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QUALITY CONTROL FOR ORDNANCE

[1957]

WATERTOWN ARSENAL
WATERTOWN, MASS.

QUALITY CONTROL FOR ORDNANCE

"Quality Control" has been recognized for some years as an economical and required tool of Ordnance Corps procurement. In its broadest and most complete sense this term may be defined as the planned application of tests or measurements to items of manufacture and the meaningful analysis of the resulting data in terms of their quality. In addition, there is a definite connotation in the term regarding improvement of quality of future items to be manufactured as a result of improved design or manufacturing procedures based upon previous test findings. In other words, Quality Control is directed at obtaining assurance that Ordnance items are procured having adequate quality to perform satisfactorily, this assurance being obtained at the least cost.

It is regarded that a Quality Control program involves the following basic elements of consideration:

1. An engineering determination of the necessary quality characteristics required for satisfactory performance of an Ordnance end item or component. Service performance requirements form the basis of this determination.

2. The selection and specification of test or inspection methods and procedures which are capable of determining that the necessary quality characteristics exist in kind and degree as required.

3. The formulation of a Quality Control plan which considers:

a. The stage during the manufacturing cycle at which the inspection should be performed in order to permit improvements in manufacturing processes by disclosure of sources of trouble.

b. The sample size

c. The permissible deviations for control of product quality.

d. Etc.

In more brief terminology, Item 1 above may be called product engineering or classification of defects; item 2 may be called inspection or test engineering; and item 3 may be called statistical planning and analysis. It is believed that all three considerations are mandatory for the procurement of satisfactory Ordnance items.

In order that an understanding of the viewpoints expressed below can be facilitated, it should be stated that the assigned mission of the Ordnance Corps group presenting these viewpoints is research and development in the field of Nondestructive Testing. A fairly complete picture of this field of activity has been presented by Dr. R. C. McMaster in his Edger Marburg Lecture of 1952, presented before the American Society for Testing Materials. A copy of this honor lecture is appended hereto for reference (Appendix A).

It is the purpose of what follows to consider item 2 above as it relates to the overall problem of Quality Control by nondestructive test methods.

The advantages of nondestructive over destructive testing techniques for Quality Control purposes have been recognized for a number of years. Predominantly, nondestructive tests have enjoyed their widest application, both in the Ordnance Corps procurement program and in industry, to the evaluation of flaws such as cracks, cavities, etc. in metals. However, it is felt that these same advantages should be made available to a greater extent than at present for the determination of other quality characteristics and in other materials. Until recently, the development of new nondestructive testing principles, a philosophy for their development and application, and the engineering associated with the design of testing equipment for the entire Ordnance Corps, has been the responsibility of a small group of about five (5) workers at Watertown Arsenal. More recently, the group at Watertown has united informally with a group of electronic engineers and scientists of the Pitman-Dunn Laboratories at Frankford Arsenal in an effort to coordinate and increase the rate of effort in this field.

In order to illustrate the tremendous improvements which can be realized from a coordinated developmental program of this type, Appendix B is attached hereto. Listed therein are past accomplishments of these two organizations in the field of nondestructive testing and a list of current work projects with an indication of expected Ordnance Corps benefit—all presented as brief abstracts.

In the past, the development of nondestructive testing methods has been financed to a large degree by the Industrial Division of the Office, Chief of Ordnance, particularly when specific end item testing problems were involved, and because funds available under Project TB4-21 have been inadequate. It has long been recognized, however, by those intimately associated with work in this field that, if new and more severe service requirements continue to become evident because of new weapons and materials development and because inspection testing must be conducted without becoming a bottleneck to production, the development of new nondestructive testing principles and techniques must be continually sponsored. Such developments, primarily falling in the technical field of applied physics, have been inadequately funded in the past under O.O. Project TB4-21, which is believed to be the only project applicable to the generalized type of developmental work involved. Some idea of the inadequacy of funding can be obtained when it is pointed out that, as a typical year, FY '53 provided only $70,000 for all developmental work in the Ordnance Corps dealing with all types of tests (chemical, mechanical, nondestructive, metallographic, etc.) with regard to metals. During the same year, approximately $4,000,000 was allocated to the development and evaluation of new and improved materials of various types for Ordnance. It can be safely stated that, with each new material improvement, a variety of testing and inspection problems is usually created. With the budget allocated to the development of all testing techniques representing only about 1 1/2% of that allocated to the development of improved materials, the problems are rapidly outstripping our ability to provide solutions.

Since much of the work contemplated for the development of nondestructive testing techniques is of a general nature, i.e., development of ultrasonic testing techniques, magnetic testing techniques and radiographic testing techniques, it is extremely difficult to obtain funds for such work from OCO groups having specific end-item interest. The contemplated program has been developed as a result of the critical analysis of the basic inadequacies of existing nondestructive techniques, rather than the need to solve a specific inspection or test problem. This type of critical study, followed by fundamental test methods development, has resulted in the past in the solution of a large number of specific problems. Such success is attributed to a complete understanding of the physical principles of the test methods, which understanding permits the recognition of basic similarities between test problems and a more rapid solution thereof.

The above approach has been devoted in past years to studies of radiographic and magnetic testing notably. The result has been that these methods were employed on a broad scale during World War II for the inspection of many types of Ordnance, i.e., cast armor, ammunition, welded gun mounts, welded tanks, and many others. Recent generalized developments in magnetic testing are being culminated in the successful construction of apparatus for more rapid and reliable examination of artillery tubes, projectiles of both large and small caliber, artillery and small arms cartridge cases, etc. The more recent work has been directed at high-speed, fully automatic testing for flaws and control of metals heat treatment where bottlenecks in production due to previous slow and relatively unreliable methods are being eliminated.

For FY '55 it is being requested that $150,000 be allocated to Watertown Arsenal Laboratory and $15,000 to the Pitman-Dunn Laboratories at Frankford Arsenal for the development of nondestructive testing methods (O.O. Projects TB4-21A, B, and C). These figures have been included as a part of the gross amount requested for all work under TB4-21, Metals Testing Methods, for Watertown and Frankford Arsenals. It should be understood that these amounts are to cover work in the generalized field of physics of nondestructive tests, the effort to apply these techniques to specific Ordnance problems being financed from other R & D or Industrial Division funds.

Although the amounts referred to above do not reflect the rate of effort which should be spent in a logical ratio of materials development effort to test methods development effort, they are regarded as appropriate to the manpower now devoted to work in this field. It is believed that general advances in preparedness, of which this effort is a part, can best be accomplished at this time, when the pressures of an emergency or war are not dictating the direction of effort. Further increase in the expenditures for nondestructive test methods development should be contemplated for the future.

APPENDIX A

Nondestructive Testing

By

ROBERT C. McMASTER

EDGAR MARBURG LECTURE

1952

PRESENTED BEFORE THE FIFTY-FIFTH ANNUAL MEETING
(FIFTIETH ANNIVERSARY MEETING)
OF THE AMERICAN SOCIETY FOR TESTING MATERIALS

Nondestructive Testing

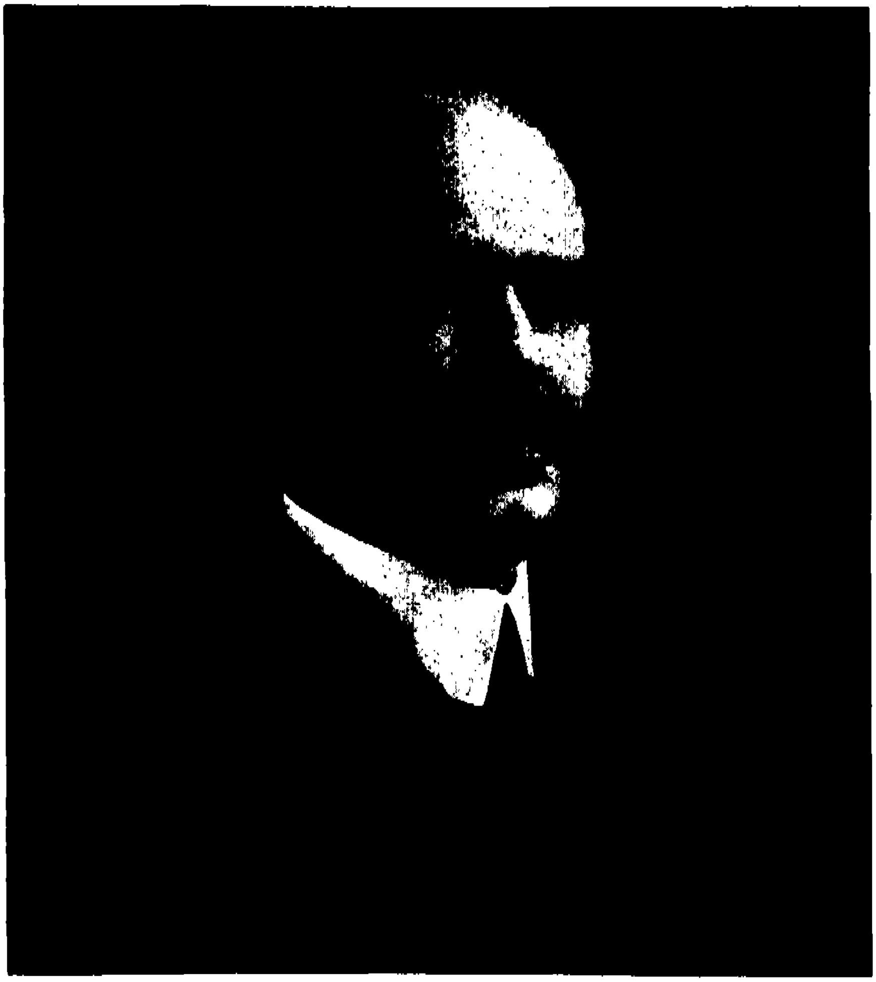
By
ROBERT C. MCMASTER

Reg. U.S. Pat. Off.

EDGAR MARBURG LECTURE

1952

PRESENTED BEFORE THE *FIFTY-FIFTH* ANNUAL MEETING
(FIFTIETH ANNIVERSARY MEETING)
OF THE AMERICAN SOCIETY FOR TESTING MATERIALS



Edgar Marburg.

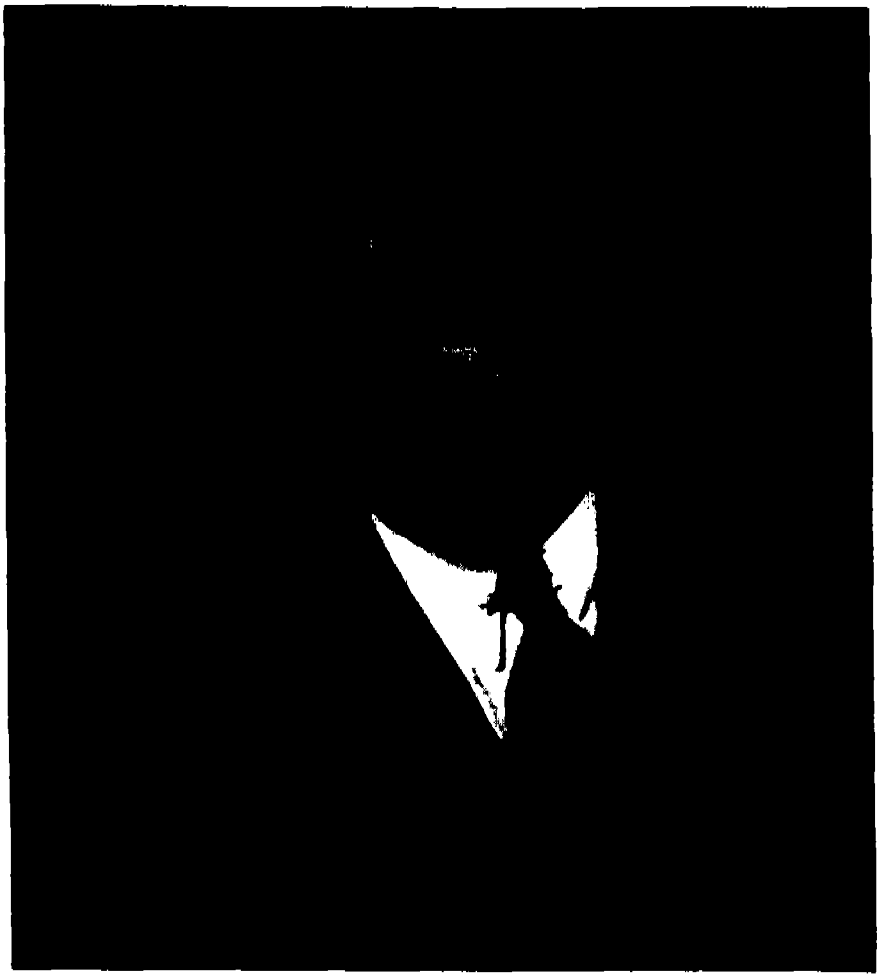
1864–1918

> *"By zeal, industry, loyalty, insight, and high ability exerted through sixteen years as Secretary-Treasurer of the Society; by guiding its actions, energizing its activities, and guarding its name, he has exercised a powerful influence on the character, standing and usefulness of the Society, and on the making of specifications and tests for the materials of engineering."*
>
> Excerpt from Resolution Adopted by the A.S.T.M. at the Twenty-first Annual Meeting, 1918.

FIRST Secretary-Treasurer of the American Society for Testing Materials, 1902 until his death. In addition to serving as an officer of the Society, Doctor Marburg was also head of the Department of Civil Engineering of the University of Pennsylvania from 1892 until his death.

EDGAR MARBURG LECTURE

THE PURPOSE of the Edgar Marburg Lecture is to have described at the Annual Meetings of the American Society for Testing Materials, by leaders in their respective fields, outstanding developments in the promotion of knowledge of engineering materials. Established as a means of emphasizing the importance of promoting knowledge of materials, the Lecture honors and perpetuates the memory of Edgar Marburg, first Secretary of the Society.



Robert C. McMaster

Dr. Robert C. McMaster is Supervisor of the Electrical Engineering Division at Battelle Memorial Institute, Columbus, Ohio. Dr. McMaster obtained his Ph.D. degree from the California Institute of Technology and has participated in the development of X-ray and other nondestructive test methods during the past ten years. He has contributed to the development of methods for radiography of spotwelds in light-alloy aircraft sheet materials and fluoroscopic methods of examination of aircraft castings and forgings which have been adopted by major manufacturers for inspection of aircraft components. Other nondestructive test developments have been concerned with the application of ultrasonics, fluorescent magnetic particles, and electromagnetic induction methods to industrial inspection problems.

Prior to joining Battelle's staff, Dr. McMaster served with the General Electric Co. and the Naval Ordnance Laboratory, and, for four years, supervised the million-volt laboratory and lightning research at the California Institute of Technology. He has also taught electrical engineering at Case Institute of Technology and in the Graduate School of the California Institute of Technology.

At Battelle, Dr. McMaster has participated in studies of the fatigue of aircraft structures; of corrosion fatigue failures of oil well drill pipe; of high-speed, high-temperature testing of metallic materials; and of other problems in industrial physics. More recently he has supervised studies in electric power communication, computers, servo-mechanisms, electronics, ultrasonics, electro-biology, and related fields of electrical engineering.

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Philadelphia, Pa.
Volume 52, 1952

NONDESTRUCTIVE TESTING[1]

Twenty-Sixth Edgar Marburg Lecture

By Robert C. McMaster[2]

Nondestructive testing is a normal human sensory technique. Its extension through scientific methods has increased its scope, sensitivity, and reliability until it has become a vital operation in modern industrial production and quality control. Misuse or omission of appropriate nondestructive tests on critical structures or equipment is sometimes disastrous. Proper application of nondestructive tests lowers production costs, increases industrial productivity, and insures reliability and safety in service.

Basically, the art of nondestructive testing includes *all possible methods* of detection or measurement of the properties or performance capabilities of materials, parts, assemblies, structures, and machines, *which do not damage or destroy their serviceability*. By definition, nondestructive tests differ from all tests and measurements which can be achieved only through damage to, or destruction of, the serviceability of the test objects. The latter are known as *destructive* tests.

Any valid law of nature may serve as a basis for a useful nondestructive test—if it provides reliable measurements that can be correlated with material properties or discontinuities and with serviceability. Modern nondestructive tests are of three general types:

1. Those involving transmission of energy,
2. Those involving transport of matter, and
3. Those involving combinations of matter transport and energy transfer,

in their probing media. *Transport of matter*, as used in mechanical gaging, fluid penetrant and leak tests; filtered particle tests, and others, is generally useful only for nondestructive testing of *exposed surfaces*, or of surfaces connected to exposed surfaces by open channels, of test objects. *Transmission of energy*, as used in X-ray, magnetic and electric field tests, and others, may reveal structure and discontinuities *within materials*, or on surfaces of *enclosed cavities*. *Combined transfer of energy and matter* provides powerful additional nondestructive test methods, such as the ultrasonic, electromagnetic induction, and nucleonic types, capable of probing very thick or very thin layers of materials, or of producing informative secondary reactions which reveal material properties. Usually more than one of these types of nondestructive tests must be employed for complete inspection of test objects in industry.

Nondestructive testing is fact finding, even when the facts are hidden from ordinary observations. It is an extension of human observations. It may or may not require a human operator to evaluate the observations. In most cases it is possible, by means of adequate research and development, to develop machines which replace some or all of the functions of a human inspector. Where standards of

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[1] Presented at the Fifty-fifth Annual Meeting of the Society, June 25, 1952, New York, N. Y.

[2] Supervisor, Electrical Engineering Division, Battelle Memorial Inst., Columbus, Ohio.

serviceability are well established and where extensive past experience exists, it sometimes becomes feasible to develop fully automatic nondestructive-testing devices. These may not only measure the significant properties of the test object but also judge and decide upon its acceptability or rejection. Such developments of automatic machines are usually justified only when:

1. A large number of inspections must be made;
2. The value of each test object is great;
3. The test object itself is cheap but is critical to human life or safety or to the performance and serviceability of a costly assembly, such as a large airplane; or
4. The object when tested is cheap, but if accepted, will be given costly further fabrication or treatments so that it is ultimately very costly. In this case, the prior nondestructive test saves the costs which would otherwise be wasted in the expensive finishing of the piece.

All too often, those who are unfamiliar with the basic nature of nondestructive tests expect them to work miracles. If X-rays or ultrasonic waves permit one to "see" through opaque solid objects, can they not be expected to provide other magic solutions to our production problems? Not at all! Nondestructive tests usually reveal only the specific kinds of defects and conditions they were designed to reveal. What to do about the situations so revealed is a problem for production and engineering management to solve. The nondestructive test can never be expected to make up for the lack of specific knowledge of the nature of materials, of the causes of service failures, or of the sources of production difficulties. However, nondestructive tests can provide additional factual data concerning such defects and conditions, on the basis of which engineering management can make a more intelligent analysis. And nondestructive tests can monitor the effects of corrective changes in production conditions or operations, to show whether or not the difficulties are being eliminated.

Misconceptions usually lead to misapplications of nondestructive tests and to failures which are not rightly the fault of the test method. A typical misconception is the assumption that if a part has been given a specific nondestructive test—let us say, by X-rays—and been passed, then the part, and the method by which it was produced, are acceptable, possibly even perfect. This is usually untrue. Nondestructive tests are *specific* to certain types of materials, conditions, and defects.

X-rays are capable of revealing a multitude of different material conditions, but there are other common undesirable conditions they frequently do not reveal. Typical of these might be laminations perpendicular to the direction of the X-ray beam, or fine, tightly closed cracks near the surface. The laminations might be clearly revealed by an ultrasonic test. The tight cracks might best be detected by magnetic-particle or penetrant inspection, as appropriate to the material in question. What a nondestructive test is capable of revealing, it usually does show reliably. But it says nothing about other possible conditions, outside the scope of its detection.

THE USES OF NONDESTRUCTIVE TESTS

There are many specific jobs which nondestructive tests can do well. However, no single nondestructive test can necessarily do them all, even for a single material. And a single job may need different nondestructive tests when the material is changed. The nondestructive tests are, in general, specific. The test must be selected in accordance with the material, the conditions to be detected, and the job to be done. Furthermore, the purpose of the nondestructive test may change in accordance with the step in the production process at which it is applied.

