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16. ABSTRACT

This final report (Phase I) discusses the nondestructive inspection methods used by the California Department of Transportation, Transportation Laboratory for the inspection of steel bridge structures during construction. These methods are radiography, ultrasonic, magnetic particle, and liquid penetrant.

It concludes that no one method by itself will provide the assurance of a structurally sound bridge.

Although the Transportation Laboratory will be unable to complete Phase II of this project, it feels it is important enough to recommend it be performed by others.

Additional information is included in this report on acoustic emission and the acoustic crack detector and magnetic crack definer developed by Southwest Research Institute.

The information contained herein is of an informative nature similar to a "state of the art" type report.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

June 1977

FHWA No. F-4-29
TL No. 636571

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

NONDESTRUCTIVE INSPECTION OF STEEL (PHASE I)

Study made by ..... Structural Materials Branch

Under the Supervision of ..... Eric F. Nordlin

Principal Investigator ..... Paul G. Jonas

Co-Investigator ..... Donald M. Lai

Research Conducted & Report by ..... Donald M. Lai

Assisted by ..... Robert H. Idleman,
Bud L. Ratliff,
and
Steven W. Rutter

Very truly yours,

George A. Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

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Attachment

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ACKNOWLEDGEMENTS

The authors of this report wish to express their appreciation for the help and advice provided by their colleagues in the California Department of Transportation, Transportation Laboratory (Translab).

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or polices of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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INTRODUCTION

In recent years several highway bridges have had catastrophic failures resulting from brittle fracture at stresses below the conventional yield stress of the member. Brittle fracture is an abrupt type failure as opposed to yielding which is a slower, tearing type failure. It usually occurs after a small flaw initiates a crack which grows by such mechanisms as fatigue, stress corrosion and hydrogen embrittlement to a critical size.

Fracture mechanics attempts to analyze a structural member using the probable initial flaw size, crack growth rate, and critical (final) flaw size. The importance of an accurate estimation of initial flaw size is immediately apparent.

Nondestructive inspection methods therefore play an important role in the accurate determination of initial flaw size. Nondestructive inspection methods such as radiography, ultrasonics, magnetic particle, and liquid penetrant have been successful in the field of flaw detection. However, a more exact, quantitative evaluation of their capabilities in terms of probable minimum detectable flaw size is necessary for a successful fracture mechanics control program for structural steels.

This project was originally proposed as a two-phase effort described below:

Phase I: Document Caltrans Transportation Laboratory's present knowledge in the following fields of nondestructive inspection of welded steel highway bridges:

1. Radiography (RT)
2. Ultrasonics (UT)

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3. Magnetic Particle (MT)
4. Liquid Penetrant (PT)
5. Acoustic Emission (AET)

Phase II: Define, possibly on a statistical basis, the smallest flaw able to be consistently detected using each nondestructive inspection method using test plates and welds containing intentionally produced flaws. Actual flaw sizes to be determined by destructive tests. Weld investigation to focus primarily on full penetration butt welds.

This report concerns itself with Phase I of this project. Because of other commitments, Phase II of this project will not be completed and will be terminated at this time.

Also included in this report, which was not part of the original project, is a discussion and evaluation of prototype acoustic and magnetic crack detector instruments developed by Southwest Research Institute.

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CONCLUSIONS

The usefulness of nondestructive inspection (NDI) is obvious since it is several steps above visual inspection and in the final analysis is a major determining factor in the integrity of a welded steel bridge structure to the extent of the amount of NDI performed, the quality of the inspection, and the specified acceptance-rejection criteria.

Of the various methods of nondestructive inspection discussed, no one method is a complete flaw detection method. Each method is useful for the detecting of particular type flaws. Thus the methods are generally complementary to each other.

Dry powder prod type magnetic particle inspection and liquid penetrant inspection are useful for the detection of flaws open to the surface. Magnetic particle inspection may also be used to detect internal flaws close to the surface.

Radiographic and ultrasonic inspection complement each other in flaw detection. They are useful in finding internal and surface flaws.

Radiography is sensitive to volume type defects in weldments, such as porosity and slag. It is also sensitive to cracks, lack of fusion, and lack of penetration when the radiating rays are parallel to the line of the defect depth.

Ultrasonics is most sensitive to cracks and lack of fusion that are normal to its sound beam path. Porosity and slag are also detectable, but with considerable difficulty in many cases.

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IMPLEMENTATION AND RECOMMENDATIONS

This final report is written to briefly inform bridge engineers, inspectors, and other interested parties of some aspects of nondestructive inspection. For those who wish to pursue the subject matter in greater detail, an NDI comparison chart of various methods (see Figure 1) and a listing of commonly used nondestructive testing specifications and standards (see Figure 2) are included in the Appendix in addition to the references. Also, training courses are offered throughout the country by various commercial testing agencies.

Since Phase II of this project is to be terminated by the Transportation Laboratory, it is hoped that others will concur with its importance and proceed with its completion.

Transportation Laboratory at some later date intends to resume Phase II unless research to this end has already been performed.

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DISCUSSION

General

The four most popular methods of nondestructive testing (NDT), or nondestructive inspection (NDI) as will be referred to in this discussion, that are used by the California Department of Transportation, Transportation Laboratory (Translab), or used by commercial testing laboratories for quality assurance and control of steel bridge weldments during construction are: radiography, ultrasonics, magnetic particle, and liquid penetrant inspection.

These methods have attained a state of development which is reflected by their increased use in industry throughout the world. With increased confidence in NDI, safety factors have been decreased in the design of structures, resulting in increased efficiency and economy.

This confidence can only be maintained, however, if NDI operators are carefully selected for these tasks. Not only must the operator have the education, physical well being, and skills required, but must have other attributes such as integrity, persistence, and conscientiousness. Since much of NDI concerns itself with interpretation of indications that are not permanently recorded, it can at times be convenient to misinterpret a magnetic particle indication or not see a blip on an ultrasonic screen.

The other extreme is the operator who is overzealous in his work and overinterprets the specifications consistently. This results in costly, unnecessary welding repairs. Unnecessary weld repairs can also be detrimental to a structure resulting from residual stresses from many repairs.

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These four methods of NDI are used by Translab primarily because of their suitability to large sized structures and field applications, and their flaw detection capabilities. In terms of equipment first cost, listed in descending order are radiography, ultrasonics, magnetic particle, and liquid penetrant inspection, with liquid penetrant inspection being significantly lower than any of the other NDI methods. In terms of inspection cost per foot (30.48 cm) of weld, listed in descending order are ultrasonics, radiography, liquid penetrant, and magnetic particle inspection.

Environmental conditions (staging, scaffolding, weather, etc.) also are an important part of NDI. Specifications should be specific as to the conditions operators work under. Even though conditions may be marginally suitable for NDI, it may affect the operator's performance over extended periods. Thus environmental conditions should be considered when written in the specifications.

Minimum operator qualifications should require certification in accordance with the American Society for Nondestructive Testing (ASNT), Recommended Practice No. SNT-TC-1A, NDT Level II, and its applicable Supplement as determined by the NDI method used. This is considered the journeyman level in NDI and requires, as in Levels I and III, minimum levels of education, experience, and the passing of written and practical examinations.

The use of Level I operators when accompanied by a Level II operator should be considered in the light of the importance of the structure and should be included in the specifications when NDT Level I personnel can be used.

ANST certification is granted by the employer who is responsible for carrying out the guidelines set forth by the ASNT. These duties are generally performed by Level III personnel, who in the

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past were also granted certification by the employer. Recently the ASNT adopted new procedures for certifying Level III candidates. These new procedures now require certification by examinations given by the ASNT. There are also rules and procedures for certification without examination based on past experience. Also adopted are a code of ethics and administrative procedures for handling complaints relative to violations of ASNT certification rules and/or code of ethics for Level III NDT personnel certified by ASNT(3).

Nondestructive inspection of steel, as its name implies, inspects or tests steel for internal or external defects without destroying anything. This is not to be taken literally, since in many situations surfaces and welds have to be ground resulting in metal removal, and paint has to be removed for electrical contact with the MT prods. However, in no case does nondestructive inspection, properly performed, alter or impair the structural integrity of the member inspected.

The remainder of this report discusses the different nondestructive inspection methods with the intent that it be useful to bridge engineers and inspectors who have been exposed to a small degree to some of the methods discussed. It is introductory in nature and does not take the technical approach normally given to research reports.

Radiographic Inspection

One of the more well known and probably the most extensively used methods of nondestructive inspection of bridge weldments is radiography, often but not correctly referred to as X-ray. Its flaw detection capabilities are in finding internal and external weld defects such as porosity, slag, and lack of

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penetration. Its confidence level for finding cracks and lack of fusion is low and depends upon the orientation of the flaw with respect to the radiation rays. The more parallel the crack or lack of fusion with respect to the radiation rays, the more chance of detection. When parallel with these rays, the confidence level is relatively high.

The performance of radiography requires special radiation emitting equipment, depending upon whether X-ray or gamma ray radiography is used (see Figures 3 and 4). X-ray equipment is electronic in nature and is quite bulky and heavy (Note: Lightweight equipment with less bulk is now available but has not been taken into consideration in this report because of lack of knowledge of its performance and durability). Therefore it is generally confined to inspection of bridge components being fabricated in the shop. Even then, this presents a problem since the X-ray radiation is generally of higher intensity than gamma ray. Therefore more extreme measures must be taken to protect workers in the area. Gamma ray equipment is more portable than X-ray, lighter in weight, less bulky, and simple to operate. It derives its radiation from a radioactive isotope. Iridium 192, one of the more popular isotopes widely used, is stored in a shielded case referred to as a projector or camera. With a cable and crank mechanism connected to the projector, the isotope can be controlled in and out of its shielded case to radiograph a weld. With its light weight and portability it can be shipped around in a radiographic camper equipped with darkroom facilities and all the necessary equipment to make a radiograph at the jobsite. It is thus widely used in the field and shop for welds from 1/2 inch (1.27 cm) to 3-1/2 inches (8.89 cm) thick. Its main disadvantage is its short half life of approximately 74 days, requiring frequent replacement.

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For thicker welds up to 8 inches (20.32 cm), a Cobalt 60 isotope is normally used. Its higher gamma ray energy level of over one million electron volts produces greater penetrating ability than Iridium, resulting in shorter exposure times and better sensitivity for the thicker welds. Because of its penetrating ability it is thickly shielded, resulting in heavy equipment relying on special carts for mobility. It thus is not conducive to field inspection, but is used when thicker members require its use. Its half life is about 5.3 years.

