Radiography (RT)
Rust bleeding through paint	Pinholes, voids, thin spots in paint	Holiday Detector

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Table 2

Applications, Advantages, and Disadvantages of NDT Methods

	Applications	Advantages	Disadvantages
Visual	Use on all materials. Use with other NDT. Use before, during, and after all phases of construction or maintenance inspection.	Easy to perform. Equipment is portable. Immediate results can be photographed for record.	Limited to surface inspection. Results depend on inspector's eyesight; eye fatigue can reduce accuracy.
Penetrant	Use on all metals; castings, forgings, welds, and on all nonporous materials. Use for field inspection.	Easy to perform. Equipment is portable. Low cost.	Limited to surface inspection. Surface must be clean and smooth. Electricity is needed if black light is used.
Magnetic Particle	Use on all ferromagnetic materials; castings, forgings, welds, and on parts of any size, shape, or heat treatment. Use for field inspection.	Easy to perform. Equipment is portable. Low cost. Can detect some subsurface flaws located near the surface.	Electricity usually required. Demagnetizing after testing may be required. Rough or corroded surfaces can mask indications.
Ultrasonic	Use on all metals and alloys, welds, structural members, forgings, and castings. Use for thickness measurement and corrosion surveys.	Relatively easy to perform. Equipment is relatively portable. Immediate results. Accurate and sensitive. Location and depth of flaw can be approximated.	Surface must be clean and smooth. Complex shapes may be impossible to inspect. Interpreting results requires training.
Radiography	Use on all metals and alloys, welds, structural members, forgings, and castings. Use for surface and internal flaws.	Detects a variety of defects. Provides film as a permanent record.	Radiation hazard. Film is expensive and requires processing time. Must be done by trained technicians.

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Table 3
Sources for NDT Contract Specifications

Inspection Method	Reference	Notes/Specifications
Visual	Structural Welding Code-Steel D1.1-90, paragraph 6.5	Good eyesight and the knowledge of what to look for are needed.
Penetrant	Structural Welding Code-Steel, D1.1-90, paragraph 6.7 and ASTM E 165-80	Specify that the penetrant materials must be compatible and shall be removed after testing. Specify dwell time.
Magnetic Particle	Structural Welding Code-Steel D1.1-90, paragraph 6.7 and ASTM E 709-80	Specify the current, prod spacing, type of particles, demagnetization, and removal of particles.
Ultrasonics	Structural Welding Code-Steel D1.1-90, Section 6 Part C and ASTM E 164-81	Specify frequency and transducer angle.
Radiography	Structural Welding Code-Steel D1.1-90, Section 6 Part B and ASTM E-94-84a	RADIATION HAZARD Specify safety precautions, film type and density, use of penetrameters, and identification numbers.

Table 4

Cost of NDT Equipment and Expendables

METHOD	APPROXIMATE COST OF EQUIPMENT (in 1989 dollars)
VISUAL	
Unaided Eye	None
Magnifying Glass	10 to 20
Boroscope	2,000 to 3,000
PENETRANT	
Red Dye Kit	60
Fluorescent Kit	360
MAGNETIC PARTICLE	
AC-DC Unit	2,500
Yoke Unit	360 to 450
Visible Particle Cans	10 each
Fluorescent Particle Cans	10 each
Black Light	280
Field Indicator	15 to 95
ULTRASONICS	
Flaw Detection Unit	3,000 to 5,000
Transducer	150
Calibration Standard	150 to 250
Thickness Measuring Instruments	1,500 to 2,000
Leak Detectors	300 to 3,000
RADIOGRAPHY	
Portable X-Ray Unit	10,000 to 15,000
Radioisotope (Exposure Device)	2,000
Radiation Source (Iridium 192)	(700 for 100 curies)
Film	
Film Holders (cassettes)	200
Penetrameters	less than 50
Lead Numbers/Letters	less than 50
Portable Darkroom with Processing Solutions and Drier	14,000 to 18,000
Film Viewer	500

Table 5.