The ultimate purpose of all nondestructive tests is to evaluate the quality, strength, discontinuities, or serviceability properties of materials, parts, structures, and assemblies, without damage to the test objects. The specific purpose may vary greatly, within this over-all objective. Typical uses made of nondestructive tests in industry include:

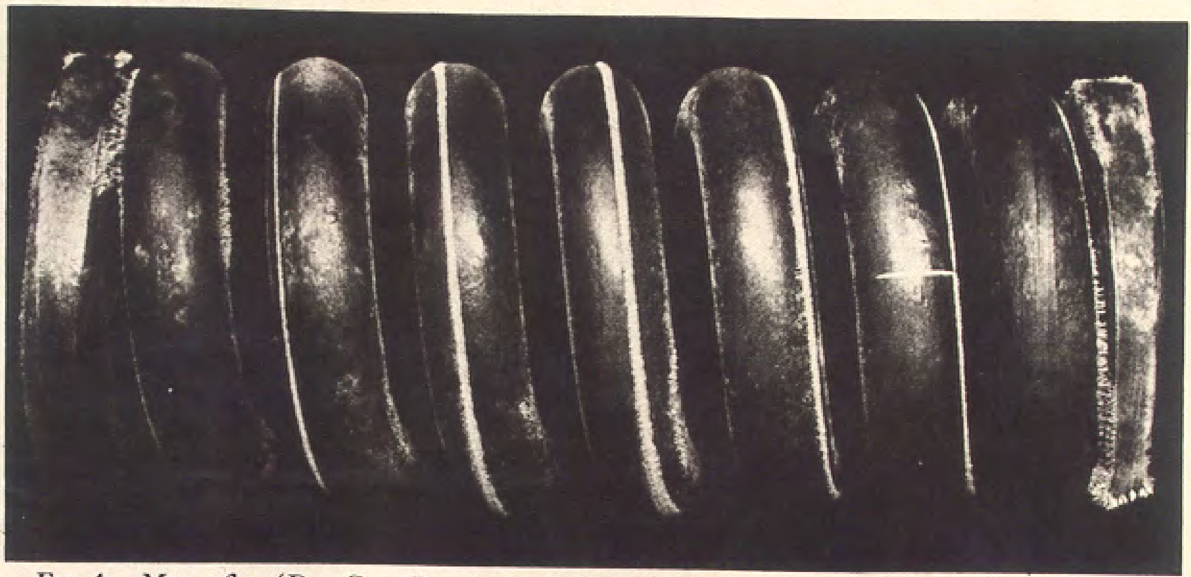


Fig. 1.—Magnaflux (Dry Grey Powder) Magnetic-Particle Indication of a Seam in a Locomotive Spring. This defect was present in the bar stock prior to its fabrication into the spring. (Courtesy Magnaflux Corp., Chicago, Ill.)

Fig. 2.—Fisher Steelsorter Used in Stock Room to Sort and Classify Mixed Steel Bars by Electromagnetic Induction Testing. (Courtesy Fisher Scientific Co., Pittsburgh, Pa.)

1. *Identification, sorting, and selection of raw materials* to determine:

(*a*) That the material meets specifications, and is actually the material it is supposed to be.

(*b*) That it is free from undesirable inhomogeneities or defects (Fig. 1).

(*c*) That it does not consist of accidentally mixed lots (Fig. 2).

(*d*) That (in case the material has previously been subject only to percentage quality control methods) every unit in the lot meets the specifications established for the lot.

2. *Checking the chemical composition*, to establish:

(*a*) That chemical composition variations within the lot are within acceptable limits.

(*b*) That processing steps have not produced damaging local variations in composition in single units (such as decarburization, "burnt steel," segregation of eutectic in alloys, excessive carbon content, etc.). Such checking is often particularly critical in the case of exposed surface layers, which may later be subjected to case-hardening or shot peening, or to corrosion or fatigue loading in service. On the other hand, damage to such surface layers may be inconsequential if they are to be removed in later processing steps. In this case, nondestructive tests sensitive only to the surface layers would be quite useless at this stage in processing.

(*c*) That all essential processing steps which influence composition have been included for all units.

(*d*) That plating, cladding, and other dissimilar surface layers are of the proper composition, thickness, and adherence.

3. *Detecting variations in metallurgical structure*, such as might accompany:

(*a*) Heat treating or annealing in oxidizing, reducing, carburizing, or nitriding atmospheres.

(*b*) Heating, cooling, and aging so as to cause transitions in structure.

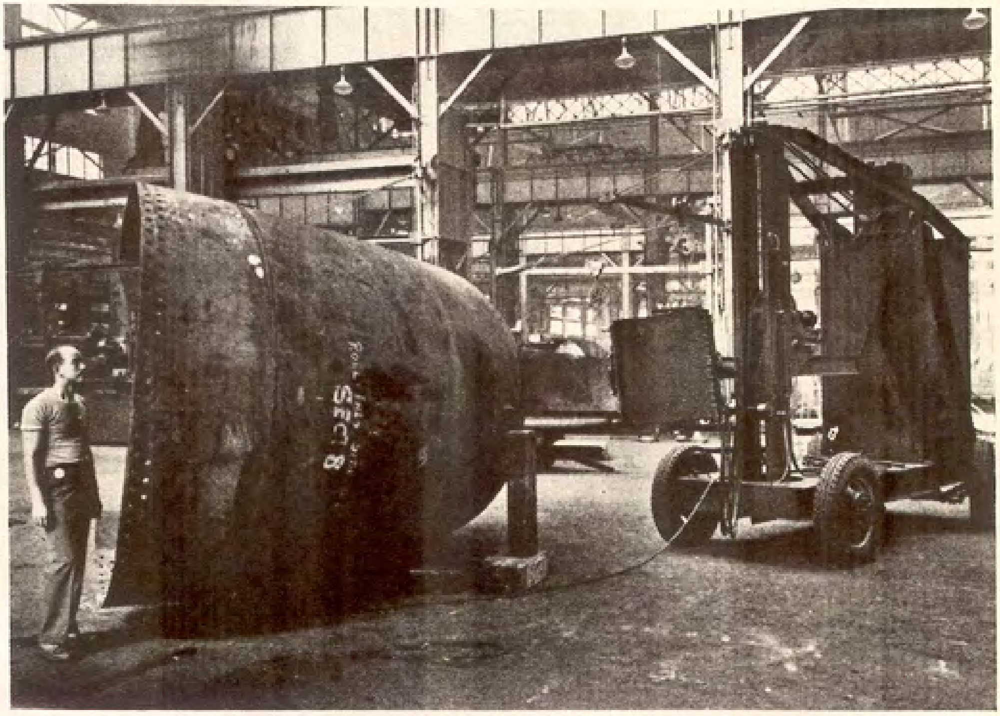


FIG. 3.—Radiography of Heavy Welded Structure with General Electric Portable 250-kvp X-ray. (Courtesy General Electric X-ray Div., Milwaukee, Wis.)

(*c*) Differences between cast and wrought structures (as might be present after fusion welding of wrought products).

(*d*) Treatments (including cooling) which influence grain size or grain-boundary conditions.

4. *Detecting conditions of mechanical stress*, particularly residual stresses following:

(*a*) Heat treating or processing.

(*b*) Shot peening or mechanical surface rolling.

(*c*) Welding or joining.

(*d*) Surface finishing (including grinding, polishing, or chemical treatments).

(*e*) Case hardening by gas or induction heating, nitriding, or carburizing, etc.

(*f*) Bending, forming, or other fabrication operations.

(*g*) Repeated service stressing.

(*h*) Loading beyond the elastic limit.

5. *Detecting internal voids and fissures:* such as,

(*a*) Pipe or gas porosity in castings.

(*b*) Shrinkage and microshrinkage.

(*c*) Flakes or transverse fissures in railroad rails.

(*d*) Incomplete penetration or porosity in welds (Figs. 3 and 4).

(*e*) Nugget cracking and porosity in spot welds.

(*f*) Laminations in rolled plate and sheet materials.

6. *Detecting internal inclusions and forgein materials:* such as,

(*a*) Dross in cast metals and alloys.

(*b*) Slag inclusions in fusion weld metal.

(*c*) Electrode pickup in spot welding.

(*d*) Internal parts misplaced or loosened during assembly.

(*e*) Foreign bodies rolled or forged into materials.

7. *Detecting surface cracks and other defects connected with exposed external surfaces:* such as,

(*a*) Fatigue cracks developed under repeated loading (Fig. 5).

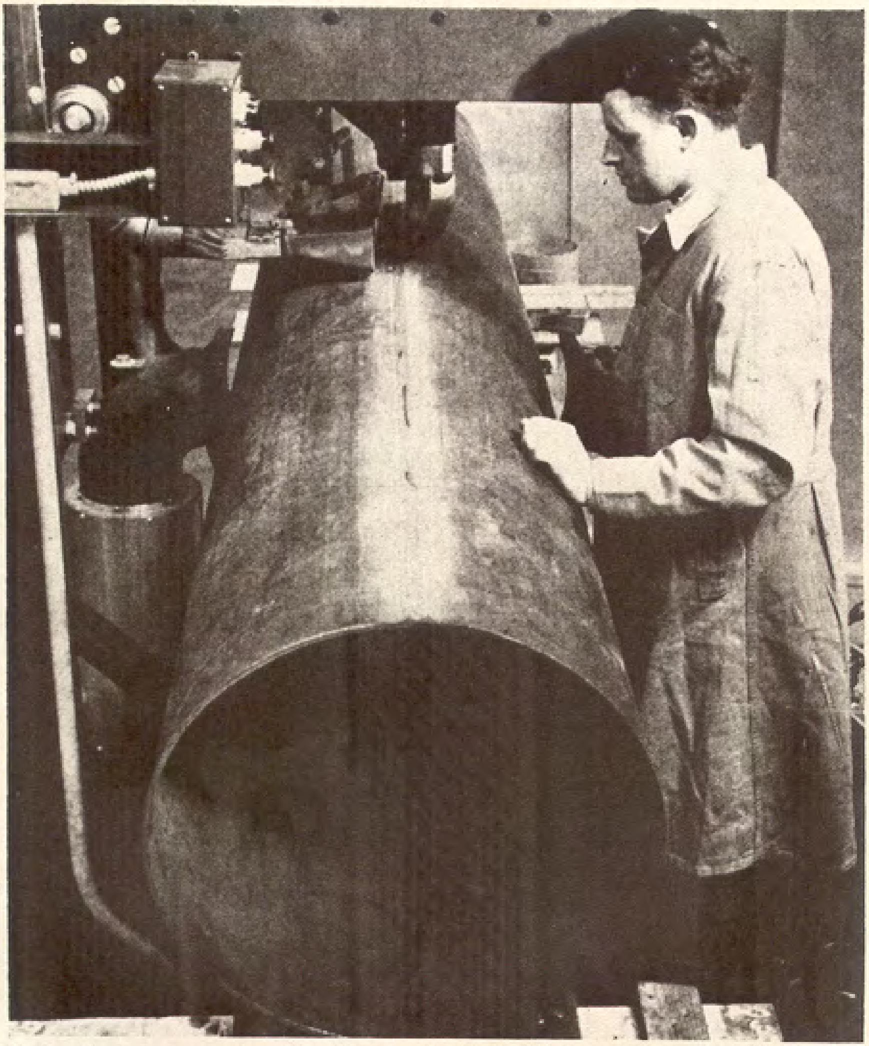


FIG. 4.—Magnaflux Automatic Dry Magnetic-Particle Inspection Unit for Resistance-Welded Line Pipe, Installed on Pipe Mill. Prompt detection of weld defects permits immediate correction of welding operation and repair of defects prior to hydrostatic proof test. (Courtesy Magnaflux Corp., Chicago, Ill.)

(*b*) Cracks resulting from surface grinding.

(*c*) Heat treating and thermal cracks.

(*d*) Seams and laps resulting from rolling and piercing or other hot forging operations.

(*e*) Cracks resulting from surface heat treatment, case hardening, nitriding, hydrogen embrittlements, etc.

(*f*) Corrosion pitting.

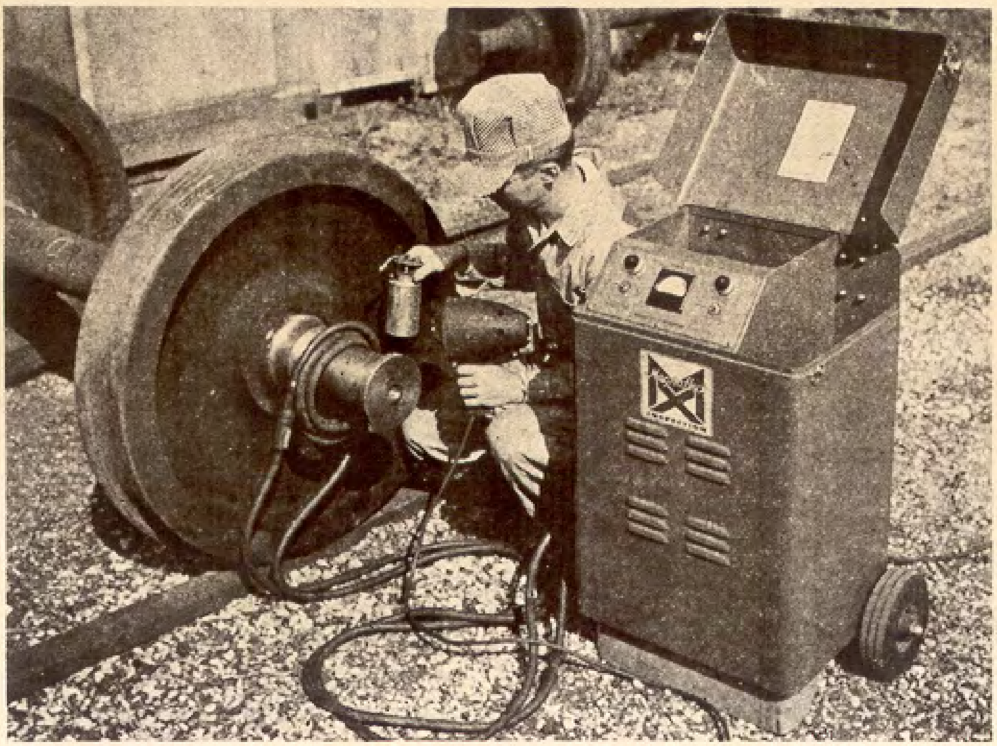


FIG. 5.—Detection of Service Fatigue Cracks in Railway Car Axle with Magnaflux Portable Wet-Method Magnetic-Particle Equipment. (Courtesy Magnaflux Corp., Chicago, Ill.)

8. *Gaging dimensions*, usually of finished parts, under conditions in which mechanical calipering by manual methods may not be feasible. Measurements which fall in this class include:

(*a*) Wall thickness of closed vessels, tubes, and pipes whose internal surfaces are not accessible (Fig. 6).

(*b*) Thickness of hot strip or other sheet materials moving at high velocities.

(*c*) Fluid levels in closed containers, such as molten metal level in furnaces and cupolas, radioactive materials in pipes and tanks, etc.

(*d*) Displacements of hidden parts of structures under high velocity or vibratory loads.

(*e*) Clearances between electrodes in sealed vacuum tubes.

(*f*) Location of internal insulation and bushings in electrical apparatus.

(*g*) Measurements of plating or cladding thicknesses.

The useful performance properties of materials or parts may be established or damaged at many different points in their production or fabrication processes. Consequently, nondestructive tests designed to detect such properties or damage may be needed at many different points in these production processes. Further damage might occur during transit, installation, calibration, or maintenance of finished products. Therefore, additional nondestructive tests may be required to detect this damage. Finally, service conditions, such as repeated loading, wear, corrosion, surface blows, and high temperatures, may also damage or destroy the serviceability of the material or part.

Thus, further nondestructive tests may be required periodically during service life.

Since the inherent useful properties of the material or part may be changed considerably during production, fabrication, or service (as, for example, during heat treating or welding or under dynamic loads), the nondestructive tests appropriate for evaluating these changing properties may vary accordingly.

For reasonable economy and efficiency in production and application, the appropriate nondestructive test should usually be applied *as early in the production or application process as the material properties permit.* For example, nondestructive tests which reveal rejectable defects in the *raw materials* may often be applied before any fabrication costs have been incurred. This saves the wasted costs of further fabricating of materials containing defects. Nondestructive tests designed to reveal damage from *fabricating processes* often may be applied *directly subsequent to the process* which may have produced the damage. This prevents the possibility of incurring further handling or fabrication costs on the worthless units. It permits immediate correction

Fig. 6.—Magnaflux Sonizon Ultrasonic Resonance Equipment Used to Measure Wall Thickness of Tubular Aircraft Component. (Courtesy Douglas Aircraft Corp., Santa Monica, Calif., and Magnaflux Corp., Chicago, Ill.)

of the process. Even more important, prompt nondestructive testing often permits more sensitive and lower cost nondestructive testing. The specific damage may often be more easily and sensitively detected before it is hidden by the effects of further processing or fabrication.

DISTINGUISHING CHARACTERISTICS OF NONDESTRUCTIVE TESTS

Most nondestructive test methods evaluate the quality, strength, or serviceability characteristics of the test objects *indirectly*. Usually, they involve the measurement of a critical or useful property (such as strength or the presence of flaws) in terms of other related, but noncritical, properties. The latter often have little or no direct significance in the application. For example, the fatigue performance of a casting may be evaluated by tests of its magnetic discontinuities or X-ray absorption. Neither of these latter two properties has any ultimate usefulness or direct bearing on the fatigue life of the casting in service.

Most nondestructive test methods involve far more than simple visual inspection of the exposed surfaces of test objects. In many cases, the nondestructive tests are designed to reveal the properties, dimensions, and discontinuities of the interior of the specimens. Nearly every basic principle of physics has been used to obtain, nondestructively, this basic information concerning the internal condition of test objects.

Nondestructive tests differ from *percentage destructive tests*, or "*coupon tests*." In coupon tests, a selected fraction of all the units in a lot are mechanically loaded to failure or are cut apart for examination. The strength or condition of the few samples is determined destructively, after which the units tested are unfit for service. Often, only a portion of the selected object is tested. This may be done by cutting a tension test specimen from one portion of it, or by sectioning it and making a metallographic examination after polishing and chemically etching the sectioned surface. Tests of this type destroy the test samples.

The corresponding advantages and limitations of destructive and nondestructive test methods are listed side by side for easy comparison in Table I. From these comparisons, one may conclude that:

1. Destructive tests are often quantitative; nondestructive tests are most frequently qualitative only.
2. Nondestructive tests usually require considerable skill, experience, and judgment on the part of the inspector.
3. Nondestructive tests are to be preferred if there is large random variability within production lots, if the product is valuable or critical in application, and if suitable nondestructive tests exist.
4. Nondestructive tests offer advantages if there are many possible causes or mechanisms of failure in service. These usually cannot all be evaluated with a reasonable number of *destructive* tests. Since several different *nondestructive* tests may be used in succession on each object, they can cover each of the possible causes for premature service failure.
5. Nondestructive tests usually cost less than destructive tests, in cases where either method can supply adequate information.
6. Nondestructive tests offer particular advantages over destructive tests in maintenance inspection during service. They usually do not require disassembly of units before inspection.
7. Nondestructive tests offer a practical means of assessing the effects of cumulative damage during service.
8. Nondestructive tests, in general, require less preparation of specimens than do destructive tests.
9. Nondestructive tests are usually faster than destructive tests. Conse-

TABLE I.—COMPARATIVE ADVANTAGES AND LIMITATIONS OF DESTRUCTIVE AND NONDESTRUCTIVE TESTS.

DESTRUCTIVE TESTS ADVANTAGES	NONDESTRUCTIVE TESTS LIMITATIONS
1. Tests usually simulate service conditions, consequently tend to measure serviceability.	1. Tests usually involve measurements of properties of no direct significance in service; the correlation between these measurements and serviceability must be proved by other means.
2. Tests are usually quantitative measurements of load for failure or for significant damage, or of life to failure under given loading and environmental conditions.	2. Tests are usually qualitative and rarely quantitative; they do not usually measure load for failure, or life to failure, even indirectly.
3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) is usually direct. Hence, most observers may agree upon the results of the test and their significance with respect to serviceability of the material or part.	3. Skilled judgment and test or service experience are usually required to interpret nondestructive test indications, and (where the essential correlation has not been proved or where experience is limited) observers may disagree in evaluating the significance of test indications.