Radiographs are produced by radiating a weld with penetrating X or gamma rays resulting in exposure of a film placed on the opposite side of the weld being exposed to these rays (see Figure 5). The amount of radiation reaching the film depends upon how much is absorbed by the weld. For the same exposure time, the thicker the weld the more absorption with less radiation reaching the film. Thus an internal void such as porosity presents less material for the ray to see, resulting in less absorption and more radiation reaching the film at the local area in line with the ray and defect. This results in a dark image on the processed film which is then interpreted as a defect. The visual detectability of an image on a radiograph depends on two factors - contrast and definition(4). The contrast is the darkness of the image of the flaw on the film in relation to the background. Definition is the sharpness or resolution of the image on the film. The degree of achievement of these parameters will determine the radiographic sensitivity.

Contrast is affected by the radiation wavelength and its spectrum, scatter radiation, film, film density, and film development.

Definition is affected by focal spot size, source to film distance, weld thickness, film, screens, radiation wavelength, and film development.

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The pentrating ability of X and gamma rays through steel is determined by their effective energy level (electron volts). This is not to be confused with intensity and exposure time which also affects penetration. As the energy level is increased, the wavelength decreases and the penetrating ability increases. Thus, one way to reduce the exposure time, if this is desirable, is by increasing the effective energy level. However, the amount of increase is limited by the sensitivity required. For a particular thickness of steel there is a particular energy level to obtain optimum radiographic sensitivity. Decreasing this energy level will increase contrast (which is desirable), increase exposure time exponentially, and decrease definition (which is undesirable). Increasing the energy level will reduce contrast (which is undesirable), reduce exposure time, increase latitude (the material thickness range imaged on a radiograph), and increase definition (which is desirable). Thus, decreasing the exposure time by increasing the energy level must be balanced with acceptable sensitivity.

X-ray and gamma ray are both electromagnetic radiation differing only in the energy level spectrum emitted. X-ray machines are rated at the maximum energy level they can emit with settings for levels lower than the maximum rating. Each setting then establishes the maximum energy level that can be radiated at that setting. In most X-ray machines about 1/3 of the emitted radiation is at the machine setting with the remaining 2/3 at energies below this setting down to zero volts. Thus the X-ray energy spectrum is said to be continuous. In the case of gamma radiation where radiation comes from an isotope, a continuous spectrum does not exist. These energies are monochromatic, that is they have only one wavelength or a narrow range of wavelengths or energy levels. These wavelengths are constant for a particular isotope; thus they lack the flexibility of an X-ray machine with its varying settings.

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Generally X-ray machines produce radiographs superior to those produced by gamma radiography. This is because of its continuous wavelength spectrum with the existance of the longer wavelengths or softer rays which improve contrast. Gamma radiography with its narrow range of wavelength spectrum being constant, will produce optimum radiographic sensitivity for a particular weld thickness. For instance, Iridium 192 achieves its optimum sensitivity for steel weld thicknesses of about 2-1/2 inches (6.35 cm). Lesser or greater thicknesses will result in reduction in sensitivity.

Film contrast increases with increasing film density when using industrial radiographic film. The density is the logarithmic ratio of the incident light on the film to the transmitted light through the film. Thus the darker the film, the higher the density. Commercial high density viewers are available for densities up to 4.0. Specified densities for gamma radiography range from 2.0 to 4.0 with densities of 2.5 to 3.5 being preferred. Minimum densities of 1.5 for X-ray radiography are acceptable because of the higher contrast obtained from X-ray.

Generally, Type II industrial film is specified for radiographic weld inspection. However, when gamma radiography is used on thin welds, the energy levels may be too high to achieve the desired contrast. Therefore a Type I high contrast film is specified which has higher image amplification producing the higher contrast and also has higher definition because of its finer grains. Thus, for Iridium 192 with weld thickesses 1 inch (2.54 cm) and below and Cobalt 60 with weld thicknesses 4 inches (10.16 cm) and below, Type I film should be used.

It should also be mentioned that Type I film is a slower speed film than Type II, thus resulting in exposure times of two to four times that of Type II film. However, this is somewhat

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offset by the fact that Type I film in this case is required only for the thinner welds relative to the isotope used.

Contrast can also be improved by the film developing process. Manufacturers generally specify a developing time range from 5 to 8 minutes for industrial radiographic film at 68°F (20°C). Using the maximum developing time of 8 minutes will result in higher contrast than developing at 5 minutes. However, the maximum time should not be exceeded because of increased film fogging, resulting in reduced sensitivity.

Radiographic sensitivity is also dependent upon film image definition or sharpness. Geometric controlling factors are effective focal spot size (X-ray) or isotope source size (gamma ray), source to film distance, and weld thickness.

For a constant source to film distance, the definition improves as the focal spot or source size decreases. Since these sizes are fixed once the equipment is purchased, consideration should be given to obtaining minimum effective focal spot and source sizes to suit particular situations.

Weld or specimen thickness also affects definition. As the weld thickness increases, definition decreases.

It can be seen that for a given X-ray machine or isotope and weld, the focal spot or source size and weld thickness are fixed geometric factors, thus fixing the definition when only these factors are considered. However, another geometric factor, source to film distance, can be varied to obtain the desired results. As the source to film distance is increased the definition increases. However, this is at the expense of increased exposure time which increases with the square of the

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distance. A minimum source to film distance is usually specified not only for definition control but also to control the amount of image enlargement. It can be determined geometrically that as the source to film distance decreases or the weld thickness increases, the projected image size increases. The Translab specifies minimum source to film distance as the distance equal to the width of the film or the distance seven times the weld thickness, whichever is greater.

X or gamma radiation emanates from the radiographic equipment to the weld to be inspected. A film cassette loaded with thin lead screens on each side of a double emulsion film is placed on the side of the weld opposite the radiation source. The lead screens when exposed to radiation energies above about 140 kilovolts emit electrons which intensify the reaction on the film dmulsion, thus reducing the exposure time. Fluorescent screens have greater intensification than lead, but are not recommended because of their inherent characteristic of reducing the sharpness of the radiograph. The screens in both cases must also be in intimate contact with the film, otherwise sharpness is lost.

Penetrameters are the accepted method to determine the quality of a radiograph. They are called "Image Quality Indicators" (IQI) and are indicative of the quality of the radiographic technique used. They are thin rectangular stripes with three specified hole sizes, made of the same or similar material as the weld to be inspected. The minimum penetrameter thickness and size of its holes are the determining factors for the level of the inspection. Most weld inspection specifies a 2-2T level of inspection. This is interpreted to mean a radiograph should clearly show the outline of a penetrameter with a thickness of 2% of the weld thickness and the hole having a diameter two times the thickness of the penetrameter. It should be mentioned

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that IQI should not be confused with radiographic sensitivity, i.e., it does not indicate in absolute terms the detectable flaw size. Being able to see a 2-2T penetrameter on a radiograph does not mean a flaw of a size 2%of the weld thickness and a diameter 4% of the thickness is necessarily detectable. The penetrameter and its holes have square edges. Thus an abrupt film density change occurs at the penetrameter and hole outline. A flaw of this size will most likely have more subtle edge density changes. The net result is, the penetrameter and its holes can be seen while an equal size flaw may not be visible under the viewer because of the lack of delineation. Even large defects can escape detection if the density change is gradual over a large area(4). However, the more visible the penetrameter image, the higher the quality of the radiograph and the higher its radiographic sensitivity.

Penetrameters should be located on the radiation side and adjacent to the weld. They should not be located on the film side. Penetrameters located on the film side have very sharp images with high contrast. Verification of whether film side penetrameters were used can be determined by measuring the penetrameter image enlargement. A film side penetrameter will indicate no enlargement.

The interpretation of a radiograph requires the ability to read subtle indications which appear on occasion and are sometimes major in severity. These subtle indications may be the result of poor radiographic practice, poor flaw orientation with respect to the penetrating rays, poor flaw boundary delineation, etc. An unground weld by virtue of its roughness and contour will result in a radiograph with many indications and varying densities which will easily mask any subtle flaw indication, which is information that should have appeared on the radiograph. To alleviate such

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situations the weld should be ground smooth and flush to the surface prior to making the radiograph. This will facilitate the interpretation.

Ultrasonic Inspection

Ultrasonic inspection is used for the detection of internal and surface discontinuities in weldments. Flaws most readily detectable by this method are cracks and lack of fusion. Other flaws detectable but with a lower confidence level and requiring more time for detection are porosity, slag, and lack of penetration which are the flaws more readily detectable with radiographic inspection. Because of this the Translab uses ultrasonic inspection as a complementary tool to radiography with radiographic inspection preceding ultrasonic inspection. When flaws are detected by radiography they are repaired and re-radiographed before ultrasonic inspection is performed. All this is done to facilitate the ultrasonic inspection which takes considerable time if porosity and slag inclusions exist in the weldment. Even with a weld free of porosity and slag, the inspection can be time consuming.

To perform an adequate ultrasonic inspection takes a minimum of 15 minutes scanning time per foot of weld length. Any less time decreases the confidence level of the inspection. This rate is the ultrasonic scanning time of a weld free of any indications which will cause the operator to deviate from the normal scan to investigate the indication. This does not take into consideration the time to clean the scan area before and after the inspection, calibrate, record the data, move equipment from one location to another, etc. When numerous indications and defects occur, it may take more than one hour to complete a foot (30.48 cm) of weld. Thus it can be seen that even though the procedural process attempts to minimize the indications other

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than crack and lack of fusion indications, the inspection is still time consuming depending upon the quality of the welds inspected. Taking into consideration the other tasks involved, it is not unrealistic to say the production rate is about 3/4 to 1-1/2 hours per foot (30.48 cm) of weld with a two man team.

Two man teams are necessary to alleviate the tedious work involved by alternating operators occasionally. Additionally, the extra man acts as a monitor of the operator's work, records all data since it is the nature of the work that recording by the operator is inconventient because his hands are usually covered with glycerin or some other liquid substance, refers to charts to provide information to the operator when called on, and assists in the clean-up and moving of equipment. This assistance is necessary to the operator so his attention is not diverted from monitoring the CRT screen while manipulating the transducer during the performance of the weld scan.