Approximate Cost of NDT Inspection

NDT Method	Inspector Costs* (in 1989 dollars)	Expendable Costs (in 1989 dollars)
Liquid Penetrant	1 man $30-$35/hr	Visible dye $5/can Fluorescent dye $10/gal
Magnetic Particle	1 man $30-$35/hr	Dry particles $6/lb Fluorescent $10/gal
Ultrasonics	1 man $30-$35/hr	Couplant mixture $5/gal
Radiography (X-ray and Gamma Ray)	2 men crew $55/hr	Film $5/in² Mileage for equipment and darkroom $0.45/mi

* The costs do not include travel and per diem.

Causes of Metal Deterioration

Corrosion

1. There are many types and forms of corrosion. Corrosion experts differ on the number, but MIL-HDBK-729 lists 16 forms of corrosion: uniform corrosion, galvanic or dissimilar metal corrosion, concentration-cell corrosion, stress-corrosion, fretting corrosion, high temperature oxidation, pitting corrosion, intergranular corrosion, erosion corrosion, impingement corrosion, cavitation corrosion, fatigue corrosion, filiform corrosion, dezinctification, graphitization, and biological causes. Many of these types of corrosion are combined for discussion because the corrosion mechanism is similar. The most frequently encountered forms of corrosion detected on locks and dams are uniform corrosion, concentration-cell corrosion, and pitting corrosion.

2. Uniform Corrosion. Uniform attack or general overall corrosion is the simplest and most common form of corrosion and may occur in the atmosphere, in water, or in soil. It occurs frequently under normal conditions of exposure and is relatively uniform over the metal's surface. This form of corrosion can be widespread but does not usually cause structural failure.

3. Concentration-Cell Corrosion. Electrochemical attack of a metal because of differences in the environment is called concentration-cell corrosion. This form of corrosion is sometimes referred to as "crevice corrosion," "gasket corrosion," and "deposit corrosion" because it commonly occurs in localized areas where small volumes of stagnant solution exist. Troublesome crevices can be sharp corners, lap joints, fasteners, flanged fittings, threaded joints, and sheet-pile interlocks. There are at least five types of concentration cells, but the oxygen and metal-ion are the most common.

4. Corrosion by oxygen concentration-cells may occur when the concentration of dissolved oxygen is greater at one point on the metal than at another point. During metal-ion concentration, a difference in potential is established between the two points of differing oxygen concentration. The point on the metal of higher oxygen concentration is the cathode, and the point of the lower oxygen concentration is the anode. The current flows from the metal to the electrolyte at the point of lowest concentration and from the electrolyte to the metal at the point of highest concentration. This action results in accelerated corrosion at the area of lowest oxygen concentration in the cell.

5. Active-passive cell action may arise with alloys that develop a protective, passivating film. If an oxygen-cell condition develops, the

absence of oxygen at the anodic area will prevent the protective film from reforming. Because of the incompleteness of the passivating (protective) film, corrosion at the exposed anodic areas is accelerated. This accelerated corrosion occurs because of the increased potential between the passive cathodic areas and the active site. Similar concentration action may be initiated where a part of the metal is shielded or covered by foreign matter or nonmetallic structural members. These circumstances will be especially effective in promoting pitting if the shielded part of the metal is in a stagnant solution while the free area is in a rapidly moving solution. Crevices and cracks will also become potential anodic areas.

6. When a metal goes into solution, there is some concentration of ions of that metal in the corroding solution. The lower the metal-ion concentration, the greater the tendency for metal to go into solution as metal ions. When the concentration of metal ions in the solution reaches saturation, the metal no longer dissolves. If the concentration of metal ions in the solution is greater at one point on the metal than at another, concentration cell action will occur. An electrical potential is established between the two points of different concentration; the metal surface in contact with the higher concentration of metal ions becomes the cathode, and the surface of the lower concentration becomes the anode. The flow of current is from the metal to the solution at the anode, and from the solution to the metal at the cathode. Therefore, at the point of higher concentration, the cathode is protected, while at the point of lower concentration, the anode is attacked. In actual service, the variation in metal-ion concentration may be due to differences in velocity or agitation. The metal ions in the corrosion products may be removed from one part of a metal at a higher rate; or they may not be removed at all from one part of the metal. In either case, such sustained action would lead to differences in metal-ion concentration.