DESTRUCTIVE TESTS LIMITATIONS	NONDESTRUCTIVE TESTS ADVANTAGES
1. Tests are not made on the objects actually used in service; consequently, the correlation between the objects tested and those used in service must be proved by other means.	1. Tests are made directly upon the objects to be used in service; consequently, there is no doubt that tests were made on representative test objects.
2. Tests can be made on only a fraction of the production lot to be used in service; consequently, they have little value when the properties vary greatly, in unpredictable order, from unit to unit.	2. Tests can be made on every unit to be used in service (if economically justified); consequently, they may be used validly even when great differences from unit to unit occur in production lots.
3. Tests often cannot be made on production parts as such and must often be limited to test bars cut from parts, or from special materials processed similarly to simulate the properties of the parts to be used in service. Preparation of the special test specimens may be very costly in some cases. Possible doubt may exist as to whether the test specimen is representative of the part as a whole.	3. Tests are made, if desired, on the entire production part; consequently, the evaluation applies to the part as a whole. Many critical sections of the part may be examined simultaneously or sequentially.
4. A single destructive test measures only one or a few of the properties which may be critical under service conditions, on a given specimen.	4. Many nondestructive tests, each sensitive to different properties of the material or part, may be applied simultaneously or in sequence, to measure as many properties correlated with service performance as may be desired.
5. Destructive tests are not usually applicable to parts in service, unless service is interrupted and the part removed from service, to be destroyed during testing.	5. Nondestructive tests may be applied to parts in service often without interruption of service, and with no loss of serviceable parts.
6. Cumulative change over a period of time cannot be measured on a single unit. If several units of the same lot are tested in succession over a period of time, to establish temporal changes in properties, the proof that the units were initially similar must be established. If the units are used in service and removed from service after various periods of time, it must be proved that each was subject to similar conditions of service, before valid data can be obtained.	6. Nondestructive tests may permit repeated checks of a given unit over a period of time, so that the rate of service damage, and its correlation with service failure, may be established clearly.
7. With parts of very high fabrication costs, the costs of replacing parts destroyed in testing may be prohibitive. Under these conditions, particularly with small production lots, it may not be feasible to make adequate tests.	7. Acceptable parts of very high fabrication costs are not lost in testing; consequently, extensive testing, or repeated testing during service, is feasible.
8. Many destructive tests require extensive machining or preparation of test specimens, and usually require massive, precision testing machines, so that the cost of destructive testing may be very high and the number of samples which can be prepared and tested in any single facility may be severely limited.	8. Little or no specimen preparation is required in many nondestructive tests. Several forms of nondestructive testing equipment are portable and are capable of rapid sorting and testing. The cost of nondestructive tests is in most cases far less than the cost of adequate destructive tests. (Exceptions exist, as, for example, in X-ray inspection of low-fabrication-cost production items, where film and inspection costs may exceed fabrication costs.)
9. The time and man-hour requirements of many destructive tests are very high, contributing to high production costs. Excessive production costs may be incurred if adequate and extensive destructive tests are used in production quality control.	9. Most nondestructive test methods are much more rapid and require far fewer man-hours or actual hours than do typical destructive tests. Consequently, they are suitable for testing large numbers, or all, of the production units, at a cost often less than or comparable to the costs of inspecting destructively only a minor percentage of production lots.

quently, production and servicing delays are minimized. The possibilities of producing large numbers of defective parts successively in production are decreased.

Nondestructive tests differ also from the ordinary measures of *industrial process control.* Industrial process control often provides limits on raw material composition, machine settings, or dimensional tolerances. Statistical methods are often used to increase the value of a limited number of measurements. The purpose of such process controls is to insure consistent high quality in the products of the process. However, some defective units may be produced, even with good process control. Such defects must be detected by other means—for example, by nondestructive testing.

Unsound Reasoning

An exception occurs in the case of *proof testing.* Proof testing is an essential nondestructive test. In proof tests, the test objects are loaded to a proof stress (simulating service stresses) at which unsatisfactory specimens should be revealed by their failure. Such proof tests are destructive of *defective* specimens. If properly designed, however, they should be completely *nondestructive* for all sound test objects. Consequently, they could be applied, if desired, to all production specimens, like any other nondestructive test.

It has been true that the testing of structural materials has been primarily *destructive* (of the test samples). This is natural, since many materials tests have been *simulated service tests.* Since the test objects are destroyed, the reliability or value of these destructive tests is critically dependent upon the *similarity of the objects actually tested to those which are placed in service.* The value of destructive tests is also dependent upon the *similarity of the test conditions to the actual service conditions.* The safe use of destructive tests depends upon this *degree of correlation* between the properties of the units tested and those of the units to be placed in service. If this correlation is excellent, the destructive tests may be reliable.

However, the properties of the individual units in a lot or group sometimes vary greatly, often at random. In this case, the correlation between the values obtained in destructive tests and the service performance may be dangerously low. Such variability between units of a group has frequently been used as a basis for rejection of entire production lots. The destructive tests provide no direct means for separating the useful pieces from the dangerous or useless objects in the same group. Thus the good units within such rejected lots are lost also. The cost of these losses may become excessive in some critical fabrication processes.

True *nondestructive* tests, on the other hand, may be applied to those objects which will be later used in service. If desired, all of the units produced may be subjected to nondestructive tests. Consequently, there is no doubt that the unit tested has properties identical to those of the unit to be used in service. *It is actually the same unit.* For this reason, appropriate nondestructive tests may be used with confidence even when the objects within a single lot or group differ greatly in properties among themselves. The useful units may be salvaged for service, even when many defective units may be present in the lot.

It is important to remember, however, that nearly all *nondestructive* test methods measure material properties differing from those which control serviceability. The value and reliability of these nondestructive tests are therefore critically dependent upon the *correlation between the property actually measured* in the nondestructive tests *and the serviceability-controlling properties* to be evaluated.

The validity of this correlation can never be safely assumed. It is open to the same doubt as the corresponding assumption, in destructive testing, that the properties of the few units tested are identical to or representative of those of all other units of the lot. In both cases, the degree of correlation must be established by means other than the tests themselves.

The two dangerous assumptions in testing are:

1. In *destructive* testing:

That the individual specimens tested truly represent the properties of the entire lot.

2. In *nondestructive* testing:

That the specimen properties actually measured do correlate reliably with those properties controlling the serviceability of the test objects.

Neither assumption is necessarily true, for any given case. Therefore, for every specific case, one must prove the underlying assumption to establish the significance of the tests. The assumptions must be proved:

(*a*) for each specific material,
(*b*) in each specific fabricated form,
(*c*) for each specific method of testing, and
(*d*) for each specific service application.

In some situations, the materials in two applications are so similar, or the service conditions are so nearly equivalent, that experience with one may be safely extrapolated to the other case. This, in general, should be done with due caution.

There are two practical ways of proving these basic assumptions. The first way is to accumulate sufficient service experience with the specific material and part under the given service conditions to be sure the assumption is true. The second way is to use destructive and nondestructive tests, each to verify the correlations assumed for the other method. For example, nondestructive tests such as X-rays and magnetic-particle inspection may be used to compare all the units in a lot. In this way, one can establish the similarity within the lot of samples to be tested *destructively* and of the remaining units to be placed in service. Alternatively, destructive physical tests may be used to establish the correlations between the properties actually measured in nondestructive tests and the serviceability of the parts.

For these reasons, it is obvious that nondestructive tests will not entirely supplant destructive tests, nor will the reverse occur. Both types of tests are essential in materials testing. They complement and support each other. Each increases the reliability of the other. Each may provide the essential proof of the basic correlation upon which the success of the other method is critically dependent, for reliable inspection of materials, parts, and structures for service applications.

THE ELEMENTS OF NONDESTRUCTIVE TESTS

Most nondestructive tests depend, for transmission of information concerning the object under test, upon a probing medium. The medium must usually be supplied from an external source. For example, this may be an X-ray tube, a magnetizing coil, an ultrasonic generator, or a spray gun. The medium may be distributed rather generally through the object being inspected, as with a broad X-ray beam. Alternatively, it may be concentrated in a narrow beam, as in ultrasonic testing. The source and type of probing medium must be selected so that its distribution upon the surface or within the test object is *modified by the presence of defects or by variations in the properties being tested.* Often, only a small portion of the incident medium is so affected. For this reason, very sensitive detectors of variations in the medium distribution are required, in order to obtain indications of the presence and nature of defects or variations in properties in the test object. The small variation of the medium in the pickup or detector unit must then be indicated or recorded by sensitive instruments or processes, such as the exposure and development of X-ray film. Finally, the indication or record must be interpreted, usually by a skilled inspector, in terms of the correlated serviceability property.

The five essential elements of most nondestructive tests are:

1. Supplying of a suitable form and distribution of probing medium from an external source to the test object.
2. Modification of the medium distribution within the test object as a result of its discontinuities or other variations in the material properties which correlate with serviceability.
3. Detection of the change in medium distribution or properties by a sensitive detector.
4. Indication or recording of the signal from the detector in a form useful for interpretation.
5. Interpretation of the indication and judgment of the corresponding serviceability of the test object.

The practicality and effectiveness of each proposed test method must be evaluated by a full consideration of each of these essential elements. Some theoretically sound test methods are not practical because no suitable source is available to supply the desired form and distribution of medium required for testing. In other cases, the source is available, but there is no practical means of coupling the source with the specimen so that the probing medium can be transferred to the test object in the desired form. Often, the significant defects or variations in properties in the test object do not influence sufficiently the distribution of the probing medium. In other cases, defects fail to influence the distribution of the medium sufficiently *at the point of detection.* In still other cases, the losses due to scattering or absorption of the medium within the test object are excessive. When this happens, the energy level at the pickup is too low for detection. Or, all too often, the indication of internal flaws or properties may be masked by the larger disturbing indications of surface geometry or of other regions closer to the detector.

The critical feature of most test methods is the detector or pickup. Often the required sensitivity to flaw indications cannot be obtained, particularly in the presence of large disturbing effects emanating directly from the source or from other sources of similar nature. In other cases, coupling the pickup to the test object is difficult. Inefficient information transfer results. Further limitations occur in the selecting of sensitivity and range. High-sensitivity detectors often operate properly over only a narrow range. The ultimate sensitivity of the detector is limited by background disturbances, many of which are unavoidable.

In a few cases, the feasibility of a proposed test may be limited by difficulties in amplifying and indicating or recording the low energy output of the pickup devices. High-gain amplifiers or high-contrast processes often have a certain amount of inherent instability or drift which makes permanent calibration difficult. They may require constant recalibration or monitoring. Some pickup signals are of such nature that they cannot be economically recorded in permanent and useful form. These conditions limit the application of many nondestructive tests.

The final requirement, obviously, is

that the test provide an indication or record that can be interpreted usefully, either in terms of the conditions within the test object or in terms of its serviceability. In some simple cases, the discrimination between acceptable and rejectable objects may be made an automatic function of the pickup signal level. In most cases, where many specimen conditions may contribute to test indications, a skilled inspector is needed. The test indications and the inspector's training must be such as to limit his errors in interpretation to reasonable frequencies of occurrence. The more indefinite and ambiguous the test indication, the less reliable its probable interpretation.

In general, a detectable change in the probing medium must be produced external to the test object, if its defects or properties are to be revealed. It is usually not feasible to introduce sensing units or detectors into identically the same space occupied by the material of the test object, nondestructively. Furthermore, if the purpose of the nondestructive test is to find defects or inhomogeneities within the test object, it is essential that these defects or discontinuities influence the probing medium in some manner different from that of the sound material of the test object. Otherwise, the defective material would be indistinguishable from the sound material.

There exists in nature a variety of forms of force, energy, and matter which can be used as probing media in the space adjacent to or occupied by the test object. Any medium which is significantly influenced by the properties of the test object it is desired to measure may possibly serve as a basis for a nondestructive test. A few common examples of such probing media are:

1. Solid matter, serving as (mechanical contact-making) probes.
2. Fluid (liquid or gaseous) matter, in contact with the test object.
3. Magnetic field energy, in static forms.
4. Electric field energy, in static forms.
5. Electromagnetic field energy, in dynamic, usually oscillatory, forms, including:
   (*a*) Visible light.
   (*b*) Infrared light and heat radiation.
   (*c*) Ultraviolet light and radiation.
   (*d*) Radio frequency electromagnetic waves.
   (*e*) High-frequency electromagnetic waves.
   (*f*) Ultra-high-frequency electromagnetic waves (microwaves).
   (*g*) Gamma rays.
   (*h*) X-rays.
   (*i*) Grenz rays.
   (*j*) Waves from the motion of particles of matter.
6. Mechanical motions of solids, liquid, or gaseous matter (energy of mass motion). These usually correspond to oscillatory or acoustic wave vibrations, including:
   (*a*) Single, steep-fronted waves or blows.
   (*b*) Low-frequency (audible) sound waves.
   (*c*) Ultrasonic (inaudible high-frequency) acoustic waves.
   (*d*) Transport of matter under pressure differences.
   (*e*) Jets or streams of matter flow, such as liquid or gas jets, electron beams in vacuum, ion beams in the mass spectroscope.
   (*f*) Large mass movements (as of solid bodies).
   (*g*) Movements of high-energy particles.
7. Forms of chemical, atomic, and molecular energy, and other lâtent forms of energy (usually associated with the state of matter), including:
   (*a*) Energy from chemical combinations and dissociations.
   (*b*) Energy from molecular to atomic combinations and dissociations.
   (*c*) Energy from ionization and recombination of electrons with atoms and molecules.
   (*d*) Energy from nuclear fission and recombination reactions.
   (*e*) Latent energy of transformation from solid to liquid and from liquid to gaseous states (latent heat of fusion or of evaporation).
   (*f*) Energy from biological processes.

NONDESTRUCTIVE TEST METHODS BASED PRIMARILY UPON TRANSMISSION OF ENERGY AS THE PROBING MEDIUM

All methods of nondestructive testing involve some use of energy transmission. This is necessary because, at some point in the process, the information must be transmitted to an observer or actuate an automatic selection device. However, some extremely useful nondestructive test methods depend primarily upon transmission of energy for *probing the material conditions*, as well as for transferring this information to a suitable point of detection outside the volume occupied by the material under inspection (Table II).

TABLE II.—TYPICAL NONDESTRUCTIVE TEST METHODS BASED UPON TRANSMISSION OF ENERGY.

Test Method	Form of Energy Used as Medium	Mechanism of Detection of Material Properties and Discontinuities	Forms of External Test Indications
Optical or visual inspection and other luminous energy tests	Visible light	Reflection, absorption, refraction, or scattering of light, etc.	Visible image, often produced with lenses or other optical aids, etc.
Radiography, fluoroscopy, X-ray gaging, xeroradiography, and other penetrating radiation tests	X-rays, gamma rays, Grenz rays	Absorption, scattering, transmission of rays, etc.	X-ray film images, xerographic images, fluoroscopic screen images, ionization gage indications, crystal or Geiger counting, etc.
Magnetic particle and other magnetic field tests	Magnetic-field energy	Distortion of magnetic field flux, attenuation of field, fringing of flux lines, caused by discontinuities in magnetic permeability, etc.	Finely-divided magnetic particle indications on exposed surfaces of test object, induced emf's in moving coil probes, variations in reluctance of Gauss meters, Hall effects in current-carrying probes, etc.
Electrified particle and other electric field tests	Electric-field energy	Distortion of electric field flux, breakdown of dielectric, corona or radio noise at defects, dielectric constant, dielectric losses, etc.	Spark over or dielectric breakdown, radio noise, capacitance values, leakage currents, ohmic resistance measurement, collection of electrified particles, etc.

As a criterion for selection of test methods in this category, it may be sufficient to note that such transmission of energy (in the form used in the test) could take place in perfect vacuum, without the motion of particles or presence of any form of matter. Electromagnetic fields, either static or dynamic, fall into this class (in those spatial regions where movements of electric charge or magnetic poles are absent).

Static electric and magnetic fields form the basis of many useful tests. Dynamic electromagnetic fields, throughout the wide frequency range now producible, provide a far more extensive base for nondestructive test methods. As a general principle, it may be recognized that the wavelength of oscillatory probing media should be comparable to (within a few orders of magnitude) or smaller than the critical dimensions of discontinuities which they are expected to detect. It is usually difficult to reveal discontinuities with waves whose length is several orders of magnitude larger than the discontinuity itself.

Visual Inspection and Other Luminous Energy Tests:

Luminous energy tests are characterized by the use of visible light to illuminate test objects. These may be scanned by eye or by light-sensitive devices such as photoelectric cells. Ordinary visual inspection and inspection with optical aids, such as telescopes, microscopes, mirrors, and lenses, fall in this class. Tests employing media other than visible light to probe the test objects are not included and are discussed elsewhere in this paper.

Visual observation is naturally the most widely used inspection method. The human eye has excellent visual perception although it is limited in frequency response to wavelengths between 400 and 700 μ. Its response varies considerably throughout this frequency range. It peaks in brightness response at a frequency near 520 to 540 μ. Its acuity and contrast sensitivity decrease rapidly as the energy level of illumination decreases within the visual frequency range. The tendency toward ocular fatigue is accelerated by the presence of glare (brightnesses within the field of view varying by more than 10 to 1), or by efforts to see at low levels of illumination or outside the optimum frequency range (470 to 610 μ).

For critical inspection under other than optimum conditions as indicated above, the attention span of the human observer is limited to reasonable periods of time. For observation at very low light levels (as in fluoroscopy), the human eye should be dark-adapted in advance. The period of intense inspection should be limited to the order of 15 to 30 min at a time, to avoid errors due to fatigue and to deterioration in visual reliability and discrimination.

The maximum visual acuity at high brightness levels exists only for that small portion of the image focused upon the fovea centralis, or "spot of clear vision," near the center of the retina. Here the layer of blood vessels, nerve fibers, and cells above the perceptors (rods and cones) is far thinner than in peripheral regions of the retina. Here also the high brightness color discrimination (frequency response) and visual acuity are at their maximum. Critical inspection, therefore, requires rapid movement of this sharp image area to various points in the inspection field. Complete *detailed* visual inspection is feasible only if each critical area can be scanned by the "spot of clear vision" of the eye.

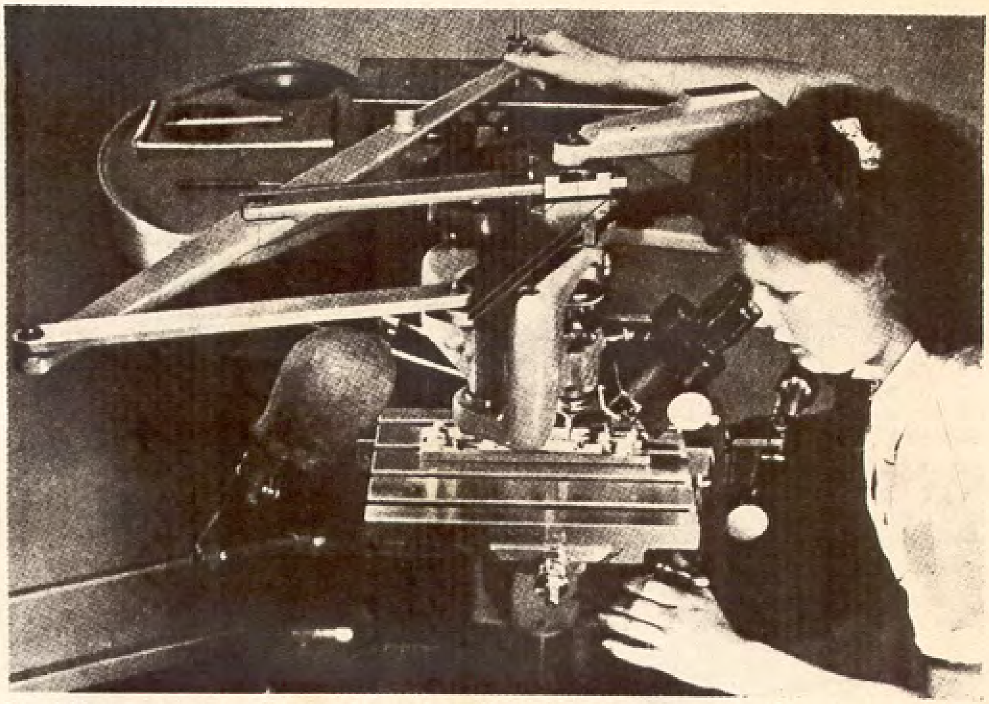


Fig. 7.—Microscopic Control and Inspection of Production Processes. (Courtesy American Optical Co., Scientific Instrument Div., Buffalo, N. Y.)