Ultrasonic inspection is performed with electronic equipment with a cathode ray tube and associated controls in conjunction with transducers, calibration blocks and a liquid couplant. Transducers contain piezoelectric crystals of ceramic material which generate sound energy when impressed with an applied voltage or conversely will generate a voltage when activated by sound energy. Transducers with frequencies of 2.25 and 5 megahertz are normally used in weld inspection of bridge steels. The cathode ray tube (CRT) displays reflected signals from possible defects which are then interpreted by the operator.

The pulse-echo method of ultrasonic inspection is used for weld inspection. With this method the operator scans the weld with a transducer which transmits beamed ultrasonic energy bursts into the steel. Between bursts the transducer acts as a receiver for

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any ultrasonic signals reflected back which represent possible defects. The signal is displayed on the CRT screen which is monitored by the operator. The ultrasonic equipment, which is calibrated prior to each weldment inspection or when the equipment is moved, allows the operator to compare the reflected signal with the calibrated signal, determine its location and length, and evaluate its severity in terms of decibels. The lower the decibel rating algebraically, the more severe the indication. Reference to specified charts based on weld thickness, defect rating, and length of indication determine whether the weld is acceptable or rejectable.

Two types of transducers (search units) are normally used - straight beam and angle beam. Straight beam transducers direct ultrasound into the steel normal to the surface and are used to detect lamellar type defects in the weld and determine the base metal soundness in preparation for angle beam examination. This preparation is necessary to insure that the base metal adjacent to the weld will allow the transmission of angle beam sound energy through the base metal, which is required of angle beam examination. Angle beam transducers are used to perform the basic weld inspection by directing ultrasound into the base metal and weld at angles to the surface. This angle is the acute angle measured from the normal to the surface to the sound beam path. Standard angles are 45°, 60°, and 70°. Figures 6 and 7 show straight beam and angle methods.

Ultrasonic inspection is used by the Translab for the inspection of grooved butt welds in primary bridge girder members such as tension and compression flanges. Prior to inspection the welds should be ground flush to the surface to eliminate the many signals from the weld crown. These signals or indications tend to obscure possible defects in the crown and create a situation where the operator is required to make interpretations with a low confidence rating.

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The grinding of the weld smooth but not flush to the surface will not suffice in ultrasonic inspection if a high confidence rating is to be maintained. The smooth curvature of a weld crown can result in spurious indications which may be interpreted as defects. Also the search unit has to be manipulated over the weld itself to complete a longitudinal scan (the scan that detects defects longitudinal to the weld), and make a transverse scan. The weld should therefore be ground not only smooth but also flush with the surface.

The cathode ray tube screen is an X-Y display, displaying blips which represent the sound reflected from an indication. The X-axis represents the time for sound to be transmitted and reflected back. Since the velocity in steel is constant, the X-axis can be calibrated to represent the distance of the sound path from the search unit to the indication. Knowing the angle the sound beam enters the steel surface, the distance and depth of the indication can be calculated or referred to on a chart.

The Y-axis represents the intensity of the sound reflected back. The height or amplitude of the blip is controlled by discrete decibel switches. The blip or signal can then be brought back to a reference screen amplitude with these switches and the decibel value is noted for comparison with the calibrated reference signal. This is the defect or indication level.

Prior to ultrasonic angle beam inspection of the weld, the instrument should be calibrated to establish a reference signal. This reference signal is the signal from a 1/16 inch (1.59 mm) diameter hole in the IIW (International Institute of Welding) block and is defined as a zero db reflector when scanned with a 70° transducer, only. Because of the bulkiness of this block it is seldom used for on-site calibration purposes and other blocks such as the "Type S.C." block are substituted with appropriate

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correction factors used(5) (see Figures 8 and 9). Thus by calibrating the machine to the sensitivity of this drilled hole, all other indications can be compared to this reference signal as long as the same transducer used for calibration is used for detecting the indications.

Ultrasound travels through steel at a constant velocity but with decreasing intensity as the sound path increases. This attenuation is approximately 2 db per unit of sound travel from the search unit to the reflector and back with a 2 1/4 MHz angle beam transducer. When evaluating the reflector, this attenuation must also be accounted for. However, when using a "Type S.C." block for calibration, the sound path from the search unit to the hole for 45, 60, and 70° transducers is 1 inch (2.54 cm). When determining the attenuation, the 1 inch (2.54 cm) is subtracted from the sound path distance before applying the attenuation factor.

When using ultrasonic instruments with attenuator switches or knobs, the indication amplitude decreases as db's are switched in. The indication rating is then determined from the following formula:

B	minus	A	minus	C	equals	D
Corrected Calibrated Sensitivity (Reference Level) (db's in)		Defect Level (db's in)		Attenuation Factor (db's in)		Defect Rating (db's)

When using ultrasonic instruments with calibrated gain control switches or knobs, the screen amplitude increases as db's are switched in. The indication rating is then determined from the following formula:

A	minus	B	minus	C	equals	D
Defect Level (db's in)		Corrected Calibrated Sensitivity (Reference Level) (db's in)		Attenuation Factor (db's in)		Defect Rating (db's)

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See Figure 10 for examples of the two types of instruments.

Ultrasonic energy is extremely attenuative in air. With the search unit interfaced with the steel surface a thin air gap exists at this interface, preventing any useful sound energy from entering the steel. This is solved by coating the steel surface with liquid, usually glycerin. This displaces the air gap with the liquid and thus couples the ultrasonic energy from the search unit to the steel.

Liquid glycerin exhibits excellent ultrasonic coupling properties. It is low in attenuation, acts as a good lubricant between the search unit and steel to facilitate movement of the search unit over the scanning surface, has a very slow evaporation rate resulting in constant attenuation properties, and can be cleaned from the surface with clean water. Its primary disadvantage is, if it is not thoroughly cleaned off, a slippery residue is left on the steel structure which creates a potential safety hazard. It is also hygroscopic and should be thoroughly cleaned off the calibration blocks to prevent corrosion from the accumulated moisture.

Two major factors governing ultrasonic sensitivity are the ability to transmit the sound to the flaw (reflector) and back to the search unit, and the ability to detect the flaw. Both factors are dependent on the wavelength which is inversely proportional to the frequency with constant sound velocity propagation. As the wavelength decreases, the attenuation through the steel increases, thus limiting the sound path travel and its sensitivity in terms of detecting small or tight flaws increases. Thus these two factors are incoordinate with each other in terms of ultrasonic sensitivity.

The selection of the transducer frequency or wavelength must therefore be balanced between these two factors.

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Another consideration in transducer selection is sound beam divergence or beam spread. Since calibration is performed on calibration blocks in close proximity to its artificial flaw, very little energy is lost as a result of beam spread. As the sound path to an actual flaw increases, much of the sound energy is lost when it reaches a flaw because of beam spread. Thus sensitivity is also affected by beam spread. Two parameters control beam spread - wavelength and transducer size. The larger the wavelength and/or the smaller the transducer size, the larger the beam spread. Thus to limit beam spread, transducer frequency and/or size must be increased. Standard angle beam transducers specified have frequencies of 2 1/4 HMZ with an effective crystal size of 1/2 inch x 1 inch (1.27 cm x 2.54 cm). It should be mentioned that sound path travel distance should be limited to a maximum distance of 10 inches (25.40 cm) because of beam spread.

Magnetic Particle Inspection

Prod type dry powder magnetic particle inspection is used for the detection of surface and some subsurface defects in ferromagnetic materials only. Surfaces to be inspected should be dry and clean for suitable electrical contact with the prods and the free flow of the dry powder. Where thin paint exists, it is necessary to remove the paint only in the locations where the prods come in contact with the surface of the steel. Where surfaces are excessively rough, such as fillet welds, interpretation is difficult and some grinding of the weld should be done. The operator should be experienced and knowledgeable in this type inspection, especially in the interpretation of indication aspect since subtle indications sometime appear which require a certain amount of expertise to make a valid judgment.

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Portable magnetic particle equipment is available for field use. They generally weigh over 50 pounds, most of which is transformer weight with large size leads for the prods because of the high current used. They generally can be connected to a 120 or 240 volt AC source. When connecting to 120 volts, the source circuit breaker should be checked for sufficient size (See Figure 11).

Magnetic particle inspection is performed by passing high current from the prods into the surface to be inspected. The current passing into the ferromagnetic material from one prod to the other induces a circular magnetic field around the prods with flux lines at right angles to the direction of the flow of current. These flux lines tend to concentrate at and near the surface the prods are located on. Where these flux lines are interrupted by a surface discontinuity such as a crack at an oblique angle of approximately 40° or less, a concentration of flux occurs or an increased magnetic field is established across the discontinuity. Maximum sensitivity occurs when the discontinuity is 90° to the flux lines. Dry iron oxide powder sprayed onto the surface between the prods will concentrate at the area of high magnetic flux density at a crack, thus providing a visual indication of a Surface discontinuity.

Alternating (AC) and half wave rectified direct current (HWDC) are normally used to induce the magnetic field. Because of the "skin effect" associated with alternating current, it tends to flow at the surface more so than HWDC. This has the effect of concentrating the induced magnetic field at the surface with the result that it is more sensitive than HWDC for detecting surface flaws but has no subsurface detection capabilities. For subsurface flaw detection, HWDC has to be used with some sacrifice in surface flaw detection sensitivity.

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Magnetic particle inspection is used in weld inspection for the detection of surface and subsurface cracking such as under bead creacking in fillet welds. For this reason half wave rectified direct current is generally used with currents of 100 to 125 amps per inch (2.54 cm) of prod space. Weld preparation is usually necessary by grinding because of the inherent surface roughness leading to irrelevant magnetic particle indications.

Liquid Penetrant Inspection

Liquid penetrant inspection is one of the more simpler methods of nondestructive inspection techniques requiring minimal skill from the operator. Its use is solely for the detection of defects which are open to the surface such as surface cracks. Surfaces to be inspected should be as smooth as possible to facilitate cleaning; however, caution should be exercised in attempting to mechanically smooth rough surfaces because of the possibility of closing over a surface opening or filling it with material which could mask a potential defect. Some disadvantages of this surface flaw detection method are that it is difficult to interpret depth of flaw, is subject to misinterpretation on porous materials, and will detect surface defects only. Advantages are that it will detect surface defects in magnetic or nonmagnetic material, has low initial cost, has the least operator dependence when compared with the other nondestructive inspection tools (when properly performed it will produce the least amount of false indications) and is easily taught and learned. Its sensitivity to the detection of surface cracks is generally slightly less than magnetic particle and ultrasonic inspection. Its production rate is slower than magnetic particle inspection but faster than ultrasonic.