7. <u>Pitting Corrosion</u>. Pitting corrosion is a common and severe form of localized attack that results in holes in metal. It is usually characterized by the observation that the depth of penetration is much greater than the diameter of the area affected. Pitting is somewhat similar to concentration-cell corrosion except crevices or threaded joints are not requisites for pit initiation. Pitting is one of the most destructive forms of corrosion.

8. Pitting usually occurs in grain boundaries at highly anodic points on the metal's surface. It is primarily the result of localized cell action. Concentration-cell action (difference in oxygen) will contribute to the damage by causing corrosion products which usually accumulate in the pits. The initiation of localized or pit corrosion can occur because of incomplete films or coatings, or because a substance, such as debris, sand, or rocks, partially shields small areas on the metals surface.

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9. Steel is susceptible to pitting attack and tuberculation by water. Pitting corrosion is located in a small localized anodic area with corrosion products forming mounds, which are called tubercules. Iron ions dissolved by the corrosion process are converted to oxides and the tubercules grow larger. Eventually, pitting attack under the tubercules results in perforation of the steel.

Metal Failures

10. Failures can originate at imperfections in the metal. Both internal and surface imperfections can reduce the strength by providing preferential paths for crack propagation.

11. **Inherent Defects**. Defects can cause a failure by being the initiation point. Defects formed in the metal during rolling or casting are classified as inherent defects. These include but are not limited to laminations, segregation, inclusions, porosity, shrinkage cavities, laps, seams, and voids.

12. **Processing Defects**. Unsuitable processing procedures can cause processing defects that can be metallurgically different from specifications. Processing defects can be so small that they are not noticed by quality control.

13. **Assembly**. Assembly failures are usually associated with mechanical assemblies, but can also occur in structural components. An example would be misalignment of rivet holes. These cause stresses and can lead to the start of a fatigue failure.

14. **Weld Repair**. When welding is done under conditions of restraint, contraction of the weld metal and heat-affected zone during cooling can induce residual stresses. These stresses can cause instantaneous cracking or can promote cracking in service. The use of excessive heat input during welding can also cause cracking.

15. **Service Failures**. Equipment and structures that are subjected to abnormally severe conditions or loadings often experience service failures. Inadequate maintenance frequently is a contributing factor in service failures. With the inspection methods identified in Part II, and with an adequate maintenance program, fatigue cracks should be located for repair before catastrophic failure occurs.

16. Service failure could also be caused by impact loading. For example, impact loading could be a barge hitting a miter gate, causing a bend in the strut arm and undue stress during the opening and closing of the gate. Further, for a miter gate, barge impact might also cause excessive loadings on diagonals, eye bars, pintles, and girders.

17. Failure due to excessive cycles of loading can occur when structures are expected to last past their design lives.

18. When a failure does occur, however, a failure investigation by those trained in failure analysis should determine the primary cause and should present corrective action to prevent similar failures. USACERL is the Corps of Engineers' primary source for failure analysis.

19. When a failure occurs, the investigator should gather as much of the service data as possible. Special attention should be given to environmental details, such as normal and abnormal loading, accidental overloads, cyclic loading, temperature, and environment. A photograph of the failed component should be part of the record.

New and Emerging Techniques

Expert Systems

20. **Application.** Expert systems will be designed by USACERL to assist area and resident engineers in performing onsite construction and maintenance activities. One expert system now being evaluated is designed to assist civil works personnel in the maintenance of miter, tainter, and sector gates at Corps locks and dams. This system identifies potential problems such as corrosion and metal fatigue that could lead to total failure and the replacement of the gate and other structural components of locks.

21. **Theory.** This expert system is microcomputer-based, containing information found in textbooks or manuals and knowledge of experience gleaned from experts in the field. Experts in the appropriate technical area were used to develop the knowledge base. The expert system questions the engineer-user for details on the maintenance problem of concern. Using this information, the expert system identifies potential problems and offers alternative solutions for correcting the deficiency.