At low light levels, on the other hand, the peripheral regions of the retina, which are lacking in color discrimination and visual acuity, provide much of the visual sensitivity. Relative motion of the test object and the observer's eye may improve reliability and discrimination in this type of vision.

Optical magnifiers and microscopes provide valuable means of compensating for the limits of visual acuity of the human eye, by enlarging small discontinuities and structural details of materials (Fig. 7). Enlarging projectors and comparators improve viewing conditions for rapid inspection of small precision parts. Industrial (wired) television systems permit observation from a distance or at otherwise inaccessible points in production (as, for example, with radioactive materials). Borescopes permit direct visual inspection of the interior of hollow tubes and of other internal surfaces, under optimum viewing conditions (Fig. 8).

FIG. 8.—Tuboscope Used in Inside Inspection of Oil Well Drill Pipe. (Courtesy Tubular Service and Engineering Co., Houston, Tex.)

Photoelectric and other automatic detection systems have replaced direct visual inspection with automatic nondestructive testing in many industrial applications, such as counting, gaging, color matching, measuring contour and surface roughness, and detecting surface flaws in sheet materials.

Visual inspection and other luminous energy nondestructive tests are the most

widely used forms of nondestructive tests in industry. However, their forms, applications, and limitations are so well known that there is little need to describe them further here.

X-ray and Other Penetrating Radiation Tests:

Test methods in which the test objects are subjected to penetrating radiation, such as X-rays or gamma rays, are included under this subject heading. Penetrating radiation tests are characterized by exposure of test objects to beams or fields of penetrating radiations. The intensities of these beams are modified by passage through or reflection from the material and defects in the test objects. The differential absorption of the radiation is a function of the material structure and properties. These include density, mass, thickness, and other properties of the test object. Scatter, internal reflection, diffraction, and production of secondary radiation within the test object introduce additional variables. Sensitive radiation detectors are employed. These include X-ray film, xeroradiographic plates, fluorescent screens, Geiger tubes, and ionization gages. These detectors transform differences in intensity of the visible radiations into visual images or electrical signals.

Long wavelength radiations such as radio waves, microwaves, heat radiation, and light generally fail to penetrate metallic materials sufficiently to serve as useful media for internal inspection. On the other hand the short wavelength electromagnetic radiations, particularly the Grenz rays, X-rays, and gamma rays, penetrate atomic lattices with relative freedom. Such penetrating short wavelength electromagnetic radiations provide a potent tool for internal inspection of materials. Their wavelengths are short with respect to the interatomic spacings in solid materials. Despite their relative ease of transmission through materials, waves in this frequency region are sensitive to material properties and discontinuities. The longer wavelength, low-energy penetrating radiations, such as Grenz rays, are most useful in examining thin layers of dense materials such as metals and alloys. They serve also in the examination of low-density materials such as organic materials, liquids, and gases. The shorter wavelength, high-energy penetrating radiations (such as high-voltage X-rays and gamma rays) are best used for examining the denser materials, such as ferrous and heavy metal alloys, and thick sections.

When electronic X-ray tubes operate with continuously applied and constant values of potential between target and cathode, the frequency (and wavelength) of the resultant X-radiation are related to the accelerating voltage applied to the electron beam. The minimum wavelength (λ_c in Ångström units) (maximum frequency, f_c) limit is given by:

$$\lambda_c = \frac{1}{f_c} = \frac{12.345}{\text{kvp}}$$

where the electron beam accelerating voltage in the X-ray tube is given in "kilovolts peak" (kvp). The major part of the X-ray emission is at greater wavelengths than this minimum or cutoff limit and consists of "white radiation" of many wavelengths.

When X-ray tubes operate self-rectified on alternating current power supplies, each conducting half cycle of current applies a wave of voltage varying from zero to the peak value and back to zero amplitude. The quantity of X-rays produced, and their equivalent wavelength or penetrating power, also change continuously, as a function of the applied voltage, during each conducting half cycle. The result is the production of radiation with a typical penetration approximately equivalent to that of monochromatic radiation produced at a constant voltage of about 59 per cent of the peak voltage applied in the a-c circuit.

The reactions between these penetrating electromagnetic waves and the materials through which they pass may be somewhat complex. For example, the incident beams are absorbed and attenuated as they pass through materials. Their attenuation is a function of material density and thickness. As the primary beam is absorbed in a material, there are produced secondary radiations (of lower energy and longer wavelength) as well as secondary particles, such as electrons. Both the secondary radiations and the secondary particles may have sufficient energies to pass through considerable thicknesses of material. These, in turn, may react with the material to produce tertiary radiations and particles.

With high-energy incident radiation, the secondary radiation tends to be directed in the general orientation of the primary beam. With lower energy incident radiation, and with secondary and subsequent generation radiations, the scatter tends to become more general in all directions. In consequence, the directional properties of beams tend to degenerate as attenuation increases and as low-energy secondaries are produced. In extreme cases, the randomly scattered degenerate radiation may approach or

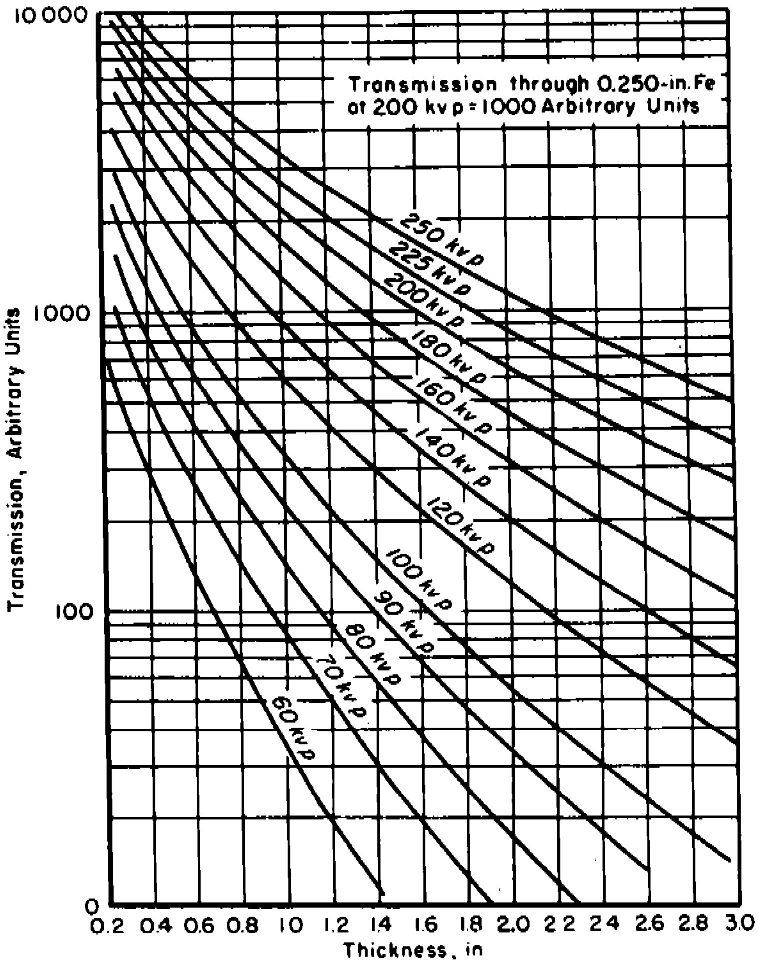
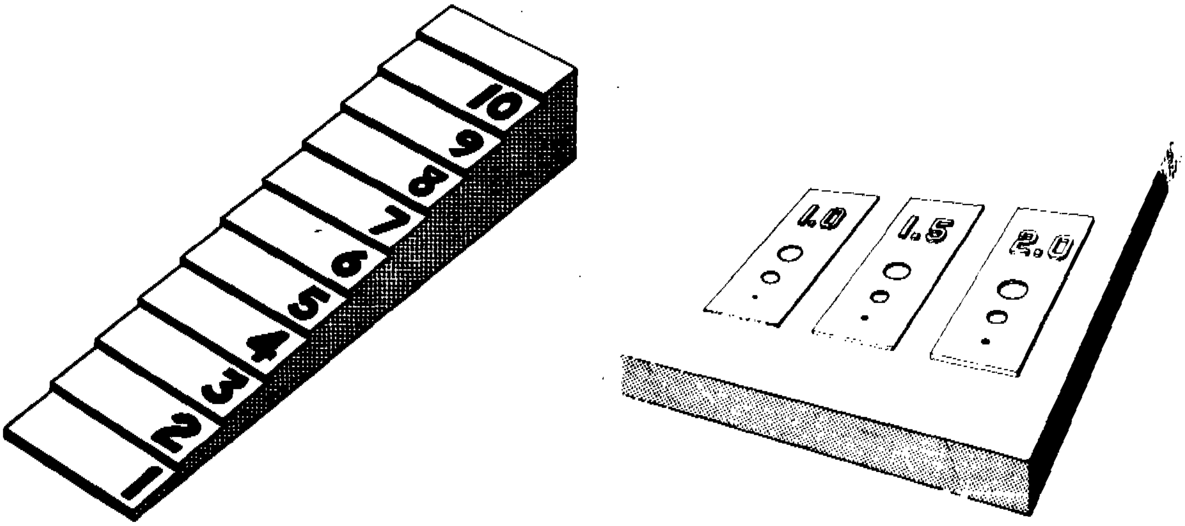


FIG. 9.—X-ray Transmission Curves for 24S Aluminum as Dependent on Material Thickness and Source Kilovolt Peak. (Courtesy H. D. Roop, Los Angeles, Calif.)

exceed the intensity of the attenuated primary beam. In this case, it becomes more difficult, if not impossible, to produce useful shadow images or radiographs. Special grids or filters are then used to screen out secondary scatter.



(*a*) Aluminum step-wedge penetrameter. (*b*) One to two per cent penetrameters.

FIG. 10.—Step-Wedge and Penetrameters.

With monochromatic radiation (of a single frequency), the attenuation of the primary beam may be expressed as an exponential function of the mass (or of the thickness and the density) of the material through which it passes. Thus, the primary beam intensity I_x within the material may be written in terms of the incident intensity, I_0, the material density, ρ, and the distance, t, of penetration, as:

$$I_x = I_0 e^{-\mu\rho t}$$

Here μ is a factor relating X-ray absorption power to the material density, ρ. The logarithm of the transmission ratio, I_x/I_0, is a linear function, for a homogeneous material, of the thickness of material through which the beam has passed:

$$\log_e(I_x/I_0) = -\mu\rho t$$

Curves for $\log_e (I_x/I_0)$ plotted as a function of material thickness, t, drawn on semi-log coordinates tend to be straight lines. In practice, however, it is difficult to obtain high-intensity beams of monochromatic radiation. It is also hard to measure the primary beam without errors introduced by secondary radiation. In practical radiography, consequently, the effects of "white" (multiple frequency) primary beams and of secondary radiation produced within the test objects cause deviations from the simple law expressed above. These cannot be ignored. Typical transmission curves for "white" radiation of several different energy distributions, for a typical industrial material, are given in Fig. 9. These curves deviate from linear because of the nonmonochromatic characteristics of the primary beams and because of the very significant contributions of secondary scatter.

The quality (sensitivity) of the radiographic image of a test object is a function of the definition and the contrast in the transmitted beam of radiation. It depends also upon the process by which the invisible beam is made to produce a visible image. The definition is related to the sharpness with which the boundaries of a discontinuity of the test object are revealed in the transmitted beam or the final image.

In homogeneous materials, the large-area contrast may be defined in terms of the minimum differences in the thickness of the test object which can be detected in the transmitted beam. Assume a difference in thickness, Δt, in the total thickness, t, of the test object. Suppose that this thickness increment causes a difference in intensity, ΔI, in the total transmitted beam intensity, I. Then the X-ray beam contrast factor, C_x, may be defined as:

$$C_x = \frac{\Delta I/I}{\Delta t/t} = \frac{\Delta \log I}{\Delta \log t}$$

The intensity of the transmitted beam, I, decreases as the material thickness, t, increases. Therefore, C_x is essentially negative. However, only its absolute value is of interest.

In practice, penetrameters are often used to establish a measure of definition and contrast in X-ray images. Standard penetrameters are fabricated to 2 per cent (or other fractions) of the specimen thickness, of material with the same X-ray absorption. Holes drilled in the penetrameter, with diameters equal to its thickness and multiples of its thickness, provide small-area images for critical viewing (Fig. 10). The penetrameters are placed on the source side of the test object during X-ray exposure. The clarity of the penetrameter images in the over-all X-ray image establishes the "sensitivity" of the radiographs. Two per cent sensitivity (meaning that a penetrameter 2 per cent as thick as the test object is clearly revealed) is a common specification requirement.

Sources of Penetrating Radiation.—Natural sources of penetrating radiation include cosmic rays and naturally radioactive materials, such as radium and the gas radon. Roentgen found that X-rays could be produced when electron beams in vacuum bombarded metallic targets. A readily controllable electronic source of X-rays then became available. With the advent of the Coolidge hot-cathode X-ray tube, the problems of cold-cathode emission in gas tubes were avoided. Practical sealed-off X-ray tubes could be produced. More recent electron-accelerating devices, such as the cyclotron, the betatron, the synchrocyclotron, the Van der Graaff linear accelerator, and their modifications, have provided new electronic sources. These are capable of producing beams with energies equivalent to several hundreds of millions of electron volts. In addition, recent developments in nuclear physics have produced a large number of new radioactive materials. These have a wide range of wavelength characteristics. They provide new, low-cost sources of penetrating radiation.

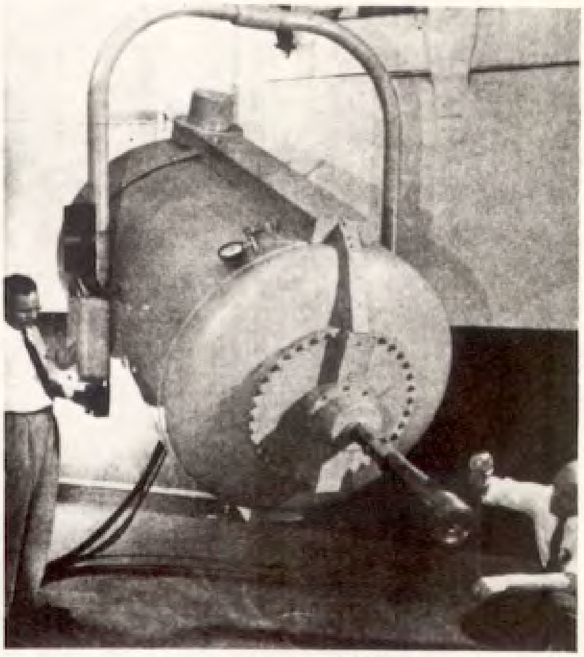


FIG. 11.—Two Million Volt X-ray Equipment Developed by Charleton and Westendorp in the General Electric Research Laboratory. (Courtesy General Electric X-ray Div., Milwaukee, Wis.)

Conventional hot-cathode vacuum X-ray tubes are now manufactured commercially for operation at various peak voltage values in the range from 5 to 2000 kvp (Fig. 11). Continuous beam current ratings are limited, in general, so that the heat dissipation at the anode (target of the electron beam) does not usually exceed about 3 kw.

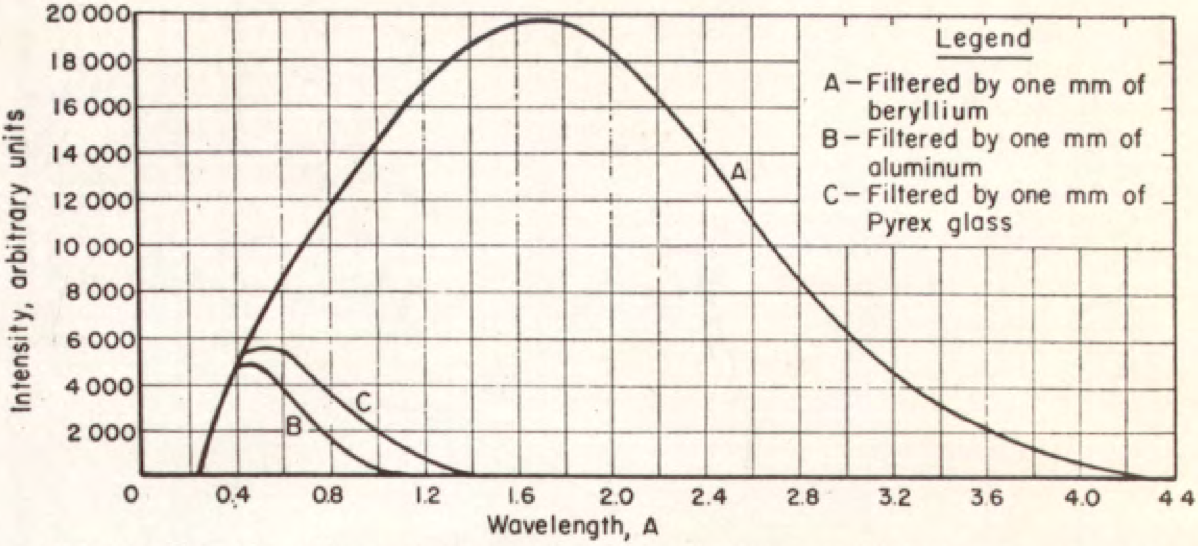


Fig. 12.—Filtration of X-rays in X-ray Port Materials. (Courtesy Machlett Laboratories, Inc., Springdale, Conn.)

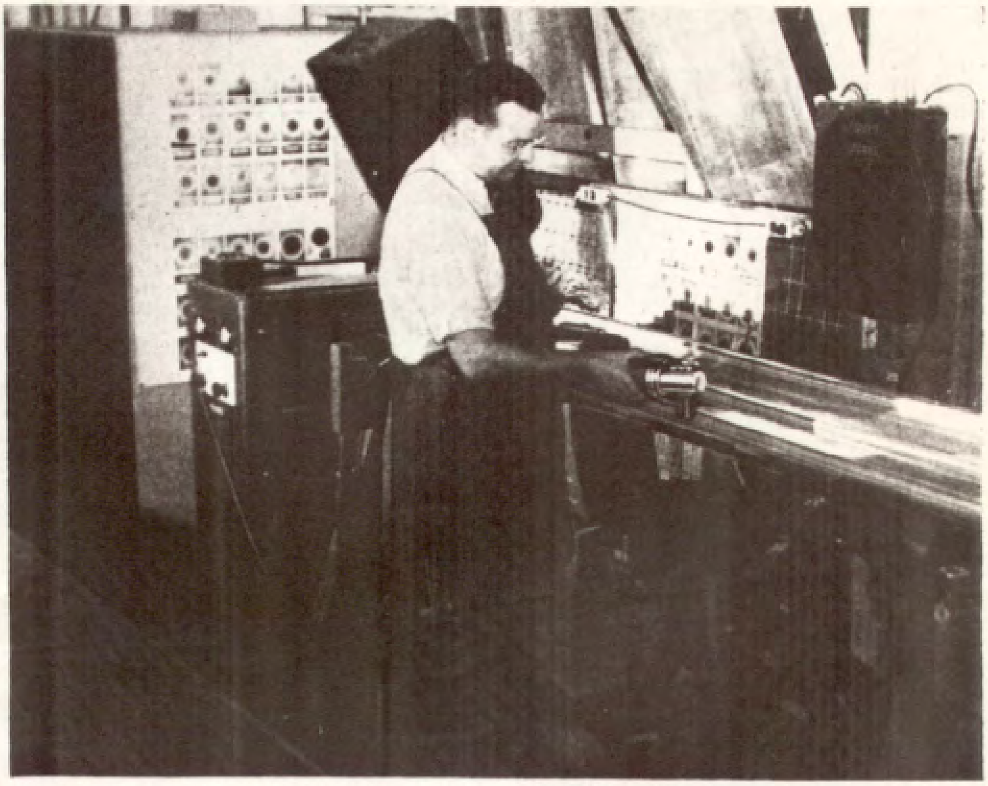


Fig. 13.—Radiographing Spot-Welded Aircraft Tail-Boom Panels in Production Welding Department, with Picker 50-kvp Industrial X-ray Unit. (Courtesy Picker X-ray Corp., New York, N. Y.)