The tools for liquid penetrant inspection are by far the lowest in initial costs than any of the other nondestructive methods

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discussed. They consist of three aerosol spray cans containing cleaner, dye penetrant and developer. These components are also available in bulk form. After the surface of the metal is cleaned, it is sprayed with the dye penetrant. The dye is also to dwell on the surface for a period of time, seeping into openings and drawn into tight cracks by capillary action. After the proper dwell time, the surface is wiped clean with a rag moistened with the cleaner. Developer, which is a white powder in liquid solution, is then sprayed on and allowed to dry. As the drying action progresses, the powder acts as a blotter soaking up any penetrant fluid left in any surface openings or cracks. Since the powder or developer has a contrasting color with the dye penetrant, a visual indication will appear which is then interpreted by the operator as acceptable or rejectable (See Figure 12).

It can be seen that if the surface is not sufficiently cleaned of dye penetrant, spurious indications will result since the developer will absorb the excess penetrant. Areas which are difficult to clean such as rough surfaces or unground welds may require a liquid penetrant kit with a post emulsifying agent. The emulsifying agent reacts with the penetrant to make it water soluble. The penetrant material can then be rinsed off after the proper emulsifying dwell time. This time is important since the primary purpose in applying the emulsifier is to allow it to react with the surface penetrant only. Excessive dwell time of the emulsifying agent will result in the penetrant in the defect openings becoming water soluble and subject to being rinsed off, thus negating indications of flaws.

There are other methods of liquid penetrant inspection which require more expensive equipment. Generally they are confined to the shop for the inspection of parts much smaller than the components that make up a steel bridge.

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Acoustic Emission

Compared with other nondestructive techniques, acoustic emission is in its infancy even though work in this method was begun by Joseph Kaiser in Germany in the early 1960's(6), when he used electronic instrumentation to detect audible sounds produced by metals during deformation. Recent years have seen this nondestructive inspection tool evolve from the laboratory into practical application with its use in inspecting aerospace components, commercial pressure vessels, high speed turbine equipment, etc. However, its application for steel bridge structures is still in the development stage but some promise of its emerging in the near future is indicated.

Acoustic emission's potential as a bridge monitoring tool will probably be directed as a first step toward being used as a survey tool of existing structures in-situ rather than new bridge construction. This however is not to suggest precluding its use in future new bridge construction.

Acoustic emission is primarily an active crack seeking device. Passive cracks or flaws are not detectable by this method. Its potential ability to seek out active cracking of at least one millionth of an inch (one millionth of 2.54 cm) and locate them at significant distances should lend itself well to use on existing structures. It does not however characterize a crack. Other nondestructive inspection methods will be required to perform this task.

Acoustic emission uses very sophisticated electronics when compared with other nondestructive inspection equipment in conjunction with piezoelectric transducers or sensors. The transducers serve as listening devices for the detection of acoustic energy propagating from the active fracture to the sensor by means of the steel media which is translated into electrical energy. This

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signal is received at a main terminal and amplified for monitoring, locating its origin, filtering the non-relevant noise, providing a display for immediate interpretation, and recording data for later interpretation. Thus many sensors can be installed on a structure, all being fed back to a main terminal, processed and interpreted immediately or at a later date. The bridge inspection concept could have the main terminal which comprises the electronic equipment in a compact and portable form, housed in a secure place at the structure, and able to be relocated from one structure to another by means of a pickup truck or van. Permanently secured sensors, selectively located on a structure and wired back to its main terminal could then be connected to the terminal equipment periodically to collect data for interpretation at a later date.

Acoustic Crack Detector (ACD) and Magnetic Crack Definer (MCD)

The Acoustic Crack Detector (ACD) and the Magnetic Crack Definer (MCD) instruments were designed as bridge inspection survey instruments with a minimum of controls and lightweight portability for use by unskilled personnel with minimum training. Both units are built to facilitate wearing as backpacks with a hand held probe for scanning and monitoring. Rechargeable self-contained battery packs are also included but no provision is made for connection to an external power source. Figure 13 shows these two instruments in use.

The ACD unit is basically an ultrasonic device without the cathode ray tube screen and its associated controls, but with a digital readout on the hand held probe for plate thickness readings or distance to flaw readouts depending on the selected mode switch position. Incorporated in the electronics is a time variable gain control which compensates for the attenuation as the

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path distance increases. Transducer frequency is approximately 2 MHz with a sound exit angle of 70 degrees. Two transducers are located in the probe, one for the laminated or L-mode, the other for the survey or S-mode. When switched to the lamination mode only the lamination mode transducer is operating. When switched to the survey mode both transducers are operating with the survey mode transducer monitored by the digital display and the lamination mode transducer triggering a green light on the probe as proof that sound is being transmitted through the steel and reflecting back from the back surface. The lamination mode can be used for the detection of plate laminations since its sound is directed normal to the surface while the survey mode is the primary mode for crack detection. Two detent control knobs to adjust for the varying surface conditions and steel attenuation when calibrating are incorporated and are contained in a key locked door. Thus the operator does not have access to the controls once the door is closed and locked. The surface condition control is graduated from 1 to 12 and is primarily a gain control which increases the sensitivity approximately 4 db beyond the digital readout threshhold during calibrations. The maximum distance control which is indicative of the maximum range of the survey is graduated from 1 to 12 feet (.30 to 36 meters). This control adjusts the slope of the time variable gain control to account for the attenuation properties of the steel. The calibration reference is from a corner of the bridge steel plate or flange to be inspected and is used to establish the threshhold sensitivity. When the control access door is closed it depresses a button whereby the receiver gain is increased by 10 db's. Thus the ACD, when calibrated, has a detection sensitivity of approximately 14 db's less severe than the corner reflector calibrated on.

The MCD unit detects surface cracks using two pairs of differential sensor coils and an electromagnet mounted on a probe. The sensors are located to detect cracks oriented 90° from each other. When

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a crack is detected by a sensor, it will illuminate an associated light displaying the orientation of the crack.

Each sensor system is a modified system of eddy current and magnetic particle yoke systems. The electromagnetic coil provides the magnetization for leakage flux measurements and also induces electric currents suitable for current perturbation measurements(7). For one pair of differential sensor coils, the magnetic lines of flux passing through a crack will leak into the air and be picked up by the sensors. The other sensors pick up disturbances in the magnetic field associated with the induced current caused by the presence of a crack.

The MCD requires no calibration. The unit is switched on and ready for scanning with its probe.

The batteries on the MCD unit were rated at one hour. However, because of obtainable battery life, the units were for all intents and purposes inoperative after 10 minutes of operation. Therefore, it was not feasible to evaluate this unit.

Caltrans Transportation Laboratory participated in a nine state evaluation of the ACD unit, resulting in the publication of an evaluation report. Listed below are the major findings in the final report of this study(8).

1. The time, manpower, and cost of making "indepth" bridge inspections are becoming critical to the point of restricting all but the most conclusive and reliable methods.

2. The magnitude of inspection area encompassing the numerous steel structures in most States necessitates an expedient and proficient crack detection technique.

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3. The accessibility of the inspection area is made difficult by geometrics, terrain, and heavy traffic volumes.

4. The discovery of very few structural steel cracks reflects the trend of many States towards a low priority of routine instrument inspections. Rather, a fatigue analysis of those bridges receiving the highest volume of truck traffic will bring to focus the structures which require more than visual inspection.

5. Calibrating the ACD to many of the older structures where there is paint build-up, pitting, and surface roughness is very difficult, often delaying inspection time and necessitating recalibration for different members of the same structure.

6. Some geometric configurations and welded details induce false readings requiring considerable interpretation of the ACD probe digital readout. Operators can then lose confidence in the instrument and may hold it unreliable.

7. The ACD instrument is operator sensitive and can cause operator fatigue.

8. If indepth inspections are called for on certain critical structures, more confidence and reliability could be placed in a well-trained, ultrasonic technician using conventional ultrasonic equipment.

9. The disadvantages with conventional ultrasonics have not been corrected with the ACD, that is (a) extensive operator training in structural mechanics, equipment operation, and data interpretation is required and (b) little or no production rate of inspected members or bridges is feasible. One additional disadvantage is the rather involved and time consuming surface preparation and distance calibration of the ACD.

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Although there was some disagreement among the committee members on the final conclusions and recommendations, the committee was able to formalize four major points of considration that best expressed their viewpoints on the ACD/MCD:

1. All nine States in the evaluation program agreed the ACD device could not be used for routine bridge inspections.

2. Six of the nine States felt the ACD in its present form could not be used in any part of the bridge inspection program.

3. The remaining three States said that the ACD was not a production piece of equipment but had some application for spot checking details.

4. Finally, the ACD/.CD Evaluation Committee recommended further development of the Acoustic Crack Detector and/or other non-destructive testing equipment.

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APPENDIX

Figures 1 thru 13

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G = good
F = fair
P = poor
☐ = unsuitable

1 — Fluoroscopy suitable only for thin sections.
2 — If beam is parallel to cracks.
3 — Special thickness gages available.
4 — Size of defect found depends on thickness of section.
5 — Defects must be open to a surface to be located with penetrants.

Our thanks to Krautkramer Ultrasonics, Inc., and Magnaflux Corp. for their help in revising this chart.