22. **Advantages.** A main advantage of this system is the ability of a "non-expert" inspector to inspect the lock installation like a seasoned professional. All areas of the problem situation are examined by the expert system, and the conclusions can be explained and justified.

23. After the initial expense of developing an inspection procedure, the knowledge expert system can be used over and over, and the information obtained in a quick, low cost situation. The results can be checked if there are doubts. Deficiencies in the conclusions can be pointed out and rectified.

24. Another important advantage of the expert system is that heuristic and deterministic information would be stored in this system; the knowledge acquired from the veterans and experts would always be available.

25. **Disadvantages.** Knowledge-based expert systems cannot go beyond what has been specifically put into the system. If some vital bit of information was not included, the system could not take those ideas or facts into consideration.

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26. The cost of equipment is quite high and developing a specific program can be expensive.

Thermal Stress Monitoring (Stress Analysis by Infrared Emissions)

27. Application. A wide range of materials has been evaluated by stress analysis using infrared emissions. Large structures can be loaded cyclically and stresses can be determined on structures in-situ. Areas of localized weakness or deterioration caused by a crack or corrosion can be detected.

28. Infrared emission equipment picks up cyclically induced peak-to-peak temperature changes caused by tension or compression on the surface of a part or structure. Since this equipment can measure temperature changes within a few tenths of a degree Celsius, it can be used in engineering design studies, product development, quality control, and is now slowly finding applications in the field.

29. Field applications include inspecting airframe structures, automotive and farm components, turbine blades, chains, and detecting stress concentration areas in welds. This equipment has been used in fatigue studies and materials testing for detecting stress anomalies. One of the major uses of this equipment has been by stress analysts in designing and modifying structures to determine areas of stress, and to reveal unacceptable levels of stress.

30. Theory. Stress pattern analysis using thermal emission is based on measuring the thermoelastic effect in structural materials. A computer controlled scanning radiometer that is sensitive to extremely small temperatures changes is used to produce stress maps.

31. Adiabatic compression or expansion produces heating or cooling of solids. Pressures in an area of a solid show up as a stressed region where heat is generated or absorbed. This phenomenon in a solid material is known as the thermoelastic effect, and is the change of temperature that accompanies the adiabatic elastic deformation of a body.

32. Infrared radiation equipment is sensitive to temperature changes of 0.001 Kelvin, and is used remotely to detect defects through observation of stress anomalies.

33. The test operation is comprised of a constant amplitude cyclic loading of the structure at a frequency to simulate service loading. Thermal radiation in the wavebound of 8 to 12 microns is emitted from the surface of the sample and is sent by the optical system to a high sensitivity detector.

34. Data acquisition is automatically controlled by a microprocessor. This information is displayed on a monitor screen as a "stress map," with stress levels represented by different colors.

35. One of the infrared units now in the field is designed so the engineer can concentrate on the interpretation of data, not its acquisition.

This unit allows scanning by either line or area scan, and also allows variation of the number of sampling points and scan time. The values are instantaneously displayed. The unit permits enhancement of displayed stress data and visual identification of compressive and tensile stress. The stress value at any point on the stress map can be displayed. The unit allows data to be transferred to and from disk or host computer.

36. <u>Advantages</u>. In structures, stress concentration often occurs at a structural discontinuity or at the edge of a weld. Strain gauges are most commonly used to test for stress concentrations in structures. Strain gauges have been used for many years with good results, but positioning the gauges can be critical. It is difficult to establish the influence of fabrication and welding or to locate accurately the concentration points on a welded structure to using strain gauges. Measuring mechanical stress by using "thermal emission" will detect stress areas without contact with the structure.

37. <u>Disadvantages</u>. This equipment has been used with success on many structural components in the laboratory but is limited on structures in the field due to the large size of the equipment. Microprocessors increase the cost of this process.

Acoustic Emission

38. <u>Application</u>. Acoustic emission (AE) techniques can be used to either replace other NDT techniques or work in conjunction with them to obtain a cost savings.