Low-voltage tubes (5 to 50 kvp) often have beam current ratings of 30 to 50 ma (milliamperes). Tubes to operate in the range from 50 to 150 kvp are usually rated for currents of the order of 10 to 15 ma. Tubes rated from 150 to 400 kvp operate with beam currents as low as 5 to 8 ma. Million and multimillion volt tubes have electron beam currents of the order of microamperes.

Each tube includes an electron-emitting cathode. The electron beam is usually focused by means of focusing cups or electrostatic field control rings located near the cathode. The electron beam impinges upon a tungsten (or other heavy metal) insert in the water-cooled copper anode structure. The collision of the high-velocity electrons with the target produces X-rays which are emitted from the surface of the target. Each X-ray tube is provided with a thin-walled or low-absorption X-ray port. The X-rays thus emerge into the ambient atmosphere. The targets are often angled. They present a minimum effective area with respect to the port, yet provide a maximum area for dissipation of heat from the electron beam. The tube ports are usually made with the minimum feasible inherent filtration (absorption of X-rays) for low-voltage applications (Fig. 12). This permits the maximum quantity of X-rays to escape from the tube into the exposure region. Beryllium, a low-density metal, has replaced mica and Lindemann-glass windows for such applications in most modern X-ray tubes which operate below 50 kvp.

FIG. 14.—150-kvp Industrial X-ray Inspection Installation, Showing Protective, Lead-Lined Hood. (Courtesy Picker X-ray Corp., New York, N. Y.)

Many specially designed X-ray tubes have been developed to meet the requirements of particular applications in industry and medicine. These include fine focal spot tubes (which allow for direct enlargement of X-ray images), tubes with large Roentgen unit X-ray output, tubes with rotating anodes for short, intense exposures, "flash tubes," and others.

Low-voltage X-ray sources (5 to 50 kvp) are used for radiography of thin materials and sheets, spot welds in light alloys, plastics and organic materials, and in X-ray diffraction studies of the structure of materials (Fig. 13). Medium voltage sources (80 to 160 kvp) find extensive use in radiography and fluoroscopy of light alloy parts in the aircraft industry and for general radiography of thin sections of denser materials (Fig. 14). Higher voltage equipment (250 to 400 kvp) is required in radiography of thicker sections of steel and other heavy materials, as well as for radiography of thicker sections of light alloys (Fig. 15). Million and two million volt sources find a wide range of potential high-volume industrial inspection applications in ordnance, heavy ferrous castings, large machined parts, and similar test objects, because the penetrating power of their radiation reduces the exposure times far below those required with lower voltage sources (Fig. 11). Induction accelerators, such as the betatron, provide practical sources of radiation in the 10 to 31 million volt range and have been constructed for op-

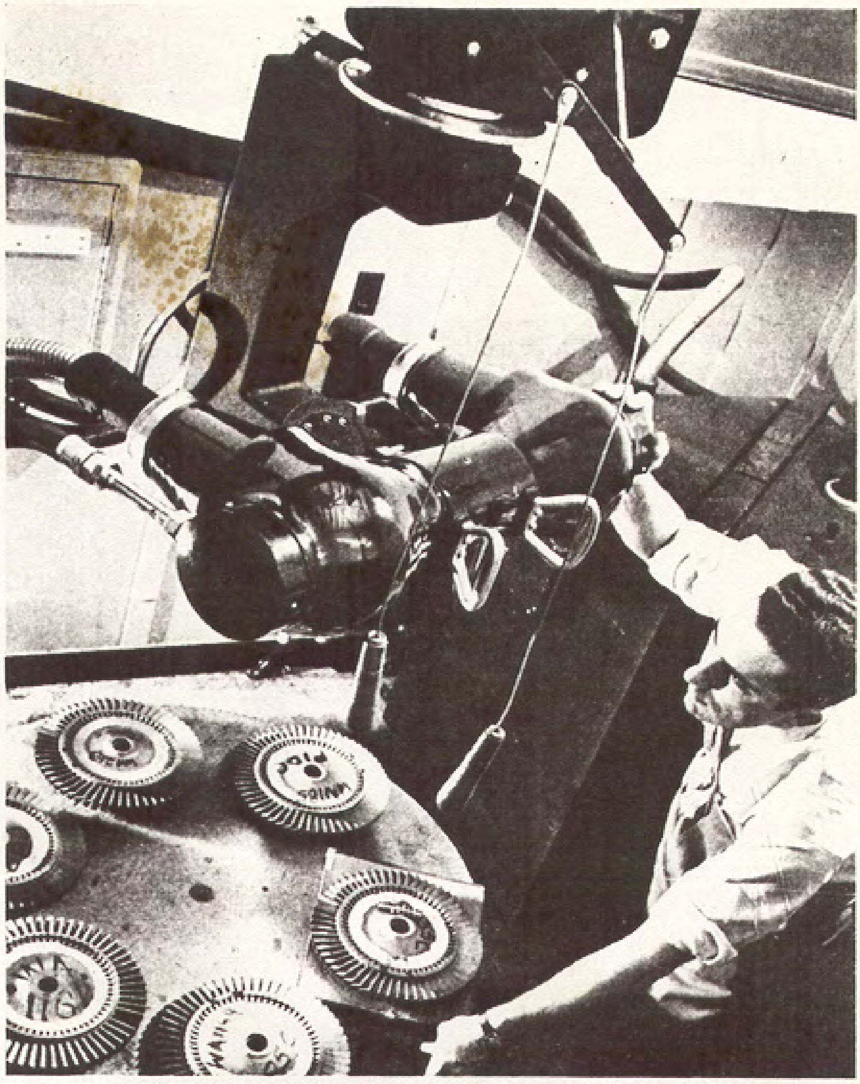


Fig. 15.—X-ray Inspection of Tungsten Alloy Aviation Gas Turbine Wheels with Westinghouse. 250-kv Unit. (Courtesy Westinghouse X-ray Div., Baltimore, Md.)

TABLE III.—THE RADIUM SERIES.

Name	Symbol	Half-Life	Radiations, mev, max		
			Alpha	Beta	Gamma
Radium	Ra 222	1620 yr	4.61	...	0.188
Radon	Rn 222	3.825 days	5.49	...	...
Radium A	Po 210	3.05 min	5.99	...	...
Radium B	Pb 214	26.8 min	...	0.72	0.35
Radium C	Bi 214	19.7 min	...	3.17	2.42
Radium C′	Po 214	1.5 × 10^{-3} sec	7.7	...	...
Radium C″	Tl 210	1.32 min	...	1.8	...
Radium D	Pb 210	22 yr	...	0.026	0.046
Radium E	Bi 210	5 days	...	1.17	...
Radium F	Po 210	138 days	5.29	...	0.77
Radium G	Pb 206	Stable	...	...	...

TABLE IV.—HARD GAMMA SOURCES.

Isotope	Half-Life	Gamma-Ray Energies, mev
Sodium 24	14.8 hr	2.758; 1.38
Gallium 72	14.3 hr	2.51; 2.21; 1.87; 1.59; and others
Radium 226	1620 yr	2.42; 2.20; 2.09; 1.82; and others
Lanthanum 140	40.4 hr	2.3; 1.65; and others
Antimony 124	60 days	2.04; 1.708; 0.732; and others
Praseodymium 142	19.3 hr	1.74; 0.49; 0.424; an others
Arsenic 76	26.8 hr	1.70; 1.20; 0.55
Barium 131	11.7 hr	1.70; 1.2; 0.50; 0.22
Europium 154	5.4 yr	1.6; 0.40; 0.34; 0.28; and others
Potassium 42	12.4 hr	1.51
Silver 110	270 days	1.48; 0.9; 0.6
Bromine 82	35 hr	1.36; 0.787; 0.465
Cesium 134	2.3 yr	1.35; 0.79; 0.60; 0.57
Copper 64	12.8 hr	1.35
Cobalt 60	5.3 yr	1.33; 1.17
Iron 59	46.3 days	1.30; 1.10
Europium 152	5.3 yr	1.23; 0.162; 0.123
Tantalum 182	113 days	1.22; 1.13; 0.22; 0.15
Rhodium 106	30 sec	1.2; 0.73; 0.51
Osmium 193	32 hr	1.2
Zinc 65	250 days	1.14
Scandium 46	85 days	1.12; 0.88
Rubidium 86	19.5 days	1.08
Zirconium 95	65 days	0.92; 0.73; 0.23
Holmium 166	27 hr	0.92; 0.081
Indium 114	50 days	0.9; 0.186; 0.15
Molybdenum 99	67 hr	0.84; 0.185; 0.77; 0.24

eration at 100 million volts and higher. Their output is a narrow beam of highly penetrating radiation suitable for the thickest objects feasible for X-ray inspection in industry.

The naturally occurring radioactive materials such as the radium-radon series (Table III) have recently been supplemented by many new pile-produced radioisotopes which produce X-rays or gamma rays suitable for radiography. Radium, radon, cobalt 60, and europium 154, for example, produce hard gamma rays (Table IV), equivalent in penetrating power to those produced by electronic X-ray sources in the million and multimillion volt range. Iridium 192, selenium 75, cesium 134, and hafnium 181, on the other hand, produce softer X-rays (Table V) comparable to those produced in X-ray tubes operating in the range from

TABLE V.—CLASSIFICATION OF ISOTOPES BY ENERGY OF GAMMA RADIATION.

Greater than 2.0 mev	Half-Life
Radium 226	1620 yr
Antimony 124	60 days
Lanthanum 140	40.4 hr
Sodium 24	14.8 hr
Gallium 72	14.3 hr
Manganese 56	2.6 hr
1.5 to 2.0 mev	**Half Life**
Europium 154	5.4 yr
Silver 110	270 days
Barium 131	11.7 days
Arsenic 76	26.8 hr
Praseodymium 142	19.3 hr
Potassium 42	12.4 hr
1.0 to 1.5 mev	**Half-Life**
Cobalt 60	5.3 yr
Europium 152	5.3 yr
Cesium 134	2.3 yr
Zinc 65	250 days
Tantalum 182	113 days
Scandium 46	85 days
Iron 59	46.3 days
Rubidium 86	195 days
Bromine 82	35 hr
Osmium 193	32 hr
Copper 64	12.8 hr
Rhodium 106	30 sec
0.5 to 1.0 mev	**Half-Life**
Antimony 125	2.7 yr
Polonium 210 (RaF)	138 days
Iridium 192	70 days
Zirconium 95	65 days
Indium 114	50 days
Cadmium 115	43 days
Ruthenium 103	41 days
0.5 to 1.0 mev (cont'd)	**Half Life**
*Niobium 95	35 days
Neodymium 147	11 days
Iodine 131	8 days
Antimony 122	2.8 days
Molybdenum 99	67 hr
Cadmium 115	2.3 days
Samarium 153	47 hr
Holmium 192	27 hr
*Wolfram 187	24.1 hr
Europium 152	9.2 hr
Ruthenium 105	4 hr
0.25 to 0.50 mev	**Half-Life**
Selenium 75	127 days
Hafnium 181	46 days
Mercury 204	44 days
Chromium 51	26.5 days
Germanium 71	11.4 days
Gold 198	2.7 days
Promethium 149	47 hr
Rhodium 105	36.5 hr
Less than 0.25 mev	**Half-Life**
Lead 210 (RaD)	22 yr
Actinium 227	21 yr
Europium 155	1.7 yr
Tin 113	105 days
Technetium 97	92 days
Tellurium 127	90 days
Cerium 141	28 days
Osmium 191	15 days
Cesium 131	9.6 days
Rhenium 186	91 hr
Gold 199	3.3 days
Ruthenium 97	2.8 days
Mercury 197	64 hr
Mercury 197	24 hr

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* Formerly columbium and tungsten, respectively.

100 to 1000 kv. Such radioactive sources have found extensive application in radiography of castings, welds, and structures in the field, and in industrial plants not equipped with appropriate electronic X-ray sources.

Detection and Recording of Penetrating Radiations.—X-rays and other penetrating radiations invisible to the human eye are detected and recorded by means of photographic (X-ray) films and papers, fluorescent screens, xeroradiographic plates, electronic image amplifiers, ionization gages, Geiger and other counting tubes, semiconductor elements, crystal scintillations, and photoelectric detection of fluorescence.

The most widely used and generally most satisfactory method of recording large-area images is by means of X-ray films, which consist of radiation-sensitive emulsions of crystalline silver bromide and gelatin coated heavily on both surfaces of an acetate compound base sheet. Fine-grain films provide high contrast and definition with some sacrifice of exposure speed (Fig. 16). High-speed X-ray films usually have larger grain size and are used with intensifying screens of lead or fluorescent materials to increase their exposure speed and reduce the effects of scattered radiation in many applications. The recently developed Picker-Polaroid-Land films permit processing without chemical solutions in tanks, in about 1 min after completion of exposure. Contrast sensitivities and definition adequate to reveal 2 per cent penetrameters are routinely obtained with X-ray films in many industrial applications. Film radiography is widely used in inspection of welds and castings, critical aircraft and ordnance components, and small parts. Very fine-grain films are necessary in microradiography and X-ray diffraction studies.

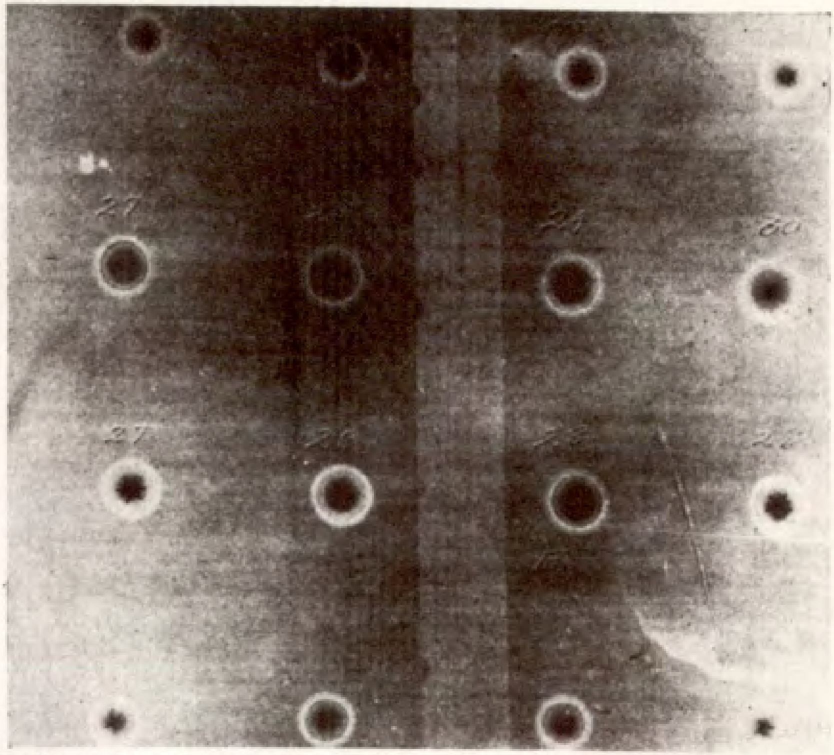


FIG. 16.—Radiograph of Spot Welds in Alclad 24S-T Aluminum Alloy, on Fine-Grain, High-Contrast X-ray Film. (Vertical strip image in center is an X-ray film penetrameter.) (Courtesy Triplett and Barton, Inc., Burbank, Calif.)

Xeroradiography, a dry electroradiographic method of recording X-ray images, is an experimental method not yet commercially available, with potential applications similar to those of X-ray films. In this process, a selenium-coated xeroradiographic plate is electrically charged and then exposed like X-ray film. During exposure, the electrical resistivity of the selenium is modified by the radiation, allowing the electrical charge to leak through where irradiation is most intense. The latent electrostatic image is revealed by dusting the exposed plate with charged particles (as in the Statiflux process) or cascading a two-component developing powder over its surface (Fig. 17). This process has shown itself capable of performance equivalent to that of fine-grain X-ray film throughout the entire range of industrial applications. Unlike X-ray film, however, the sensitive plates may be used repeatedly and do not accumulate fog during prolonged storage in contaminated areas.

FIG. 17.—White Powder Cloud Development of Electroradiographic Images on Selenium Plate (Courtesy Battelle Memorial Institute, Columbus, Ohio.)

In *fluoroscopy*, the X-ray images are continuously revealed for visual inspection by means of zinc-cadmium-sulfide fluorescent screens. Usually no permanent records are made, although the fluorescent screen images may be photographed (photofluorography) if a permanent image is desired. The fluorescent screens now available lack the high gamma (contrast amplification) inherent in most X-ray films and have larger grain size than films. Their image brightness is lower than the optimum illumination used in viewing films. These limitations reduce the contrast sensitivity and definition of fluoroscopy below the ultimate attainable with radiography, but in many applications it has been shown feasible to attain adequate inspection levels with light-alloy parts with high-brightness fluoroscopy, where the test object can be moved relative to the X-ray source and fluorescent viewing screen. O'Connor and others have recently demonstrated the improvement attainable by use of fine focal-spot sources and direct X-ray enlargement of the images prior to their incidence upon the fluoroscopic screen.

Electronic image amplifiers compensate for the brightness limitations of fluoroscopy and permit viewing from a distance. In presently available commercial form, the X-ray image impinges upon a suitable fluorescing screen, in contact with a photoelectric emitting surface. The photoelectron image is electrostatically intensified and focused upon a smaller diameter fluorescent image screen (Fig. 18). Even after optical enlargement to the full size of the original image, the intensified image conveys more useful information under more suitable viewing conditions than the original image viewed upon a conventional fluoroscopic screen. Conventional industrial television systems have been used in connection with electrostatic image amplifiers and other X-ray image reproduction systems.

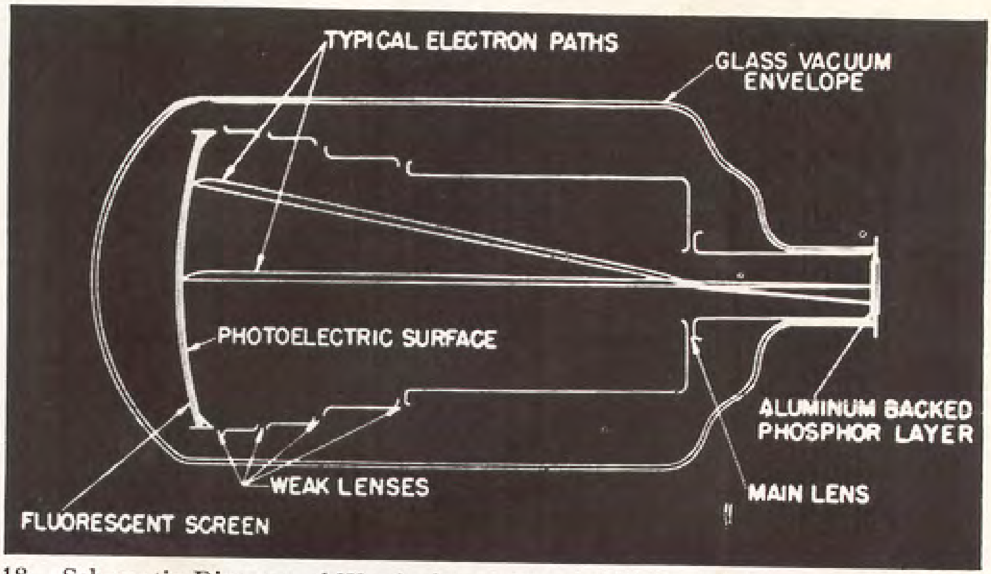
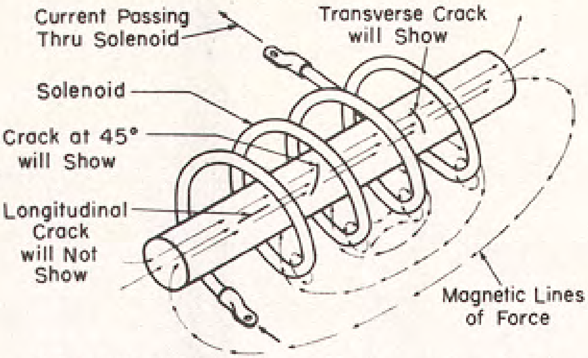
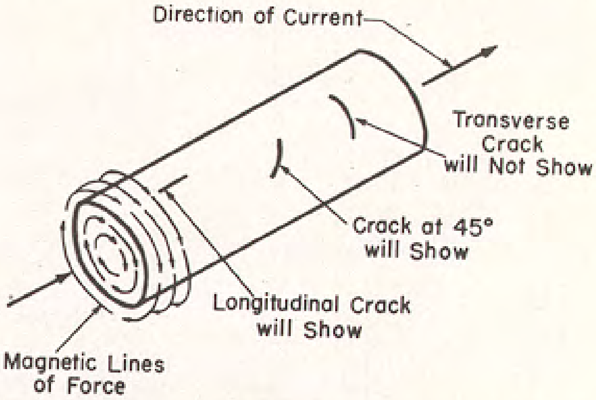


Fig. 18.—Schematic Diagram of Westinghouse Fluorex (Coltman) Electrostatic Brightness Amplifier for Fluoroscopic X-ray Images. (Courtesy Westinghouse X-ray Div., Baltimore, Md.)