NONDESTRUCTIVE EXAMINATION TEST COMPARISON

			GENERAL							SHEET AND PLATE			WELDS					PROCESSING		IN SERVICE				
													WITH BEAD		WITHOUT BEAD									
			MINUTE SURFACE CRACKS	DEEPER SURFACE CRACKS	INTERNAL CRACKS	INTERNAL VOIDS	THICKNESS	METALLURGICAL VARIATIONS	THICKNESS	LAMINATIONS	HOLES	INTERNAL CRACKS LACK OF FUSION AND PENETRATION	SLAG INCLUSION/POROSITY	INTERNAL CRACKS LACK OF FUSION AND PENETRATION	SLAG INCLUSIONS/POROSITY	SURFACE CRACKS	HEAT TREAT CRACKS	GRINDING CRACKS	FATIGUE CRACKS, HEAT CRACKS	STRESS CORROSION	BLISTERING	THINNING	CORROSION PITS
PENETRATING RADIATION[4]	X-RAY			F[2]	F[2]	G	F	F	G[3]		G	G[2]	G	G[2]	G	P	P		P	F	P	F	G
	FLUOROSCOPY[1]				P	F					G	F[2]	F	F[2]	F							P	P
	RADIUM AND RADIOISOTOPE			F[2]	F[2]	G	F	F	G[3]		G	G[2]	G	G[2]	G	P			P	P	P	F	P
ULTRASONIC AND SONIC	CONTACT PULSE REFLECTION	OVER NORM. TO SURF. ½"			G	G	G	F	G	G	G				G				G		G	G	P
		SEND AND RECEIVE			G	G	G	P			G				G				G	G	G	G	G
		ANGLE BEAM	P	G	G	G		P		F	F	G	P	G	F	P	F	P	G				P
		SURFACE WAVE	G	G												P	F	G	F	F			
	IMMERSION PULSE REFLECTION	NORM. TO SURF.			G	G	G	F	G	G	G				F								
		ANGLE BEAM	P	G	G	G				F	F	F	F	G	F	G	F	P	G				
	THROUGH TRANSMISSION				F	G		F		G		F	F								F		
	RESONANCE				P	P	G	P	G	G											G	G	P
	METER THICKNESS GAGE (under 3")						G		G	G											G	G	F
	SONIC and MECHANICAL VIBRATION			P				G															
MAGNETIC PARTICLE	A.C.	WET	G	G						F		F		F		G	G	G	G	G			
		DRY	F	G						F		F		F		G	G	G	G	F			P
	D.C.	WET	G	G	P					G		F		F		G	G	G	G	G			
		DRY	F	G	F	P				G		G	G	G	G	G	G	G	G	F			P
ELECTRO-MAGNETICS	EDDY CURRENT		F	G			F	G	P				P		P	F	G	F				F	
	MAGNETIC PROPERTY ANALYSIS		P	F	P	P	F	G	F				P		P	P	G	F	F				
	LEAKAGE FIELD PICKUP		F	G	F					P			F		F	G	G	F	G				
	D.C. CONDUCTION		F	F	P	P	F	P	F	P	P					F	F	F	F	F		F	
PENETRANTS[5]	VISIBLE DYE PENETRANT		F	G						F	P					G	G	G	G	G			F
	FLUORESCENT DYE PENETRANT		G	G						F	P					G	G	G	G	G			F

Figure 1. N.D.I. COMPARISON CHART

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No. 426 Commonly used nondestructive testing specifications and standards

NDT Method	Issued By	Number	Title	Where to Obtain
All	BuShips	MIL-STD-271D	Military Standard Nondestructive Testing Requirements for Metals	Supt. of Documents Washington, D.C. 20402
All	U. S. Govt.	MIL-I-6870A	Military Spec. Inspection Requirements Nondestructive: For Aircraft Material and Parts	Any government military agency
Penetrants	U. S. Govt.	MIL-I-19684	Inspection Penetrants	Any government military agency
Penetrants	S.A.E.	AMS 2645	Fluorescent Penetrant Inspection	S.A.E. 485 Lexington Avenue New York, N.Y. 10017
Penetrants	ASTM	E 165-65 (1971)	Liquid Penetrant Inspection	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Magnetic Particle	U. S. Govt.	MIL-I-6868A	Inspection Process Magnetic Particle	Any government military agency
Magnetic Particle	ASTM	E 109-96 (1971)	Dry Powder Magnetic Particle Inspection	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Magnetic Particle	ASTM	E 138-63 (1971)	Wet Magnetic Particle Inspection	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Radiographic	U. S. Govt.	NavShips 250 -1500	Standards for Welding of Reactor Coolant and Associated Systems and Components	Any government military agency
Radiographic	ASTM	E 94-68	Recommended Practice for Radiographic Testing	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Radiographic	AWS	D 3.4-52	Rules for Welding Piping in Marine Construction	AWS, 2501 N.W. 7th Street Miami, Florida 33125
Radiographic	ASTM	E-142-72	Controlling Quality of Radiographic Testing	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Ultrasonic	ASTM	E 164-65	Ultrasonic Contact Inspection of Weldments	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Ultrasonic	ASTM	E 127-64	Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Ultrasonic	ASTM	A 609-70	Longitudinal Beam Ultrasonic Inspection of Carbon and Low Alloy Steel Castings	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Ultrasonic	ASTM	A 577-70a	Ultrasonic Angle-Beam Examination of Steel Plates	ASTM, 1916 Race Street Philadelphia, Pa. 19103
Visual	MSS	SP-55	Quality Standard for Steel Casting (Visual Method)	Manufacturers Standardization Society of the Valve and Fittings Industry 1815 N. Fort Meyer Drive Arlington, Virginia 22209

Figure 2. LIST OF COMMONLY USED N.D.T. TESTING SPECIFICATIONS AND STANDARDS

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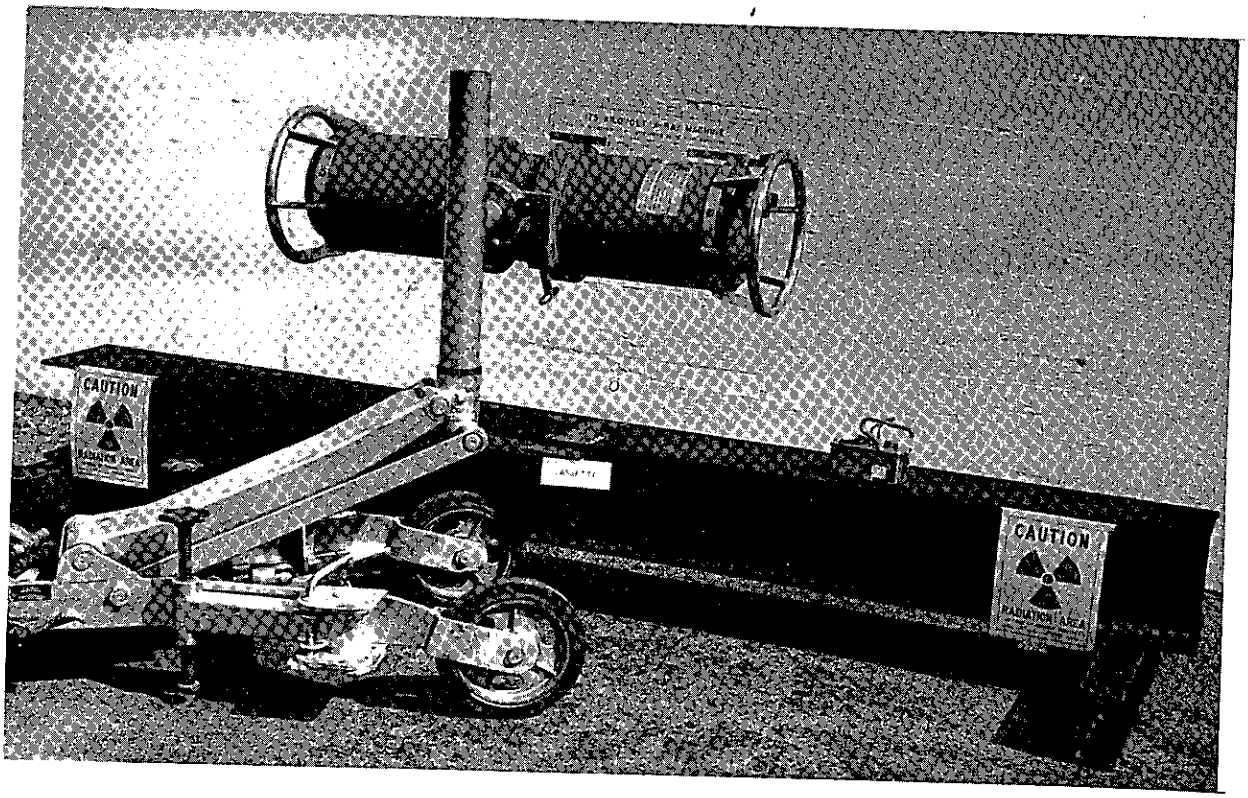