39. Generating acoustic emissions usually requires that a stress be applied to the structure undergoing testing. Bridge structures may be stressed by traffic loading; wood bridge structures by static or dynamic wind loading. Materials undergoing welding are stressed thermally. Pipelines and pressure vessels may be stressed pneumatically or hydrostatically.

40. Acoustic emission has been used to detect defects during or immediately after welding. This early detection enables a defect to be repaired before it is covered with other weld passes. Later detection of this defect by radiography or ultrasonics could require considerably more grinding or gouging and rewelding, introducing undesired heat which produces a large grain structure.

41. After welding, residual stresses are sometimes relieved in a material by cracking. Acoustic emission will determine when and where cracking is occurring.

42. Acoustic emission can be used for inservice monitoring of critical or problematical components. The major advantage lies in the ability of this method to monitor the degradation occurring in inaccessible areas without interfering with the normal daily operation.

43. Acoustic emission has been used to examine and monitor the behavior of metals, ceramics, composites, rocks, and concrete for rupture, yielding, fatigue, corrosion, stress corrosion, and creep. AE has been used as a nondestructive test during manufacturing to determine phase transformation in metals and alloys and to detect defects (pores, inclusions, and quenching cracks). AE has been used successfully during the fabrication process for metal structures.

44. Acoustic emission is presently being used to monitor crack propagation on highway bridges. This technique can be easily adapted to steel lock and dam structures. Lock gates and associated components would be stressed when opening and closing, creating the acoustic emissions.

45. _Theory_. Acoustic emission can be defined as a transient elastic wave generated by the rapid release of energy within a material. These emissions can come from plastic deformation such as twinning or grain boundary slip, phase transformations, or crack initiation and crack growth. The energy released by a single dislocation is normally too small to detect. However, many dislocations often combine to form an avalanche of movements, which the AE equipment can detect.

46. When a material is strained beyond its elastic limit, it emits a characteristic noise signal called acoustic emission. Crack formation occurs at surface notches or at points where the local stress exceeds the fracture stress. The AE signals generated by a crack are emitted in bursts of high-frequency sound waves. Acoustic emission is unlike most other nondestructive test methods in that the energy comes from the material itself.

47. Acoustic emission relies on the fact that when a crack is growing, it releases random bursts of energy in the form of high-frequency sound waves. A piezoelectric transducer is attached to the structure to convert the stress waves to low level and high impedance electrical signals. Filters are used to eliminate mechanical (low frequency) and electromagnetic noises. Since AE signals are characterized by their broad bandwidth spectrum, filters allow a choice of operating frequency. Other components (amplifier, threshold detector, and counter) are required before the signal is fed into the mini-computer where it is transformed to traces on a plotter or cathode ray tube.

48. _Advantages_. Inprocess equipment is simple to use and can be set up quickly. The transducer location is not critical. The equipment is comparatively inexpensive and is not affected by rough surfaces. Electronic data processing equipment greatly simplifies interpretation of the results. Various field tests have shown excellent correlation between radiography and acoustic emission in detecting weld defects. AE equipment will detect active flaws with high sensitivity.

49. _Disadvantages_. Acoustic emission will only work while defects are growing under mechanical or thermal stress (the structure has to be loaded).

On complex structures, the signal interpretation can be difficult, with limited accuracy of localization. This is due to the large number of different mechanisms that contribute to the emission. There is a lack of sensitivity to certain kinds of porosity and to incomplete penetration. Background noise creates the most trouble for acoustic emission. The rubbing and fretting of surfaces that slide over one another, and high-velocity fluid flow involving a turbulence are the most troublesome. Filters can remove much of the background noise but this can involve more expense and expertise of others than operators. Most AE analysis is conducted using microprocessors or mini-computers which increase the cost of the inspection method.

Vibration Analysis Using Accelerometers

50. **Application**. Equipment seldom breaks down without warning. Equipment and hydraulic problems are almost always characterized by an increase in vibration levels which can be measured. A bathtub curve (Figure A1), is a plot of vibration level vs time.