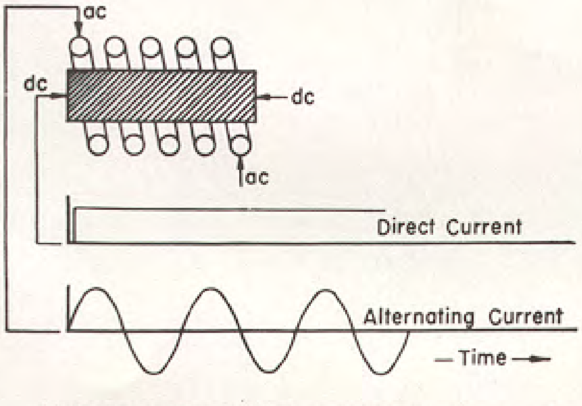
Ionization gages and Geiger counters detect X-rays because of the abilities of penetrating radiation to ionize air and other gases. The ions produced during irradiation of detection chambers produce electrical signals suitable for revealing the intensity of irradiation at the detector locations. Such devices find application in X-ray gaging and radiation monitoring, but because of their relatively large size (as compared with the resolution of X-ray films) are seldom suitable for revealing the detail in X-ray images. The combination of fluorescent screens or phosphors with electronic photomultiplier tubes have provided altenative systems with sensitivities and applications comparable to those developed with ionization gages and counters.



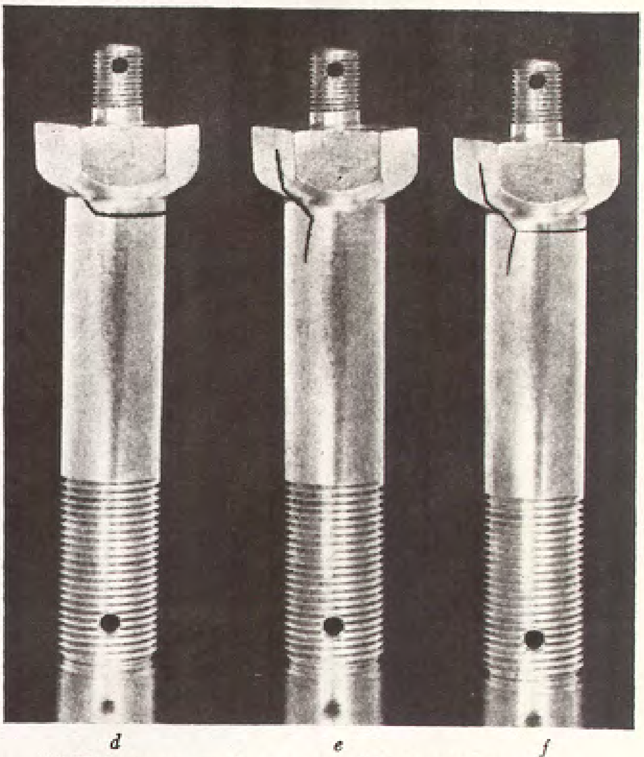
(*a*) Longitudinal magnetization by passing current through solenoid surrounding test object in magnetic-praticle inspection.



(*b*) Circular magnetization by passing current through test object in magnetic-particle inspection.



(*c*) Combined longitudinal magnetization (by a-c solenoid) and circular magnetization (by d-c through test object) or complete magnetic-particle inspection. (Duovec Magnetization using Coil and Circular Magnetization.)



(*d*) Transverse crack as revealed by longitudinal magnetization.

(*e*) Longitudinal crack as revealed by circular magnetization.

(*f*) Complete crack pattern in same test object as revealed by combined longitudinal and circular magnetization.

FIG. 19.—Methods of Magnetization and Defects Revealed in Magnuflux Magnetic-Particle Inspection of Aircraft Part. (Courtesy Magnaflux Corp., Chicago, Ill.)

Scintillations in crystals and fluorescent liquids, in combination with photoelectric detectors such as the photomultiplier tube, have provided X-ray counters and intensity gages suitable for certain applications. And *semiconductor* elements, such as the cadmium sulfide detector, take advantage of the ability of X-rays to modify their electrical resistivity, to provide electrical signals corresponding to X-ray intensity. Their relatively smaller size than the other counters and gages permits better resolution of X-ray image intensity distributions, but they do not yet match films and screens in definition of image.

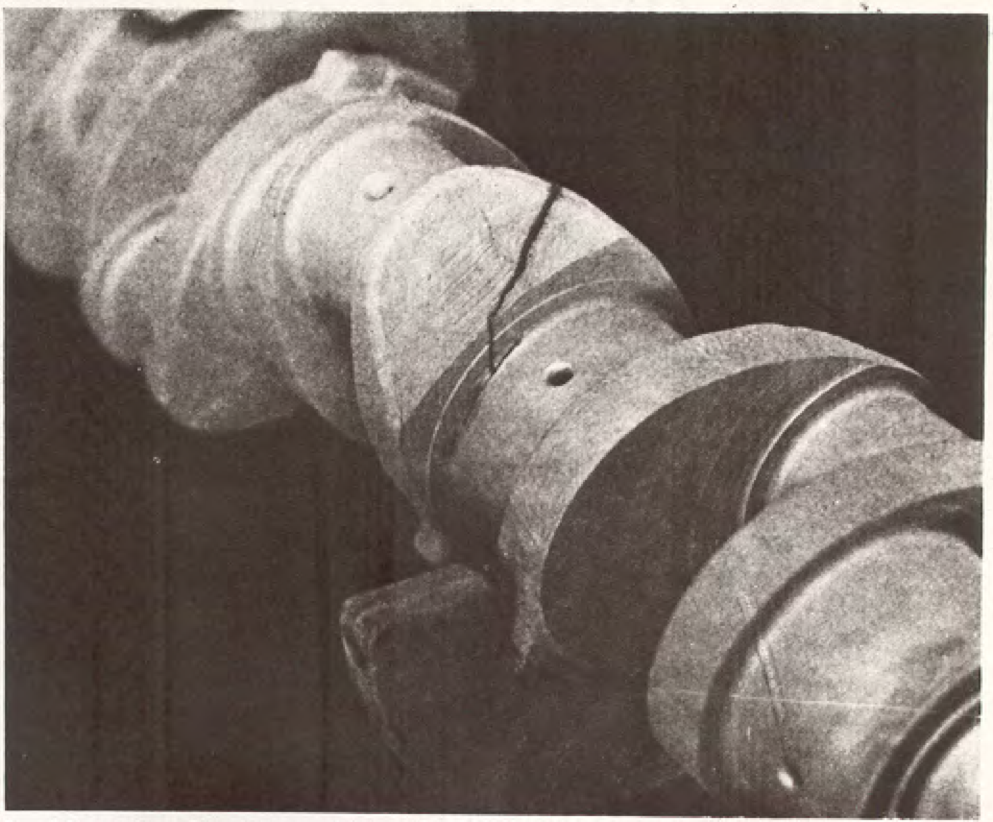
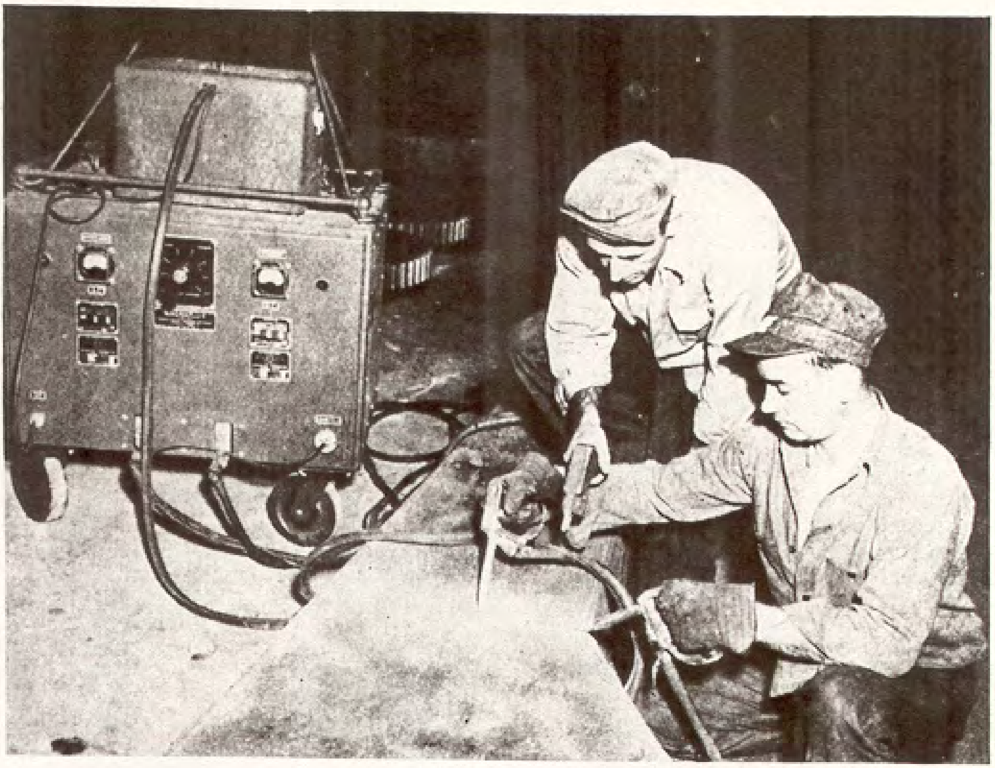


FIG. 20.—Magnaflux Dry Magnetic-Particle Indication of Crack in Crankshaft. (Courtesy Ferro-Spec Laboratories, Los Angeles, Calif.)

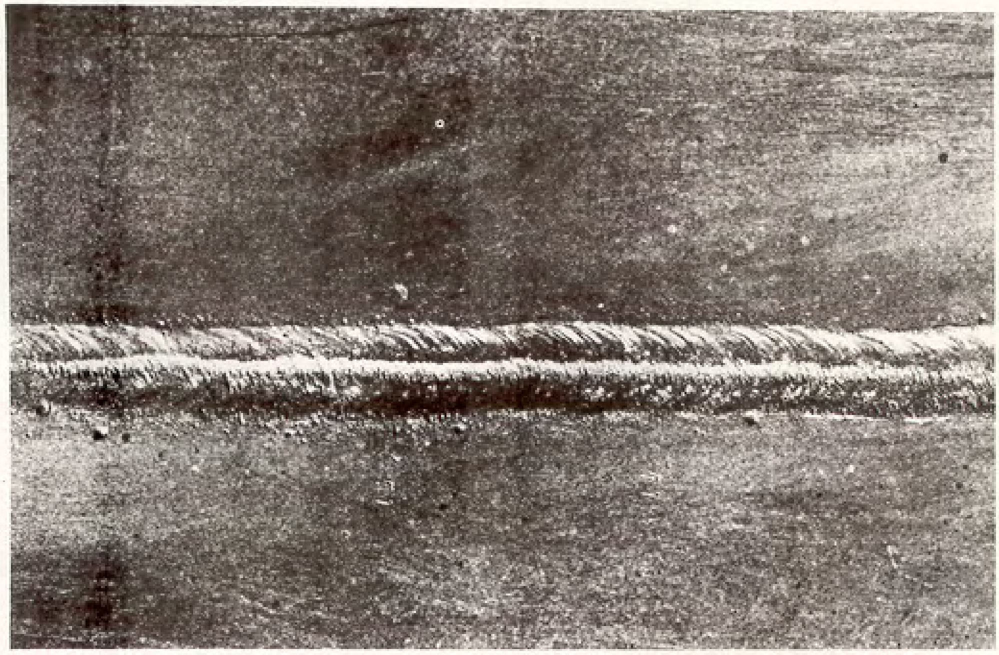
Magnetic Particle and Other Static Magnetic Field Tests:

Test methods in which magnetic fields are used as the medium with which to probe the test object (and not the associated effects such as electromagnetic induction or flow of electrical currents) are classified as magnetic field tests. Static magnetic field tests are generally limited in application to ferromagnetic materials, such as iron or steel, whose magnetic permeability varies greatly from that of air or vacuum. The probing magnetic field used in the test may be measured in terms of several different properties, including permeability, remanence, coercive force, flux density, residual flux, leakage flux, and stored magnetic energy. However, since it would be difficult to introduce probes within most test objects, most practical detectors operate in the magnetic leakage field just outside the surface of the test object.

The test objects may be magnetized by placing them within solenoids carrying electrical currents, by passing electrical currents through the material of the test object, by placing the object between the poles of externally excited magnetizing yokes, and by combinations of these methods. The method of magnetization must be selected so as to establish lines of magnetic flux transverse to the possible direction of discontinuities in the test object, if these are to be revealed (Fig. 19). For surface inspection,



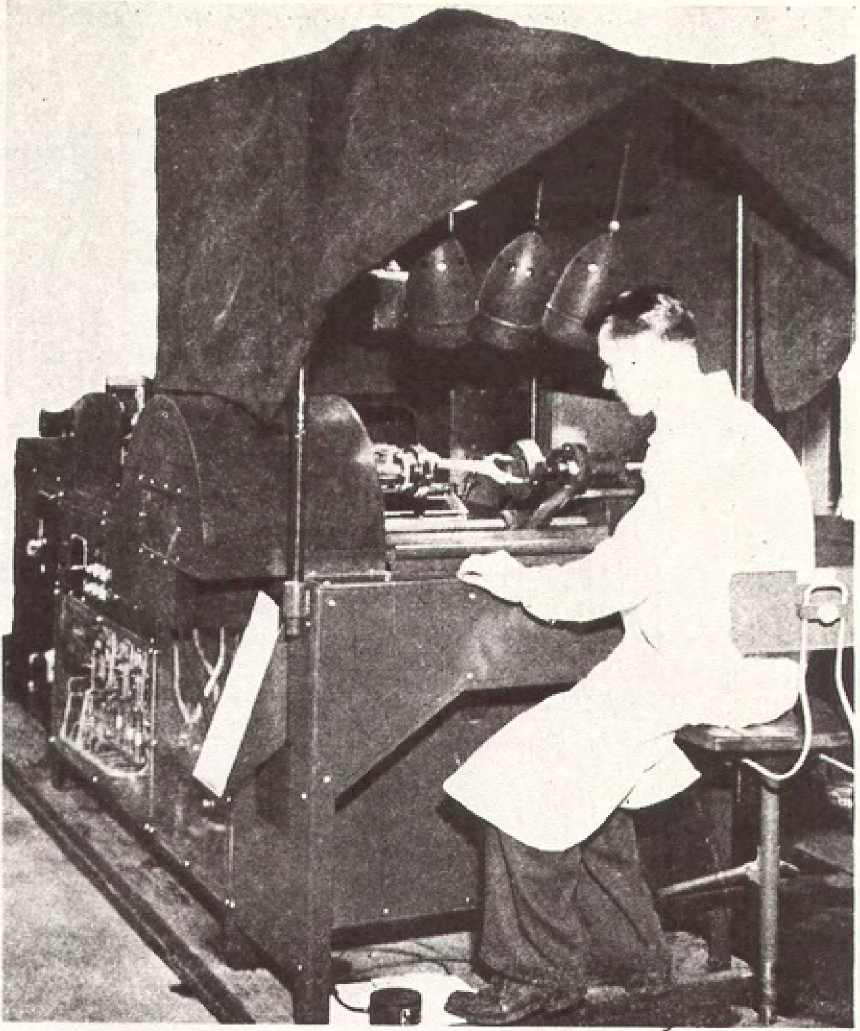
(*a*) Inspection.



(*b*) Indications of subsurface defect in fusion weld.

FIG. 21.—Magnetic-Particle Inspection of Welds in Fabricated Steel Structural Member. (Courtesy Magnaflux Corp., Chicago, Ill.)

alternating-current excitation may suffice, but for detection of discontinuities below the surface, direct current, d-c surge, rectified half-wave a-c, and similar magnetization methods may be preferable because of the "skin effects" which limit the penetration of rapidly varying magnetic fields.



(*a*) Automatic Magnaflux handling and magnetizing equipment.

(*b*) Magnaglo fluorescent wet magnetic-particle indications of defects.

Fig. 22.—Magnaglo Wet Fluorescent Magnetic-Particle Inspection of Connecting Rods. (Courtesy Magnaflux Corp., Chicago, Ill.)

The most widely useful and sensitive method of detection of discontinuities in magnetic field inspection is by means of the *magnetic particle* (*Magnaflux*) method. These finely divided, lubricated, ferromagnetic particles tend to align themselves on the surface of the test object over discontinuities which produce surface leakage magnetic fields (Fig. 20). Their distinctive colors, or fluorescent coatings reveal their indications clearly and show the location, shape, and extent of the discontinuities with remarkable sensitivity. For rough castings, welds, and some field-inspection applications, dry magnetic powders may be applied with an air gun or other applicator, for optimum resolution of surface and subsurface defects (Fig. 21). For production inspection of finished machined parts, suspensions of the indicator particles in suitable liquid media provide an optimum means of application and greatest sensitivity of indications. Automatic machines for handling and magnetizing the parts, applying the magnetic particle indicators, and displaying the parts for inspection have been developed for large production applications (Fig. 22). Today the magnetic-particle inspection method exceeds by far, in number of installations, the number of X-ray units in service. It finds application in production inspection of machined parts for automotive, aircraft, railroad, and many other industries; for field inspection of welds and castings, pipe lines, oil well drill pipe and sucker rods; for service inspections for fatigue and other fractures in the railroad, petroleum, air transportation, and many other fields.

Other methods of detection of magnetic field discontinuities include *induction pickup coils*, whose relative motion through the leakage magnetic field induces varying flux conditions within coils having many turns. These electromotive force signals are electronically amplified and actuate visual or auditory indicators or produce graphic records. *Permeance pickup* methods include methods in which a permeable core material in the pickup coil is magnetized by the leakage magnetic field, changing the impedance of the pickup coil to alternating-current excitation from an external source. Such permeance methods have found applications in gaging the thickness of coatings over magnetic base materials. Signals from electrical detection coils have been successfully applied in the facsimile recording of the magnetic discontinuities revealed on the internal surface of gun tubes and other special applications.

Electrified-Particle and Other Electrostatic Field Tests:

A static electric field is used as the medium with which to probe the test object, in electric field tests. Since it is generally impossible to establish significant electric field gradients in metallic conducting materials (in the absence of heavy electric currents), such tests are suited generally only to dielectric or insulating materials. They find particular application in the evaluation of electrical insulating materials, glass, ceramics, porcelain enamels, and other nonmetallic materials. The electric field patterns and discontinuities may be revealed by the use of electrified particles or electrometers, or by electric circuit measurements of the dielectric properties or breakdown of the test object.

The dielectric materials under test may be subjected to electric fields by spraying their surfaces with electrostatically charged particles, by placing them between electrodes connected to external sources of electrical potential, or by inserting them in high-voltage, low-current circuits suitable for measurement of charging or leakage currents. The latter methods are widely used in conventional tests of high-voltage electric power equipment. The former method has found wide application possibilities in the ceramic industry, in examination for cracks in glass, ceramics, and glazes or ceramic coatings.