Figure 3. 175 KVP X-RAY MACHINE AND FILM SET-UP

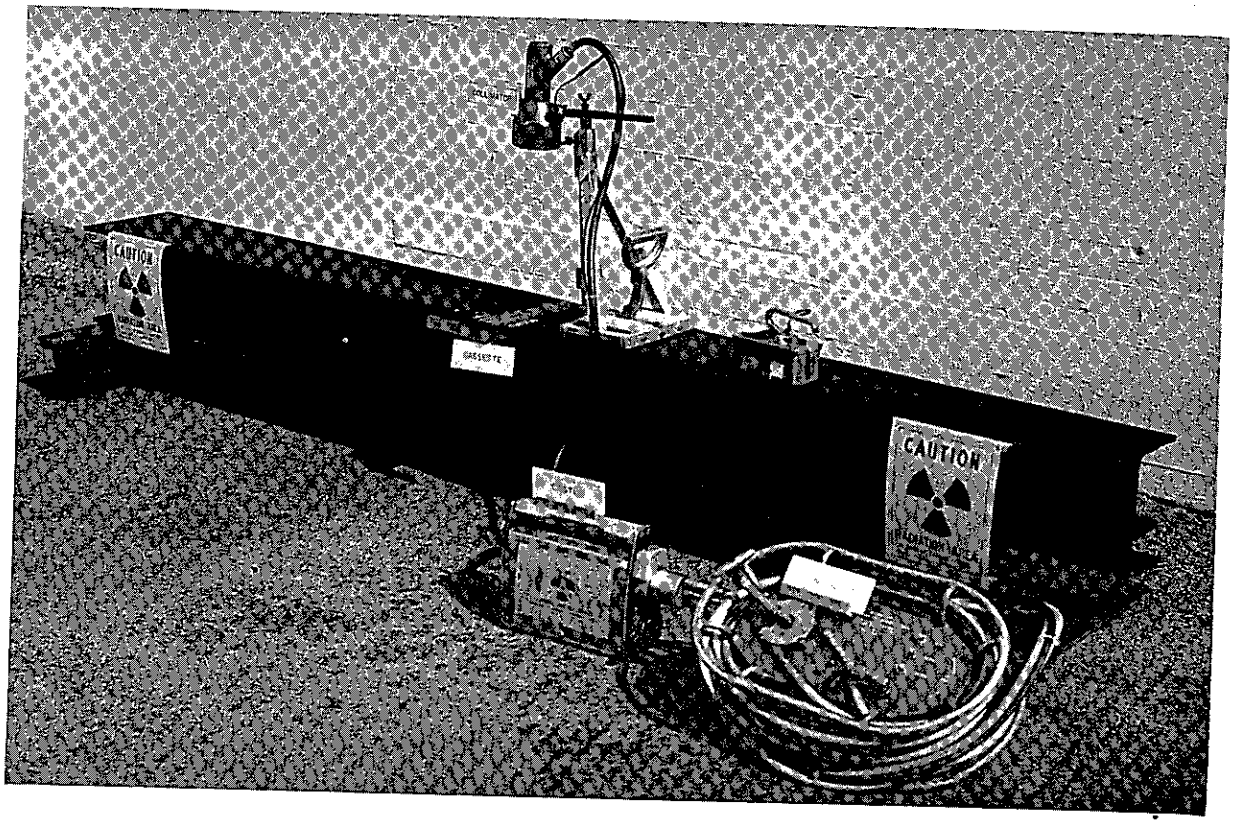

Figure 4. IRIDIUM 192 GAMMA RAY PROJECTOR AND CONTOLS

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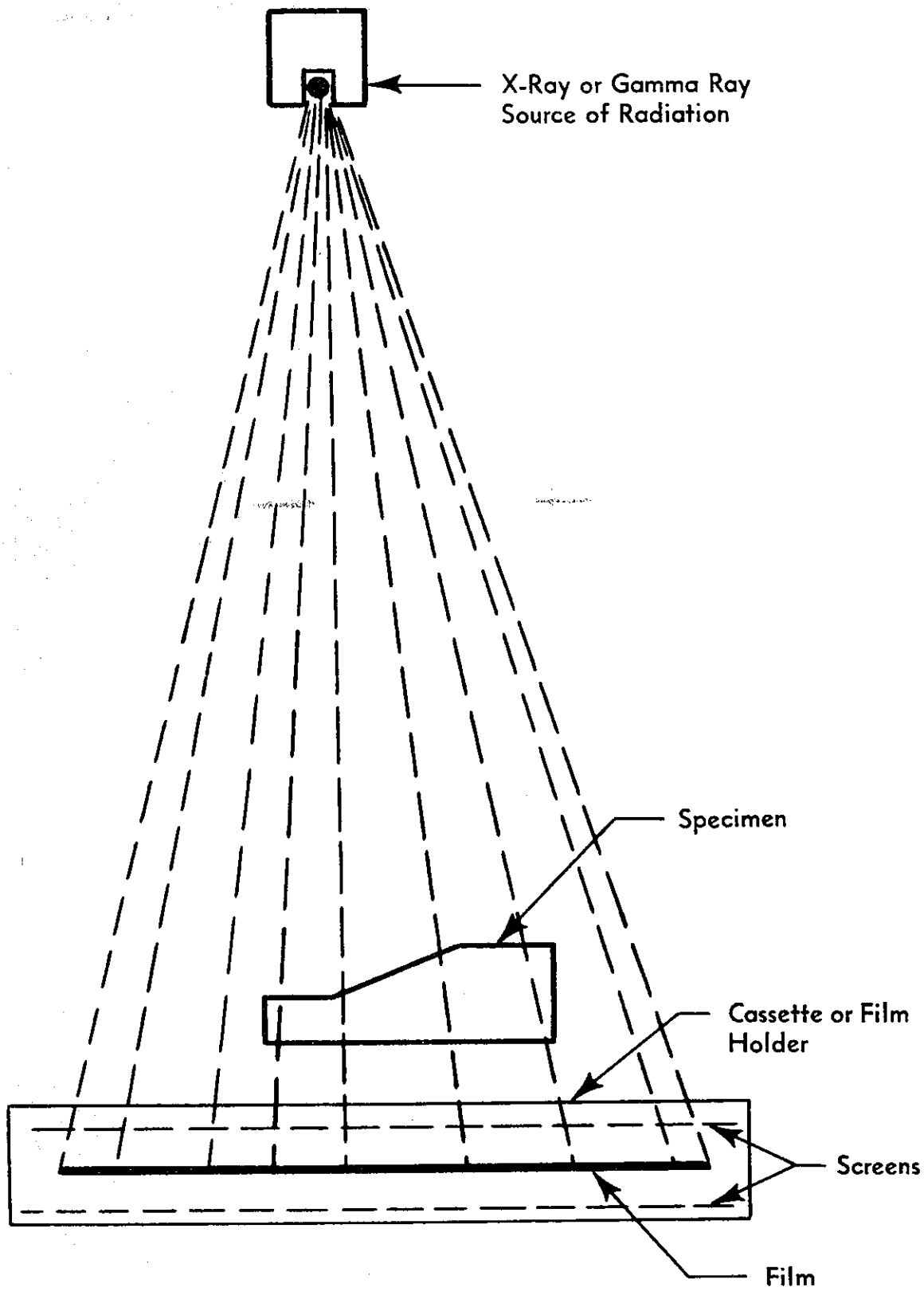

Figure 5. RADIOGRAPHIC EXPOSURE ARRANGEMENT

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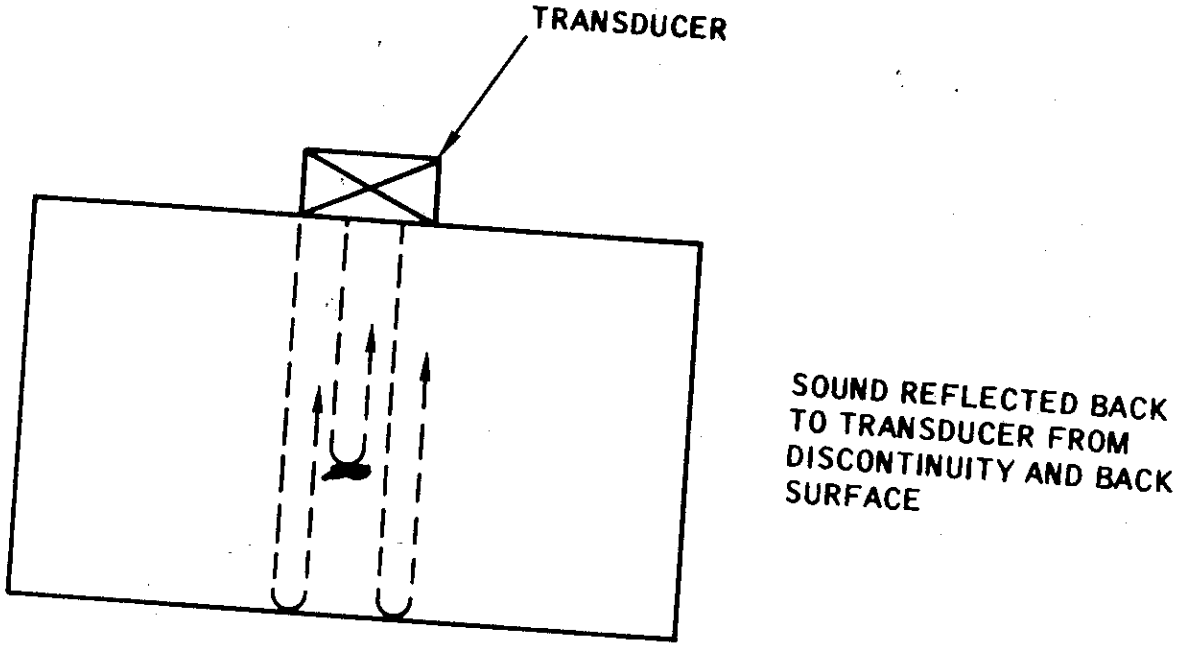