51. Normal preventive maintenance procedures are set up at fixed intervals; normally based on the minimum life expectancy of the machine or component. As shown by the bathtub curve, by delaying repairs until vibration levels indicate the need for repair, unnecessary repair, shut-down, or dewatering is avoided. The vibration level which may be allowed or accepted before repairs are to be made will have to be determined by experience. In the manufacturing industry, the vibration level limit is normally set at two or three times the vibration level considered normal. This could be 6 to 10 dB above a "signature" or reference vibration that was previously plotted for this specific piece of equipment.

52. Mechanical failure due to metal fatigue is the most common effect of vibrations. However, there are other causes of metal fatigue. Bearings, pumps, motors, sumps, hydraulic cylinders, shafts, gate leaves, gears, and
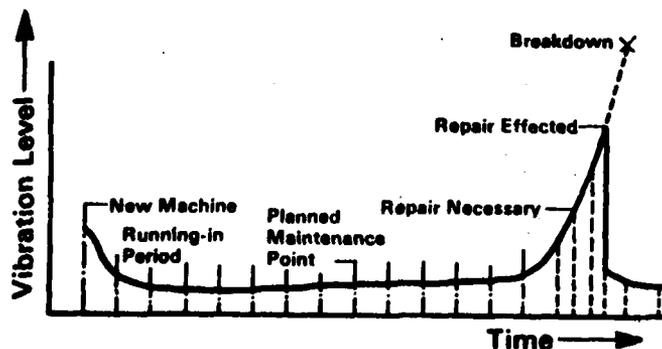

Figure A1. Bathtub curve

almost any part that moves will produce vibrations. In gears, tooth deflection under load and tooth wear will give rise to a tooth meshing frequency. The three parameters (acceleration, velocity, and displacement) can be used to measure vibration.

53. <u>Theory</u>. The fatigue phenomenon starts by local yielding in a material. The yielding takes the form of planes of atoms sliding over other planes. This sliding is caused by a combination of local stress concentrations and dislocations of irregularities in the crystalline structure of the material. When slip bands have been formed under cyclic loading, they progress to form minute cracks which eventually join together to produce major cracks. When the crack becomes so large that the stress in the remaining material cannot be accommodated, the crack propagation becomes unstable and failure occurs.

54. Vibration pickups are mounted on the object under test to detect the stress noises being created along the slip bands. The heart of this inspection system is the pickup or accelerometer, a small, lightweight, self-generating device with no moving parts. This device is also called a piezoelectric transducer or piezoelectric accelerometer.

55. Piezoelectric accelerometers exhibit greater sensitivity and higher frequency response than other types of vibration transducers. The two accelerometer configurations in common use are the compression and shear. Accelerometers are usually mounted on a part or structure by using cement, bolts, or permanent magnets. Hand-held accelerometers are convenient for quick survey work but can give gross measuring errors and repeatable results cannot be expected. The transducer is mounted and is connected to a vibration meter which is a measuring and indicating device. A frequency analysis is made of a part or structure under stress to determine its "signature" vibration which is characteristic of that particular material under stress without any slippage in the atomic layers.

56. During maintenance inspections, another test is made to determine if there is a change in the signature analysis. When a change occurs, the inspector uses the bathtub curve to decide when to repair or replace the item being tested.

57. <u>Advantages</u>. A wide range of equipment is available to measure vibrations. A single frequency band meter yields a simple vibration reading. Another meter produces a full analysis and comparison with reference spectra each time. Narrow band analyzers can provide a hard copy of the measured spectra in any parameter (acceleration, velocity, or displacement) in less than a minute. The inspector can determine the remaining useful life of a part and schedule repair or replacement. Vibration measurements can be used to determine when a machine will break down or to check the quality of repair.

58. **Disadvantages**. All piezoelectric materials are temperature depen-
dent, so that any change in the ambient temperature will result in a change in
the sensibility of the accelerometer. Sensitivity temperature calibration
curves must be used. Cable connectors, plugs, and the socket of the trans-
ducer must be protected from humidity and moisture by a silicone grease
coating.