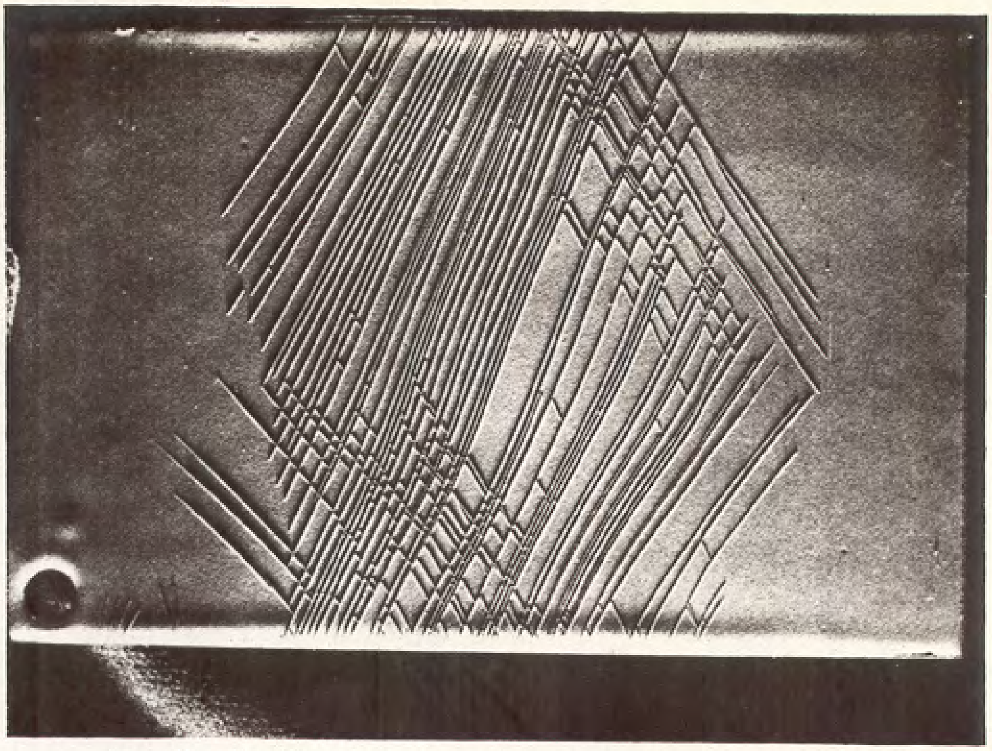


FIG. 23.—Statiflux Indications of Cracks in Porcelain Enamel.
(Note that cracks occur perpendicular to direction of stress. The secondary stress cracks do not cross the original stress. This determined the sequence in which failure stresses were applied.) (Courtesy Magnaflux Corp., Chicago, Ill.)

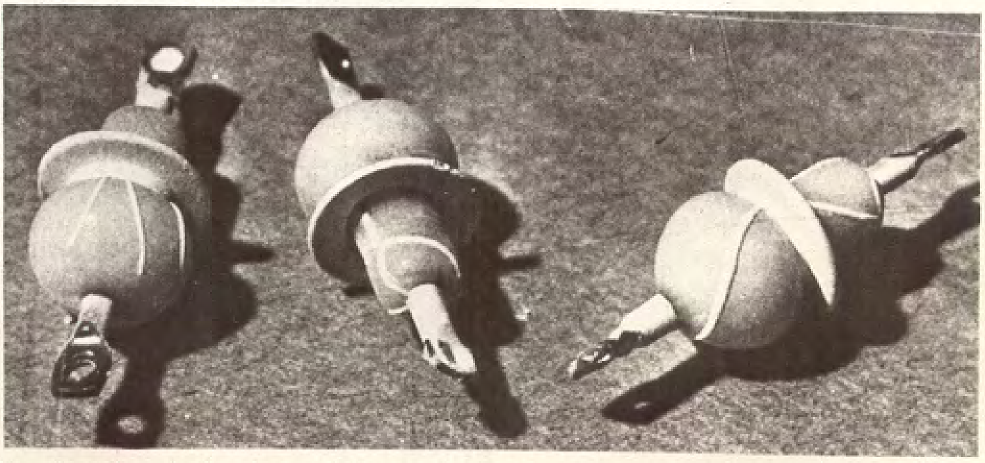


FIG. 24.—Statiflux Indications of Cracks in Typical Glass-to-Metal Bushings (about $\frac{1}{2}$-in. in length) Used in Electronic Equipment. (Seals cracked by improper soldering procedures.) (Courtesy Magnaflux Corp., Chicago, Ill.)

The most sensitive and useful method of detecting local discontinuities caused by cracks in dielectric materials and coatings is the use of electrified calcium carbonate particles charged by triboelectrification when sprayed through rubber nozzles in an air gun ("Statiflux"). These finely-divided electrified particles have high mobility and great sensitivity to local surface field conditions and to the presence of sources of electrons. Such sources of electrons may be provided from the base metallic materials in porcelain-coated sheets, or by use of a liquid penetrant in cracks in ceramic or dielectric materials such as glass. These electrified particles collect over the dielectric discontinuities very much as the magnetic particles collect over cracks and discontinuities in ferromagnetic materials. The technique is so sensitive that fine cracks, invisible to the eye, may be revealed by remarkably high build-ups of the electrified-powder indicator (Fig. 23). In addition to the detection of cracks in ceramic materials, this method finds an extremely useful application in the examination of parts such as electrical bushings, where it reveals defects not detectable by other electrical test methods (Fig. 24).

NONDESTRUCTIVE TEST METHODS BASED PRIMARILY UPON TRANSPORT OF MATTER AS THE PROBING MEDIUM

All movements of matter involve some energy transfer, if only to supply the frictional losses of such motion. However, in many nondestructive test methods whose probing medium is transport of matter, the energy requirements are negligible (Table VI). No special external power sources are required in these tests.

TABLE VI.—TYPICAL NONDESTRUCTIVE TEST METHODS BASED PRIMARILY UPON TRANSPORT OF MATTER.

Test Method	Form of Matter Used as Medium	Mechanism of Detection of Material Properties and Discontinuities	Forms of External Test Indications
Mechanical Calipering and other dimensional gaging tests of exposed surfaces of test objects.	Solid steel or alloy probes, electric contacts, energy fields, etc.	Movement stops upon contact with surface of test object, or electrical contact, valve effect, etc.	Caliper setting, micrometer reading, visual examination of spacing, "Go" or "No Go" feel of probe, electrical indications, air pressure indications, etc.
Leak test with fluid under pressure	Water, oil, dyes, liquids, (with low viscosities and surface tensions), radioactive liquids, halogens, air, helium, natural gas, hydrogen, steam, halogen vapors, radioactive gases, etc.	Fluid penetrates discontinuities in walls of test object, under hydrostatic pressure, is detectable at an accessible surface	Visible jets or wetting, attraction and binding of powders with good visibility, fluorescence under ultraviolet light, etc., radioactive indications, positive ion detection, bubbles forming in immersion liquid, mass spectroscope indications, radioactive emanations detected, halogen vapor detected by positive ions, etc.
Penetration or leak test with low surface tension liquids	Kerosine, oils, water, with wetting agents, etc.	Fluid penetrates discontinuities open to exposed surface of test object	After surface cleaning, trapped liquid penetrants seep out and spread over surface near defects, with visible wetting, attraction of powder pigments, fluorescence, radioactive emanations, evaporation, positive ion detection of halogens, etc.
Penetration test with low surface tension liquids carrying solid particles in suspensions	Kerosine, oils, water with wetting agents, etc., with solid particles in suspension	Fluid penetrates discontinuities, filtering particles of solids out on surface at defects	Filtered particles on surface visible, or fluorescing under ultraviolet light, radioactive emanations, etc.
Brittle lacquer tests	Brittle lacquer	Elongation of base material cracks lacquer bonded to surface	Cracks (often dyed) in brittle lacquer coating

Such tests as depend primarily upon transport of matter for their probing medium have one basic limitation in common. In the gross sense, two kinds of matter, or two bodies, cannot occupy exactly the same space at the same time. Water will not pass through solid steel walls which have no openings or passageways. The rate of transport of gases through solid, nonporous bodies is almost infinitely slower than in free space. For these reasons, nondestructive tests based primarily upon transport of matter are only suitable, in general, for inspection of accessible surfaces of test objects.

There must exist open space, or a passageway, for the probing medium to reach the surfaces to be inspected. In general, the probing medium will not penetrate beyond these surfaces. It stops its advance when it contacts the solid material of the test object. It may, of course, advance through any cracks, channels, or passageways into the material of the test object—but only so far as those openings extend. This behavior is quite unlike that of penetrating radiations, such as X-rays. And it differs considerably from that of high-energy particles, such as neutrons, or of ultrasonic mechanical vibrations, which can penetrate deeply into materials.

Tests dependent primarily upon transport of matter for their probing medium are of three general classes. The first class is that in which solid probes are used to detect the surface of the test objects, as in *mechanical calipering and gaging*. The second involves the use of fluids, usually under externally applied static pressure, in *pressure and leak tests*. The third involves the use of liquids, usually acting only under surface tension and capillary forces, in *liquid-penetrant testing*. In most nondestructive tests, these media apply negligible stress to the test objects. However, in a special class of *proof tests*, the solid, liquid, or gaseous medium applies *stress to the test object*. These stresses are assumed to be harmless to good test objects. They are expected, however, to reveal defective test objects or materials by causing them to distort or fail under the proof stress. Each of these general types of tests is discussed in more detail in the balance of this section of the paper.

Mechanical Caliper or Other Dimensional Gaging Tests:

Mechanical calipering or gaging tests are characterized by measurements through probing media of the dimensions or position of surfaces of test objects. Ordinary manual calipering or gaging instruments and operations are typical, but devices which carry out such measurements by other means or included also. In most cases, the method involves a means of detecting dimensional differences quickly and sensitively, often with automatic indication or sorting of acceptable and rejectable articles.

Just as nondestructive tests based on transmission of luminous energy are an extension of the human sense and skill of *seeing*, so mechanical calipering or gaging tests are an extension of the human sense of *touch or feeling*. In fact, a skilled inspector can often do a remarkably good job of estimating surface finish by touching the object with his fingers. A mechanic with a highly developed sense of "feel" can readily detect a difference in contact by dimensional changes as small as 0.00025 in. Many mechanical gaging instruments, such as "Go-No Go" gages, depend upon the operator to detect by feel the reaction of the test object upon the gage. More elaborate and more precise instruments require the use of the observer's eye to read vernier scales or indicators. Modern instruments of great sensitivity or precision often resort to all the basic principles of nondestructive testing, and use electrical contacts, magnetic field detection, capacitance micrometers, penetrating radiations or particles, flow of liquid or gaseous matter, or other techniques to sense and transmit information in mechanical gaging. Thus, sensitive automatic calipering or gaging most often becomes a true nondestructive testing method, independent of the operator's sensory sensitivity or skills. And like nondestructive tests for other material properties, many modern sensitive gages use electronic circuits to amplify, compare, and evaluate the gage measurements.

A large complement of simple *mechanical comparison gages* exists and is well known to every production engineer, mechanic, and tool room attendant. These include linear rules and scales, angle protractors, dividers, calipers with and without vernier adjustments, radius gages, surface gages, and so on. Many precision gages and calipers are complete with mechanical amplification of the settings, in the form of micrometers and verniers. For repetitive measurements of the same dimensions in production, fixed plug, ring, snap, and other forms of gages exist. Precision gage blocks are available to check these fixed gages. Dual fixed gages, set to the upper and lower tolerance limits in production, often serve as "Go-No Go" gages in industrial quality control measurements. More elaborate mechanical displacement amplifiers, in the forms of rack and pinion units and trains of gears, are used in precision dial gages and indicators. Thread gages of various types measure the numerous critical parameters of threaded connections, often by ease of fit or by tolerance limits. These types of mechanical gages are well described in the literature and are well known in industry, so no further discussion of them will be included here.

FIG. 25.—Carson Electrical Micrometer for Precision Thickness and Displacement Dimensional Gaging. (Courtesy J. W. Dice Co., Englewood, N. J.)

Each of the simple mechanical gages mentioned above detects contact between the gaging pickup and the test object by the mechanical force or pressure exerted by each upon the other. This is not essential in mechanical gaging. Other methods can sense mechanical contact without the application of sensible force. In cases where it is essential to gage the dimensions of hollow objects with very thin, flexible walls, such as altimeter capsules, it is undesirable to exert any significant force whatsoever upon the test object.

The *electrical micrometer* (Fig. 25) was devised for just this type of measurement, but it has proved its value in many other precision measurements. Contact between the micrometer spindle and the test object surface is detected by means of the flow of a minute electric current across the closed contact. With this device, measurements may be reproduced to a few microinches—an improvement of the order of ten times or so over conventional micrometers depending upon force as a response to contact.

An intermediate approach to this principle is applied in several other mechanical gages. For example, the use of microswitches, which may be actuated with very light mechanical forces, as limit switches in many industrial electromechanical devices is typical. In these applications, an intermediate mechanical lever or amplifier detects contact with the test object by pressure and is bent or displaced to open a sensitive electrical contact operating in a similar low-voltage, low-current electronic detector circuit.

Several modern gages and comparators use a highly accurate "reed" mechanism as the contact-sensing member. When the floating spindle of the gage is moved by contact with the test object, the reed is caused to bend. The bending movement is amplified through extension arms to break an electric circuit which controls signal lights or other indicators.

The *capacitance micrometer method* permits gaging without physical contact with the test object. This is basically an electric field nondestructive test method. It takes advantage of the fact that the electrical capacitance between separated conductors is an inverse function of the distance between them. Indications of microinch sensitivity have been obtained on laboratory instruments based on this principle.

An analogous principle, using a form of magnetic field nondestructive testing, has been applied in various forms of the *inductance micrometer*. With ferromagnetic test objects, the surface of the test object may be used as the movable armature of a magnetic circuit with variable air gaps. Since the inductance of coils wound upon such a variable reluctance magnetic core varies rapidly with air gap spacing, this method also provides a very sensitive test. It has been applied, for example, in commercial instruments designed to measure the thickness of nonmagnetic coatings on ferromagnetic base materials, or the thickness of magnetic coatings on nonmagnetic bases.

The *linear differential transformer* provides an electromagnetic induction nondestructive test method applicable to mechanical gaging. The microformer consists of a small, movable iron core sliding within a cylinder upon which are wound three coils. The central coil is excited with alternating current from an oscillator. It serves as the primary of a transformer. The two identical outer coils serve as balanced secondary windings. These are connected in series opposition. As the iron core moves from its central reference position, the voltage induced in one secondary coil is increased, while that in the other decreases. The net output signal, of the order of 6 microvolts per microinch displacement, may be readily amplified to provide a large output proportional to the displacement of the iron core. Since the cores are exceedingly small (in microformers designed for small displacements), they may touch the surface of the test object while exerting negligible force. A large number of commercial instruments and servomechanisms now employ such linear differential transformers to detect mechanical displacements with great sensitivity and reproducibility.

Another gage consists of a *vacuum tube* whose output current is controlled by means of a *movable control grid*. The movable control grid, as it approaches the cathode, controls the flow of electrons, just as varying voltages applied to the grid circuits control the plate current in conventional electronic amplifiers. In this way, mechanical displacements are converted into electronic signals.

The electrical *wire resistance strain gage* provides another means of converting mechanical displacements into electrical signals. The commercial strain gage has a gage constant of about 2.0; that is, the fractional change in electrical resistance is twice as large as the fractional change in length which produced it. Two such gages mounted on a flexible member responding to displacement of the surface of the test object provide one arm of a Wheatstone bridge. The balance of the Wheatstone bridge, the source oscillator, and electronic amplifiers can be located in a separate unit. Measurements to microinch sensitivities are feasible with this method.

An alternative method uses *unbonded wire resistance strain gages*. Here the resistance wires extend between pegs, one set of which is fixed and the other set of which moves with the surface of the test object. This method has been applied in the aircraft industry for rapid elongation measurements.

The operation of a *magnetic field gage* designed to measure the thickness of nickel coatings on nonmagnetic base materials, or of nonmagnetic coatings on iron or steel, is based upon the magnetic attraction of a small permanent magnet to the coating material being measured or its backing. With annealed nickel coatings, the attractive force between the bar magnet and the nickel coating is practically linearly proportional to the thickness of the coating.

Nonmagnetic coatings on iron or steel interpose the equivalent of an air gap between the permanent magnet and the ferromagnetic base material. The greater the thickness of this intervening layer, the less the attractive force on the magnet.

The operation of *electromagnetic induction micrometers* for measuring the thickness of insulating coatings on conducting nonmagnetic base materials is based upon the electromagnetic inductance effect which the covered base metal has on the probe coil. The oscillating current flowing in the inductor probe induces eddy currents in the base metal. The intensity of these eddy currents varies with the distance between the probe coil and the base metal. The closer the probe to the conducting base metal, the greater the eddy current intensity. The test object serves as a short-circuited secondary of a transformer, of which the probe coil is the primary winding. The eddy currents produce a change in the effective inductance of the probe coil. This causes a change in the frequency of the oscillator to which the probe is connected.

Two other methods of detecting mechanical displacements have received little recognition in mechanical gaging, since both are primarily suited to dynamic, rather than to static, measurements. The first is the *piezoelectric pickup*, such as is commonly used in phonograph pickups. This type of pickup is used in surface-roughness-measuring instruments. Piezoelectric bimorphs of high sensitivity have been developed; under suitable conditions, these might be modified to serve in gaging. The second is the *magnetostrictive pickup* which, to date, has primarily been used only in sonar (underwater sound ranging and detection) reception. Nickel, which is negatively magnetostrictive, contracts when magnetized by passing an electric current through a magnetizing coil surrounding it. If it is stressed so as to change its length, it induces an emf in its magnetizing coil. Thus, it could be used to record mechanical displacements as well.

One other basic principle of nondestructive testing has been well developed for mechanical gaging. It depends upon the flow of a fluid as its medium of detecting the location of the surface of the test object. For example, *air gages* are quite simple. Air under a low pressure head is allowed to escape through an orifice. The orifice is actually the space between the gaging head and the surface of the test object. The rate of escape of air is a measure of this distance. The rate of air escape is metered with another orifice associated with the air supply unit. The pressure drop across this metering orifice may be measured with a water manometer. The air gage provides remarkable sensitivity and amplification of the displacement between the gage head and the work surface. It measures the actual dimensional variations with precision adequate for narrow tolerance production. Measurements can be carried out continuously over a surface, such as the inside or outside diameters or tubes or shafts.

A unique *vacuum cup gage* was used to measure sheet thicknesses and the strength of bonding of thin sheets to base materials. The cup was placed over the sheet, and partial vacuum drawn within the cup. The deflection of the sheet was detected with a sensitive dial indicator.

Nearly all of the preceding nondestructive gaging methods could be applied to the simultaneous gaging of many different dimensions of test objects. The same methods of multiple gaging may be applied in succession to test objects of the same series, to sort and classify parts by dimensional groups. In addition to classifying the useful units into dimensional classes, the out-of-tolerance units can be automatically rejected by such devices.

Fluid Pressure and Leak Tests:

Pressure and leak tests employ fluids under pressure to apply proof stress to test objects or to reveal defects and discontinuities by the flow of fluids through them. Hydrostatic proof tests may be nondestructive of acceptable test objects, even though defective units may fail under their applied stresses. Leaks through container walls may produce visible indications, loss of pressure, or other identifying indications, such as gas bubbles visible when the object is immersed in water during gas pressure tests.

Hydrostatic *proof* tests are commonly applied to pressure vessels and seam-welded pipe for high-pressure gas lines at the time of their fabrication. More recently, entire sections of high-pressure gas lines between valves or compressor stations have been subjected to similar hydrostatic pressure tests after installation, prior to use in service, to avoid the disastrous explosions which can result when such pipe lines fail in service. In addition to proof testing, pipes have also been tested by filling them with compressed air under pressure and observing any decreases in pressure resulting from leaks.

Pressure *leak* tests have found many applications and new detection methods have been developed. It is common practice to immerse pressure containers under water and fill them with gas or air under pressure, so that leaks can be detected by observing if bubbles of gas escape. Viscous fluids, such as soap solutions, are employed where the escaping gas produces bubbles in the surface films. Fluorescent liquids, similar to those used in fluorescent-penetrant tests, may be used with smaller objects as the fluid for hydrostatic-pressure leak tests. The brilliant fluorescence of such fluids, leaking through the container walls, makes inspection with ultraviolet light sources rapid and reliable (Fig. 26). The use of helium gas and mass-spectrometer leak detectors has greatly increased the sensitivity of many gaseous leak tests. With halogen compounds, as in refrigerator systems, leaks may be detected most sensitively with the positive ion detector.