Figure 6. STRAIGHT BEAM SCANNING TECHNIQUE

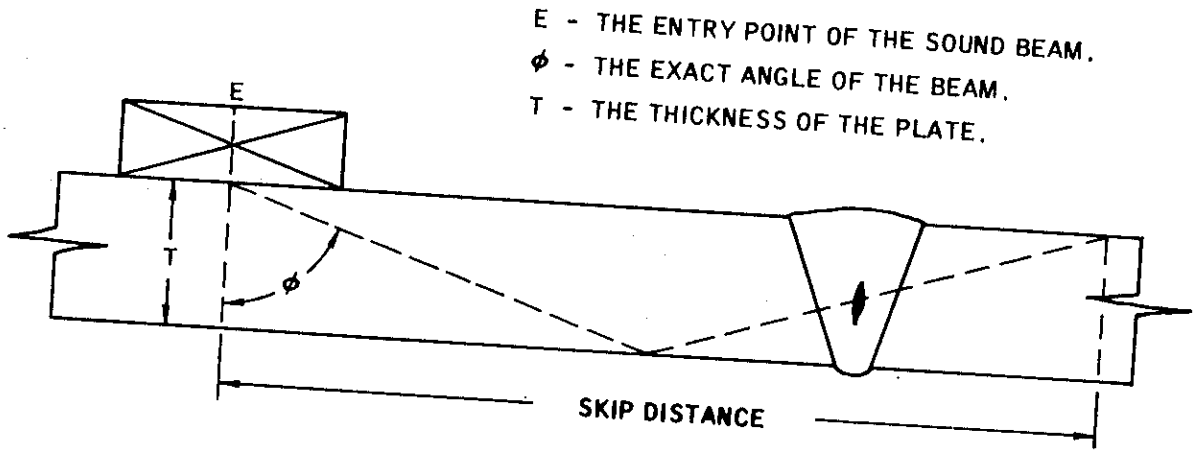

Figure 7 ANGLE BEAM SCAN OF UNGROUND BUTT WELD

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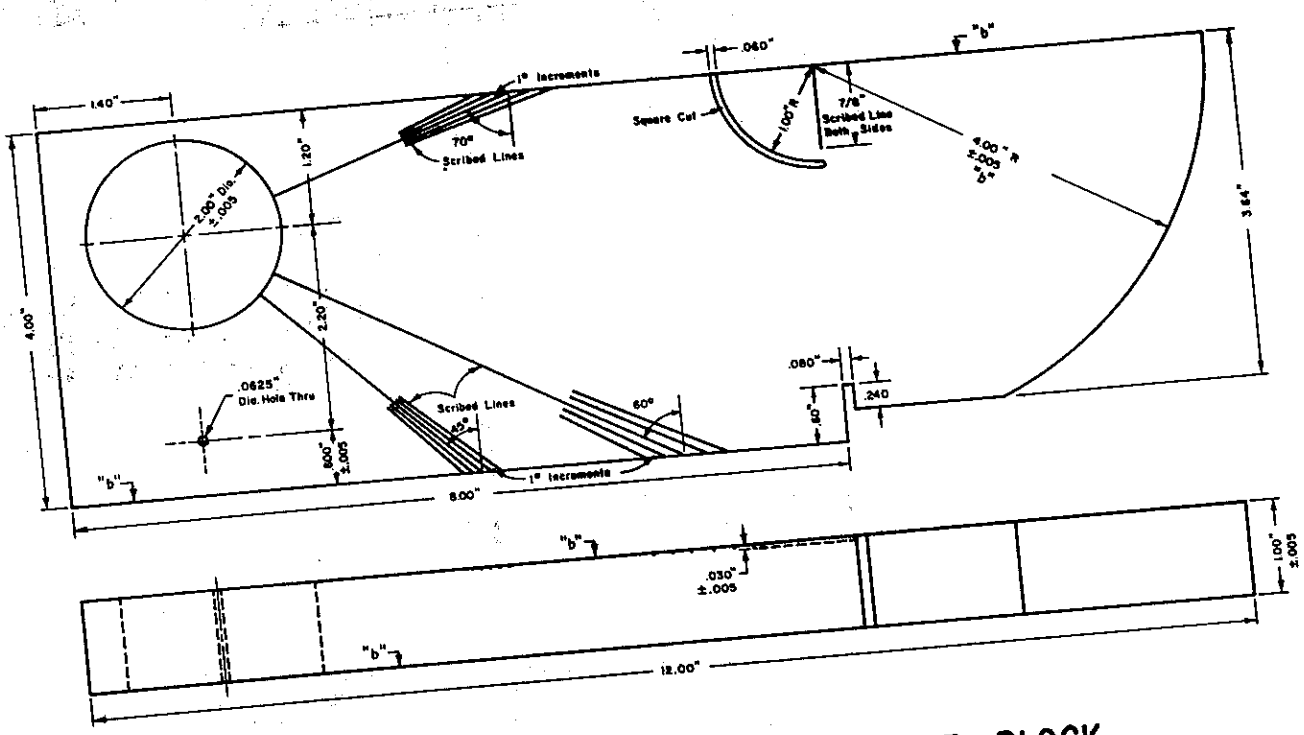

Figure 8. I.I.W. ULTRASONIC REFERENCE BLOCK

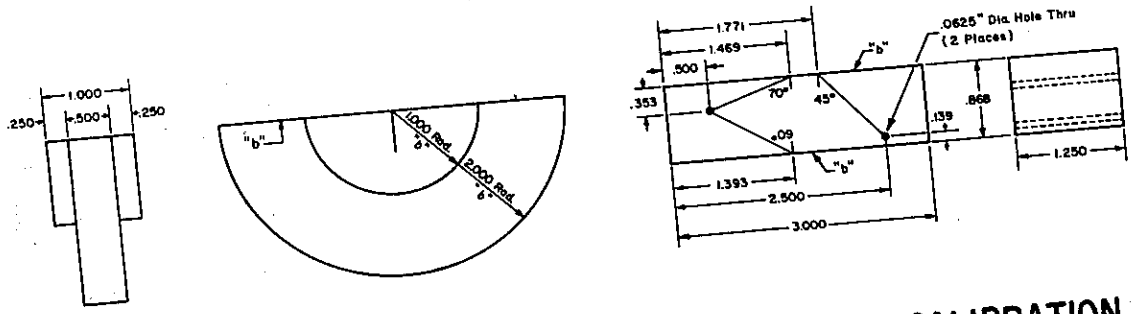

Figure 9. DISTANCE CALIBRATION AND SENSITIVITY CALIBRATION BLOCK

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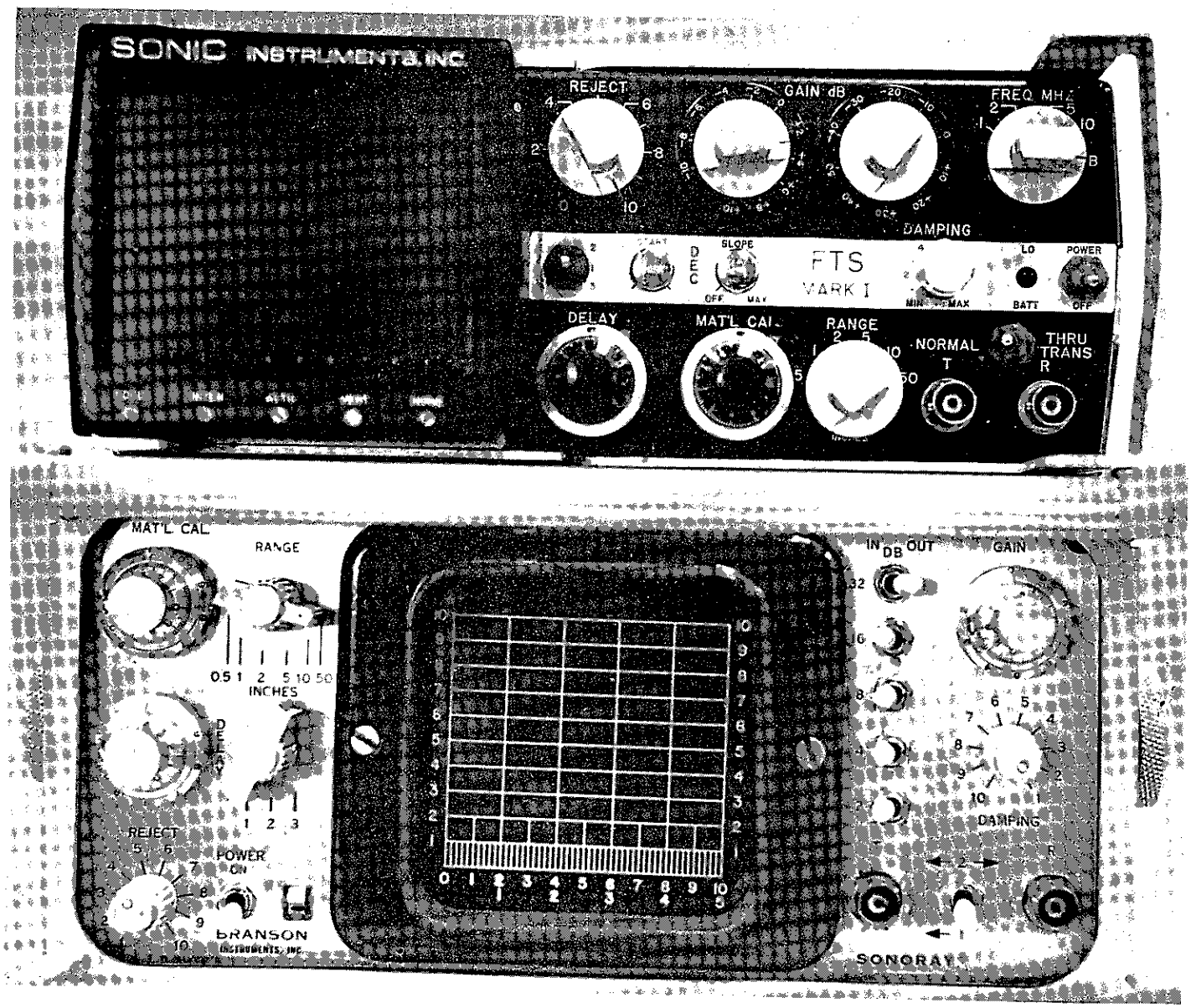

Figure 10. EXAMPLES OF THE DIFFERENT TYPE ULTRASONIC INSTRUMENTS. TOP INSTRUMENT FEATURES CALIBRATED GAIN CONTROL. LOWER INSTRUMENT FEATURES CALIBRATED ATTENUATION CONTROL

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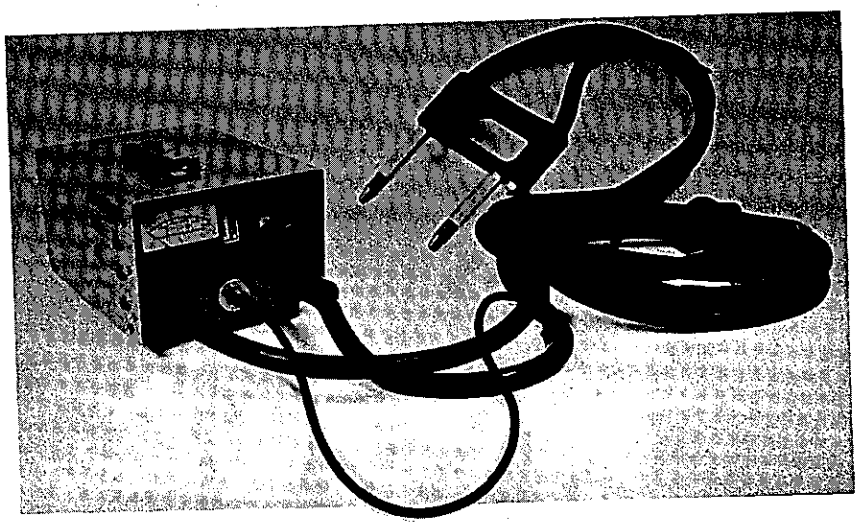
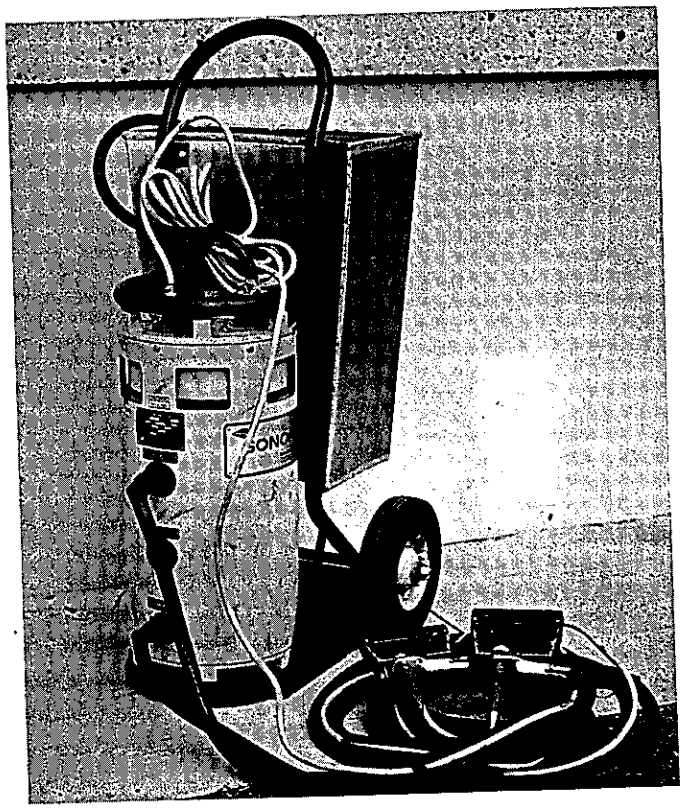