APPENDIX B: TESTING LABORATORIES

The following testing laboratories were listed in the annual reference issue of Materials Evaluation, an official journal of the American Society for Nondestructive Testing. This is only a partial listing of laboratories in the United States that perform some or all methods of nondestructive testing.

ALASKA

Alaska Welding Center, Inc.
3021 Davis Road
Fairbanks, AK 99701
(907) 456-5962
Service: Worldwide

International Supply, Inc.
P. O. Box 74810
3025 Davis Road
Fairbanks, AK 99701
(907) 456-8378
Service: Worldwide

ARIZONA

Metalogic
275 S. Black Canyon Hwy.
Phoenix, AZ 85009
(800) 528-5428
Service: Worldwide

CALIFORNIA

Erdman Instruments
1179 Romney Drive
Pasadena, CA 91105
(213) 255-4802
Service: Continental US

Globex Corporation
730 Monroe Way
Placentia, CA 92670
(213) 946-1405
Service: Worldwide, especially
Western US, including AK and HI

Industrial Testing International, Inc.
11370 Trade Center Dr., Suite 1
Rancho Cordova, CA 95670
(916) 635-3294
Service: US and Puerto Rico

Q.C. Services, Inc.
26062 Eden Landing Rd, Suite 1 & 2
Hayward, CA 94545
(415) 782-3660
Service: AZ, CA, ID, IN, NV,
OR, TX, UT, WA

Valley Testing Service, Inc.
1295 Sunrise Gold Circle, Unit D
Rancho Cordova, CA 95670
(916) 635-3430
Service: US and Puerto Rico

X-ray Products Corporation
7829 Industry Ave.
Pico Rivera, CA 90660
Service: CA

CONNECTICUT

BRAND Examination Services &
Testing Company (BESTCO)
Essex Plaza, P. O. Box 818
Essex, CT 06426
(203) 767-2113
Service: Worldwide

FLORIDA

Q.C. Laboratories, Inc.
2870 Stirling Road
Hollywood, FL   33020
(305) 925-0499 or 949-3166
Service: Worldwide

Q.C. Laboratories, Inc.
26 North Kent Ave.
Orlando, FL   32805
(305) 425-0908
Service: Continental US

GEORGIA

Applied Technical Services, Inc.
1990 Delk Industrial Blvd.
Marietta, GA   30067
(404) 952-8705

IDAHO

Northwest Xray, Inc.
P. O. Box 738
Idaho Falls, ID · 84301
(208) 529-4494
Service: US and Puerto Rico

ILLINOIS

CONAM Inspection
1245 W. Norwood
Itasca, IL   60143
(312) 773-9400
Service: CA, IL, MA, MN, OH, PA, TX

MAGNAFLUX Quality Services
7300 West Lawrence Ave.
Chicago, IL   60656
(312) 867-8000
Service: US and Puerto Rico

MAGNETIC Inspection Laboratory, Inc.
(MIL Inc.)
9551 W. Berwyn
Rosemont, Il   60018
(312) 678-5415
Service: IA, IL, IN, MI, MN, OH, WI

INDIANA

Calumet Testing Services, Inc.
P. O. Box 1510
Highland, IN   46322
(219) 923-9800 or (312) 474-5860
Service: IA, IL, IN, MI, WI

LOUISIANA

O.S.I. Mobile Lab, Inc.
P. O. Box 395
Harvey, LA   70059
(504) 368-4424
Service: Worldwide

X-Ray Inspection, Inc.
P. O. Box 51651
Lafayette, LA   70505
(318) 233-7676
Service: US and Puerto Rico

MAINE

Quality Assurance Laboratories, Inc.
80 Pleasant Ave.
South Portland, ME 04106
(207) 799-8911
Service: New England, NY, Eastern
Canada

MARYLAND

Industrial Quality, Inc.
P. O. Box 2397
Gaithersburg, MD 20879
(301) 948-0332
Service: Worldwide