MAGNETIC PARTICLE PORTABLE



MAGNETIC PARTICLE LAB. EQUIPMENT

Figure 11. MAGNETIC PARTICLE EQUIPMENT USED FOR SURFACE AND SUBSURFACE DETECTION

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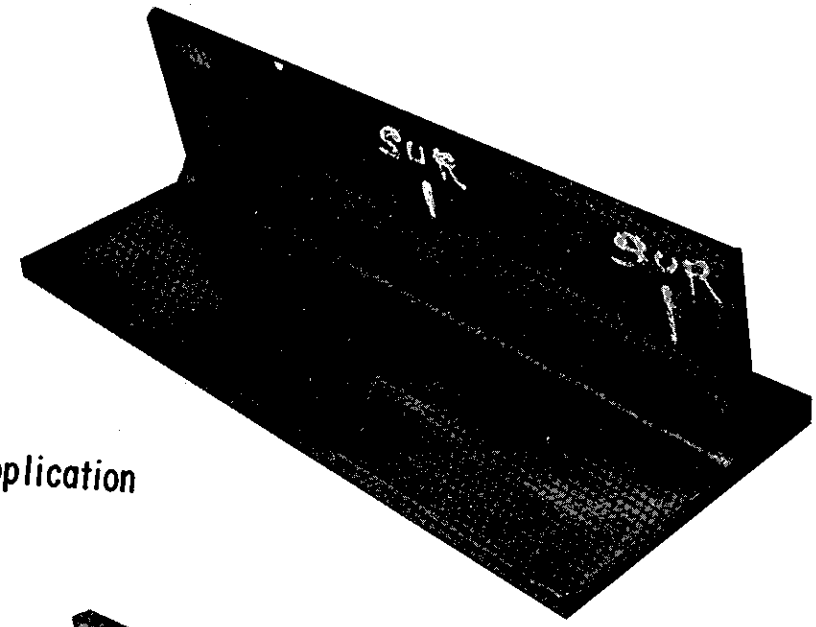
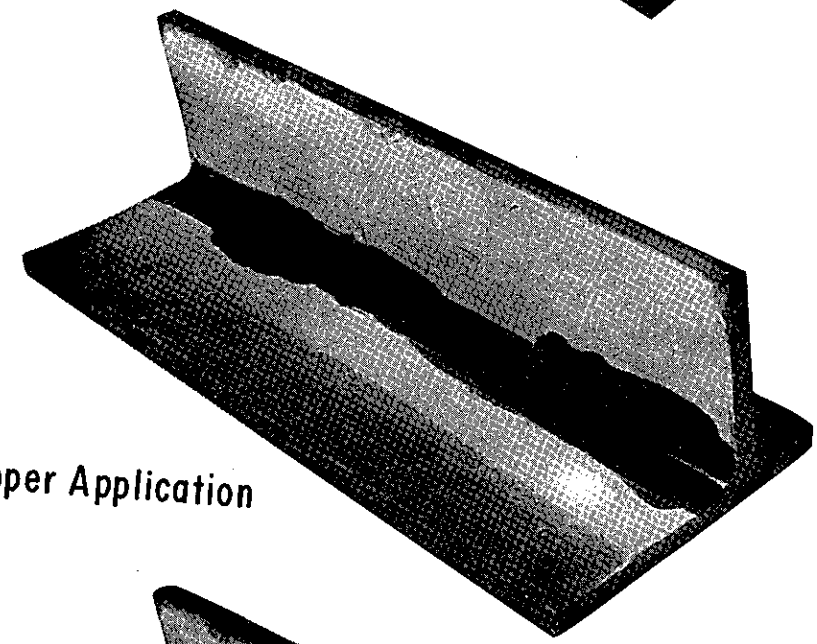
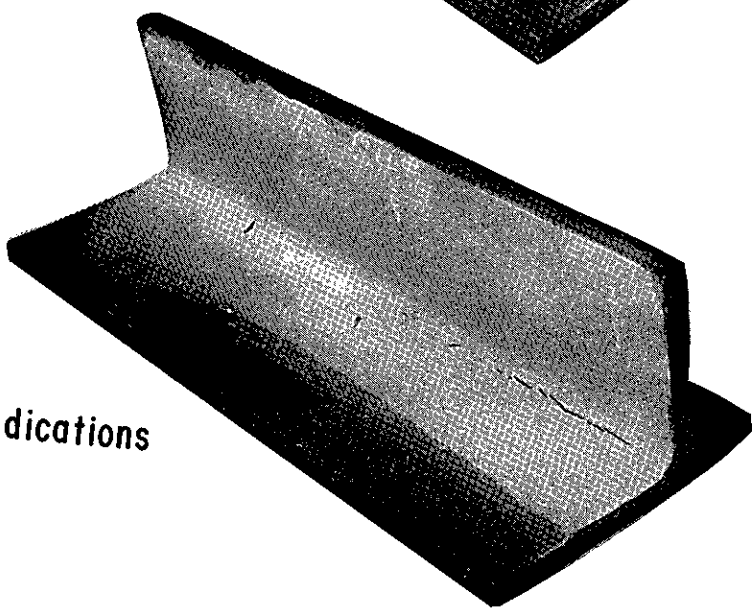


a. Dye Application



b. Developer Application



c. Flaw Indications

Figure 12. DYE PENETRANT EXAMINATION

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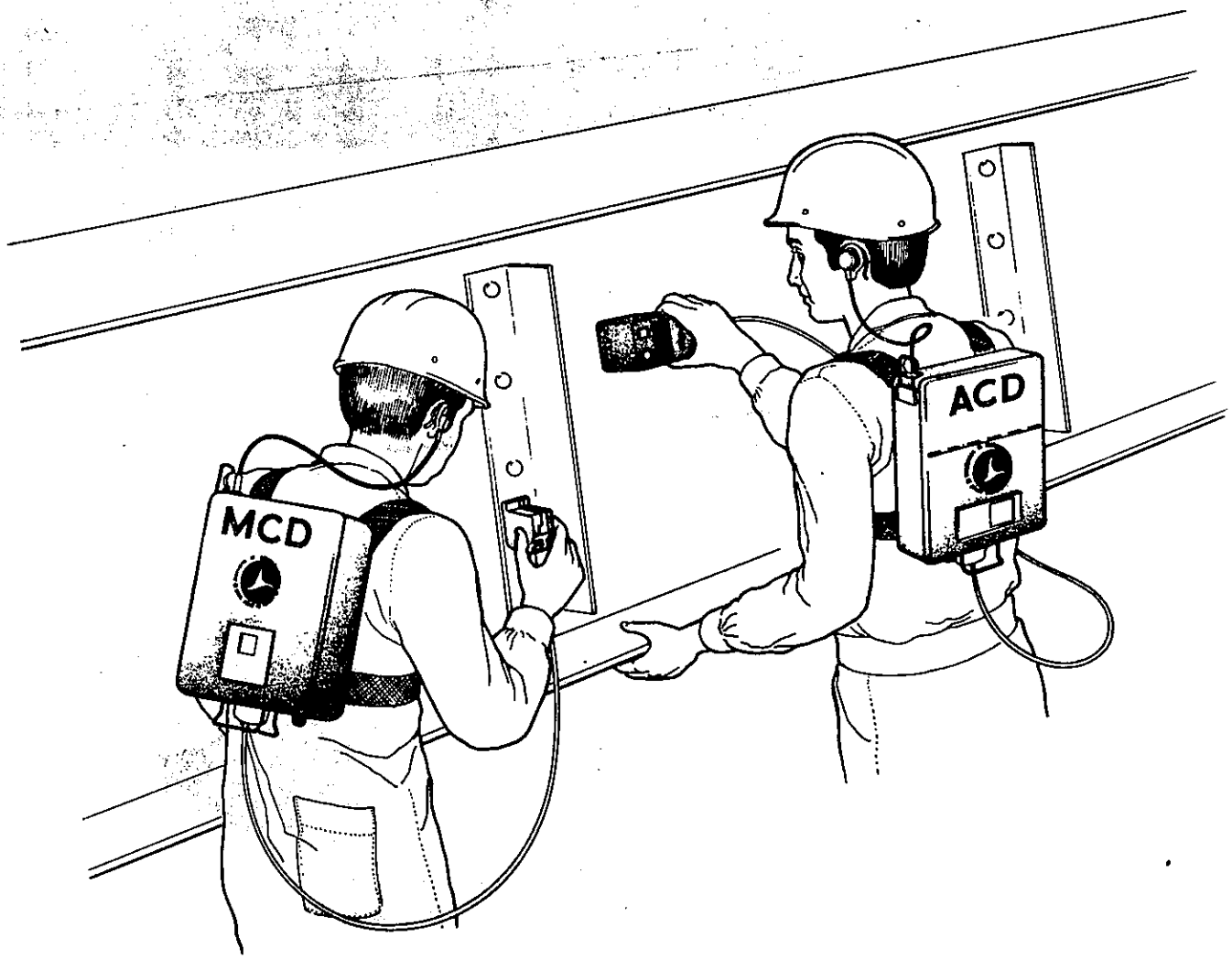

Figure 13. A.C.D. AND M.C.D. INSPECTION

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