MICHIGAN

Michigan NDT, Inc.
P. O. Box 296
Chelsea, MI 48118
(312) 475-2979
Service: Continental US

X-R-I Testing, Inc.
1370 Piedmont
Troy, MI 48083
(313) 524-1444
Service: IN, KY, MI, OH

NEW HAMPSHIRE

Space Age Testing Services Co.
O'Shea Industrial Park
P. O. Box 636
Loconia, NH
(603) 528-4082
Service: New England

NEW JERSEY

Alicia Research & Testing Labs, Inc.
R.R. 1, Box 150 AA
West Creek, NJ 08092
(609) 296-0800
Service: Worldwide

Eastern Testing & Inspection, Inc.
9220 Collins Ave.
Pennsoken, NJ 08110
(609) 662-0333
Service: Continental US

Ebasco Services, Inc.
Building 100A Port Kearny
South Kearny, NJ 07032
(201) 460-5953 or 344-8400
Service: Worldwide

Physical Acoustics Corp.
P.O. Box 3135
Princeton, NJ 08540
(609) 452-2510

OHIO

Collins & Associates Technical
Services, Inc.
7991 Ohio River Rd.
Wheelersburg, OH   45694
(614) 574-2320
Service: Worldwide

Herron Testing Laboratories
5404 E. Schaaf Rd.
Cleveland, OH   44131
(216) 524-1450
Service: Worldwide

Midwest Testing Laboratories, Inc.
8598 Industry Park Drive
Piqua, OH   45356
(513) 773-1013
Service: Continental US

Q.C. Laboratories, Inc.
637 Redna Terrace
Woodlawn, OH   45215
(513) 771-7820/7824
Service: Continental US

Welding Consultants, Inc.
889 N. 22nd St.
Columbus, OH   43219
(614) 258-7018
Service: Worldwide

Dayton X-Ray Company
705 Albany St.
Dayton, OH   45407
(513) 228-4176
Service: Continental US

Lambda Research, Inc.
1111 Harrison Ave.
Cincinnati, OH   45214
(513) 621-3933
Service: Worldwide

Privett Inspection
10581 Lemarie Dr.
Cincinnati, OH   45241
(513) 733-5017
Service: US and Puerto Rico

Systems Research Laboratories,
Inc.
2800 Indian Ripple Rd.
Dayton, OH   45440
(513) 426-6000
Service: Worldwide

PENNSYLVANIA

Echo Ultrasound, Inc.
P. O. Boc 552
Lewistown, PA 17044
(717) 248-4993
Service: Worldwide

NIC Testing Services, Inc.
4621 Royal Ave.
Coraopolis, PA   15108
(412) 262-3092
Service: Worldwide

Universal Technical Laboratories,
Inc.
P. O. Box 372
Collingdale, PA   19023
(215) 586-3070
Service: US and Puerto Rico

Industrial Testing Laboratory
Services Corp.
635 Alpha Drive
Pittsburgh, PA   15238
(412) 963-1900
Service: US and Puerto Rico

Pittsburgh Testing Laboratory
850 Poplar St.
Pittsburgh, PA.   15220
(412) 922-4000
Service: Worldwide

West Penn Testing Laboratories,
Inc.
482 West Eighth Ave.
West Homestead, PA 15120
(412) 462-3717
Service: Continental US

RHODE ISLAND

ITT Grinnel Corp.
260 West Exchange St.
Providence, RI   02901
(401) 831-7000

TENNESSEE

World Testing, Inc.
72 East Hill St.
Mt. Juliet, TN   37122
(615) 754-4147
Service: Continental US

TEXAS

NDE-AIDS, Inc.
1189 Mercedes St.
Benbrook, TX   76126
Ph. Metro 429-8823
Service: US and Puerto Rico

UTAH

Universal Testing Co.
3574 South 500 West
Salt Lake City, UT   84115
(801) 266-6461
Service: Continental US

WISCONSIN

Wisconsin Industrial Testing, Inc.
4250 N. 126th St.
Brookfield, WI   53005
(414) 781-0105
Service: Continental US