Liquid-Penetrant Tests:

Liquid-penetrant inspection of the surfaces of test objects depends for its operation upon the mass transport of the penetrating liquid into the defects and discontinuities open to the surface. The penetrating liquids are initially applied to the objects by dipping, rinsing, spraying, or brushing. The liquids are left on the surface of the object for a period of time sufficient for them to penetrate all surface defects to which a passageway exists. The remaining penetrant is then cleaned from the exposed surface of the object, and the object is usually dried. It then is allowed to stand until that penetrant trapped within the defects and surface discontinuities has a chance to leak out. The indications produced by surface wetting near these defects are developed by various means to expose them clearly to the inspector.

The *oil-and-whiting* inspection method is the oldest of the penetrant methods in common industrial use. The addition of visible dyes has increased the visibility of its indications. The method is highly sensitive when applied carefully by skilled operators. The materials for *dye-penetrant inspection* are now commercially available in sealed spray cans. Four basic materials are supplied, as follows:

1. A liquid solvent, used as a pre-cleaner, where grease or other dirt obscures the surface.

2. A red liquid penetrant to be sprayed, brushed, or dipped onto the surface, at a temperature over 60 F. Because of its high penetrating power, the liquid is drawn or dissolves its way into even fine defects. It is allowed to remain on the surface of the test object long enough to enter the finest cracks expected.

3. A water-miscible liquid-remover solvent which aids the wiping action in removing surface penetrant. For rough sand-cast or welded parts, the cleaner of step 1 may be used to facilitate wiping the surface clean.

4. A developer consisting of a volatile liquid suspension which dried to form a light powdery coating.

The developer serves three functions:

(*a*) It draws the penetrant out of defects onto the cleaned surface of the part by solvent and blotting action.

(*b*) It masks out slight traces of surface

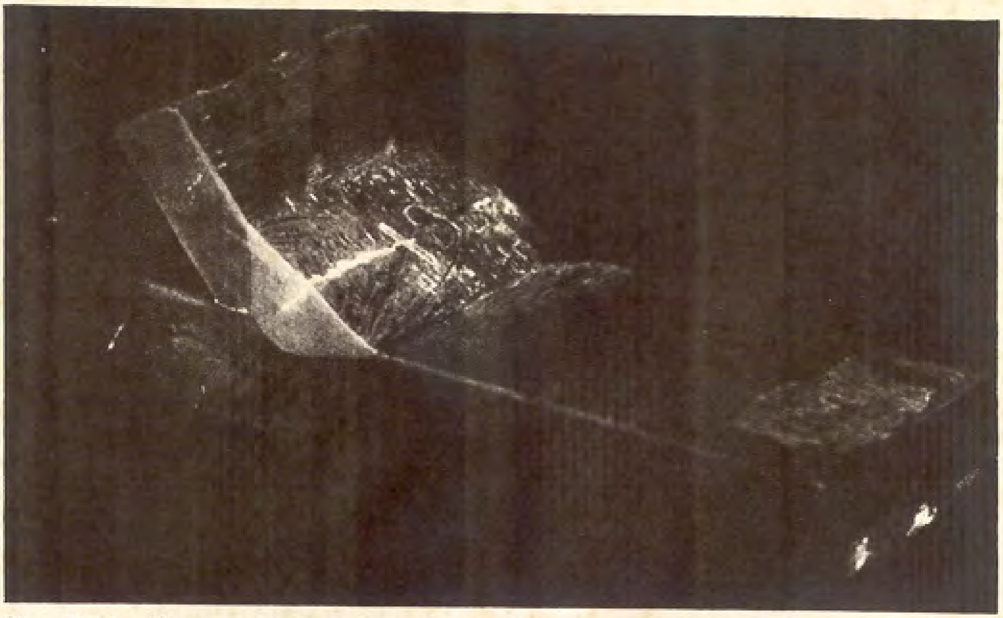


FIG. 26.—Zyglo Fluorescent-Penetrant Indication of Crack in Stainless Steel Weld Bead, Illuminated with Ultraviolet "Black" Light. (Courtesy Magnaflux Corp., Chicago, Ill.)

penetrant that may not have been removed completely.

(*c*) It serves to provide high color contrast between its white background and the bright red defect indications.

The dye-penetrant inspection method may be applied to locate defects open to the surface on many different materials, such as aluminum, magnesium, brass, cast iron, steel, stainless steel, carbides, stellite, plastics, and so on. It is suitable for indicating surface cracks (such as shrinkage cracks, grinding and heat-treatment cracks, fatigue cracks, and forging bursts), defects (such as seams and laps, cold shuts, and lack of bond between joined metals), surface porosity (such as shrinkage porosity or gas porosity in machined castings), and through leaks (in welds and other portions of container walls). The dye penetrants provide an easy through-leak test for walls up to about ¼ in. thick. The penetrant is sprayed on one side of the wall and allowed to be drawn through the leaks by capillary force. No pressure is required. After the penetrant has soaked through, the opposite face of the wall is inspected by applying the developer. Leaks show as bright red spots on the inspected side. The normal penetration rate in leak testing is very rapid. Coarse porosity in the leakage path provides little capillary force and slows penetration. Prior water or moist-air tests must be avoided, since trapped moisture in the leaks plugs fine passages, stopping the penetrant.

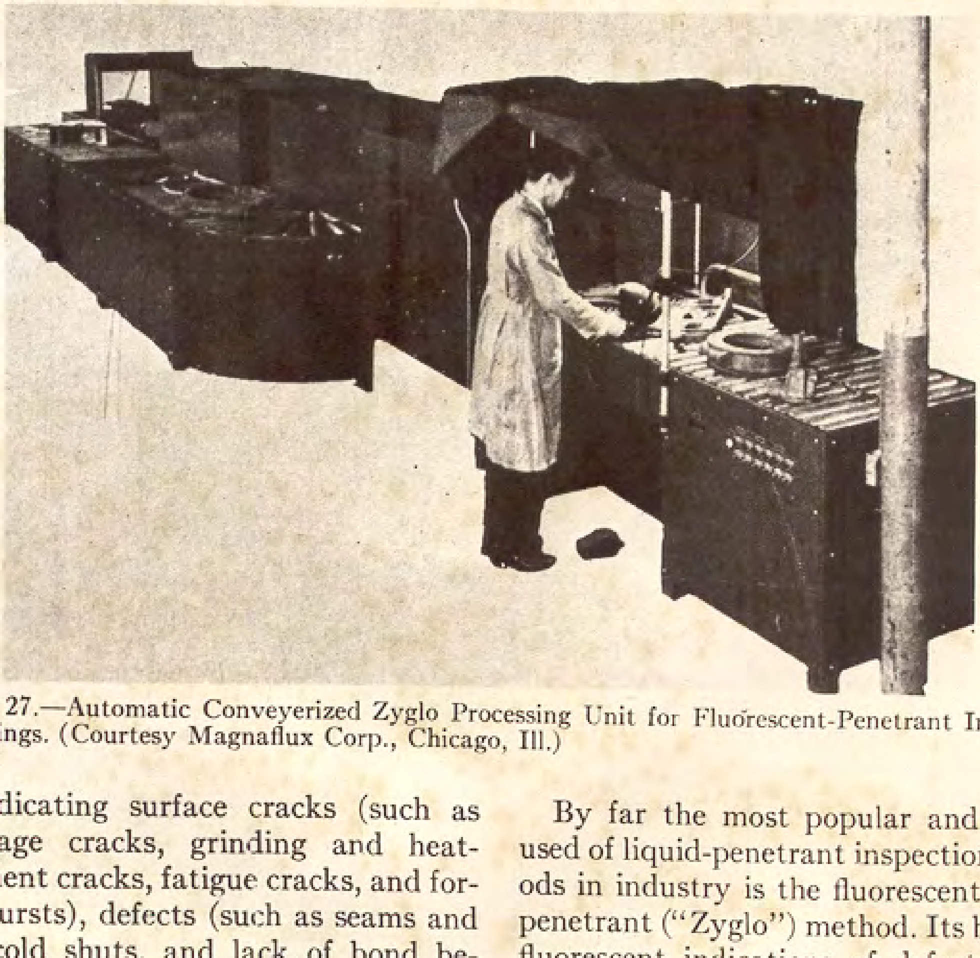
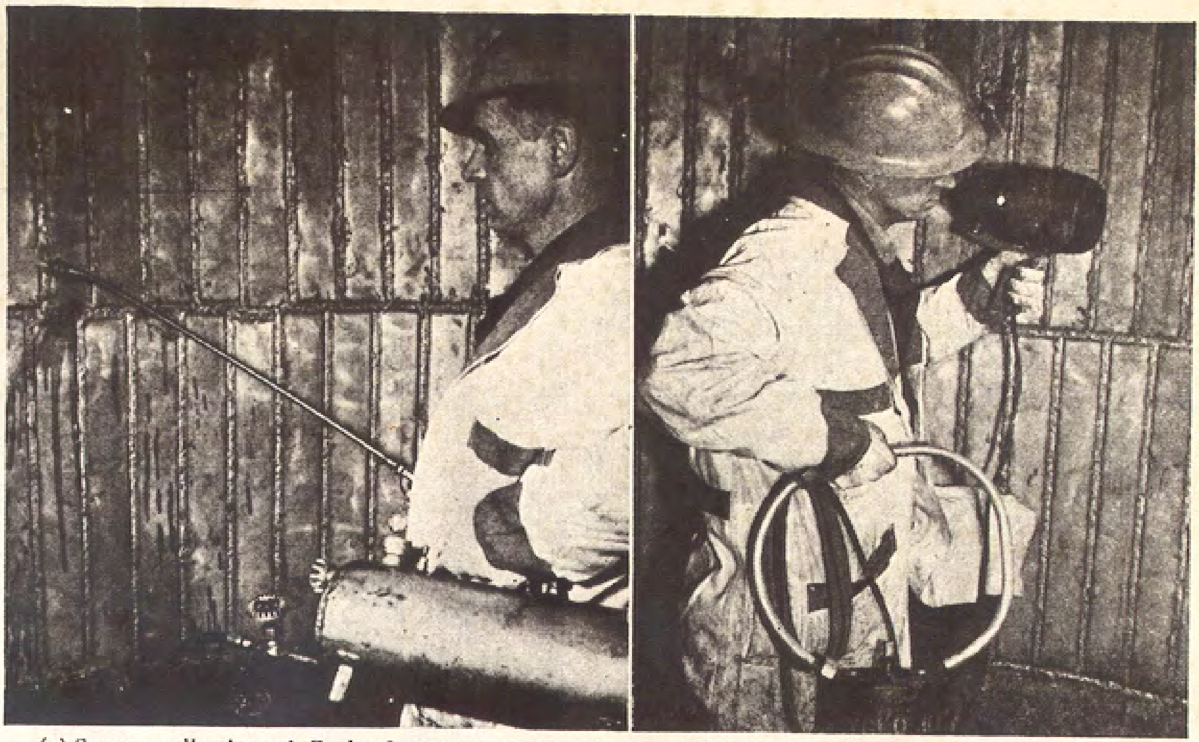


Fig. 27.—Automatic Conveyerized Zyglo Processing Unit for Fluorescent-Penetrant Inspection of Castings. (Courtesy Magnaflux Corp., Chicago, Ill.)

By far the most popular and widely used of liquid-penetrant inspection methods in industry is the fluorescent liquid-penetrant ("Zyglo") method. Its brilliant fluorescent indications of defects stand out under ultraviolet light with contrast not attainable with dye colors in ordinary white-light illumination (Fig. 26). In consequence, even minute defects are extremely clear and prominently visible. These high-contrast indications speed up inspection and increase the reliability of inspection, since it would be difficult to fail to see the fluorescent indications.

Completely mechanized equipment



(*a*) Spray application of Zyglo fluorescent penetrant to welded liner in storage tank.

(*b*) "Black light" examination of Zyglo indications in welded structure.

(*c*) Detail of Zyglo fluorescent-penetrant surface indications in welds.

FIG. 28.—Zyglo Fluorescent-Penetrant Method of Inspection. (Courtesy Magnaflux Corp., Chicago, Ill.)

exists (Fig. 27) for carrying out the basic steps in fluorescent-penetrant inspection. The penetrant is usually applied simply by dipping the parts (in a suitable basket) into the liquid penetrant. Larger parts may be handled by brushing or spraying (Fig. 28 (*a*)).

Since the fluorescent penetrant is water-washable, rinsing is done simply, either manually or automatically, by spraying water over the parts in a rinse tank. The use of water makes this step much less critical than the solvent cleaning used in most dye-penetrant methods, since the water does not tend to remove the penetrant from the true defects. Parts are next dried by hot-air oven or blower, or manually by wiping. Developing may be carried out either by wet or dry methods. In the *wet method*, the parts are dipped into a colloidal water suspension of a special developer, and then placed in a drier. A uniform layer is deposited on the surface of the part. This results in increased brilliance and contrast in the fluorescent indication. In the *dry method*, parts are dusted with a dry developing powder while placed in a tank containing the powder. The powder helps draw the penetrant out of the flaws by capillary action, resulting in brilliant indications on a suitable background.

The inspector's observation of the parts is carried out in a darkened booth equipped with ultraviolet lamps. These illuminate the test object with "black light" of 3650 Ångström units wavelength. The penetrant indications fluoresce brilliantly under this illumination, with a characteristic green color near the eye's maximum response frequency. The manner in which these indications "flash up" is one of the most dramatic forms of indication in the entire nondestructive testing field.

The fluorescent-penetrant method of inspection can also be readily applied to

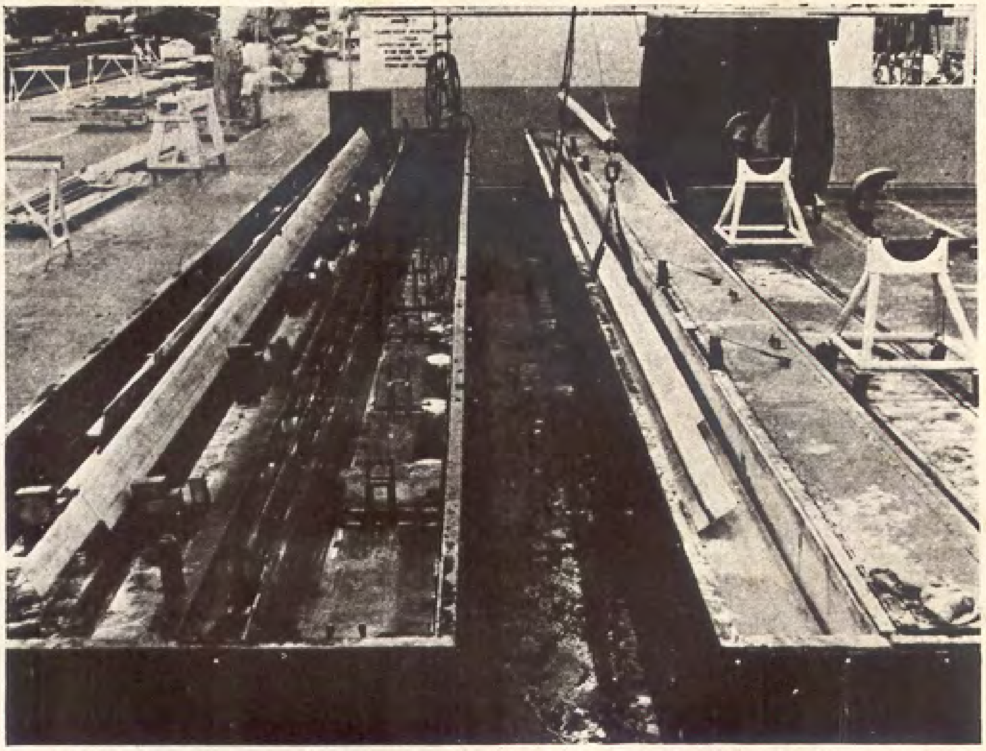


Fig. 29.—Zyglo Fluorescent Liquid-Penetrant Inspection of Aircraft Spar Caps. (Courtesy Douglas Aircraft Corp., Photo Laboratory, Santa Monica, Calif., and Magnaflux Corp., Chicago, Ill.)

large structures in the field. Figure 28 shows successively the spray application of Zyglo penetrant, the inspector's examination with "black light," and typical weld-defect indications found on a welded storage tank structure. The increasing size and critical loading of aircraft structures has led to careful fluorescent-penetrant inspection of primary structural elements such as wing spars, for which long inspection units have been especially designed (Fig. 29). The method is now widely used throughout industry for inspection of nonferromagnetic materials such as the light alloys, stainless steels, and ferromagnetic materials which it is undesirable to magnetize.

Filtered-Particle Tests:

Filtered-particle tests employ selective mass transport to locate cracks open to the surface in porous materials. The probing medium is a liquid dispersion of particles, often coated with fluorescent pigments. When applied to a porous body, such as an unfired ceramic, the liquid carrier is absorbed into the body through accessible surfaces. Where discontinuities, such as cracks, connect with the exposed surfaces, they absorb liquid along their interfaces to so great an extent that the suspended particles are drawn to the site of the defect. Here, being larger than the defect opening, they filter out to produce striking indications (Fig. 30).

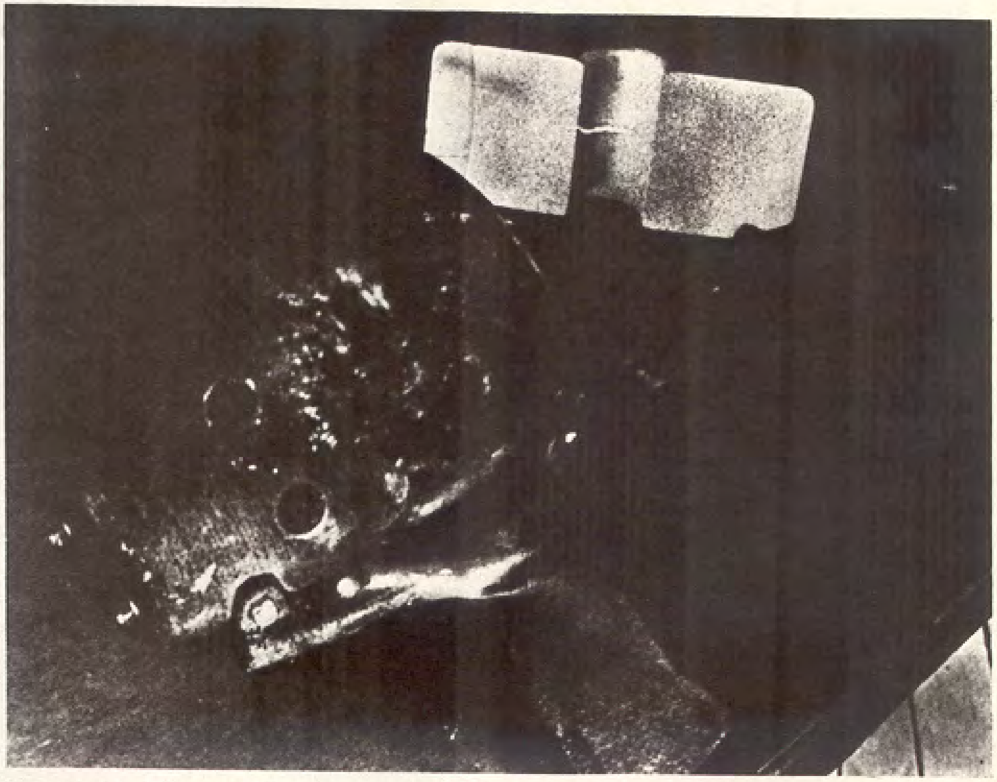


FIG. 30.—Partek Filtered Fluorescent Particle Indication of a Crack in a Sample of Unfired Clay. (Courtesy Magnaflux Corp., Chicago, Ill.)

Commercially available inspection fluids consist of a light petroleum distillate carrying in suspension a wide range of particle sizes in the micronic range. They may be applied to test objects by spraying, by dipping, or with simple devices such as an eye-dropper or oil squirt gun. With fluorescent-coated particles, a "black light" source of ultraviolet illumination is used.

The filtered-particle ("Partek") inspection method has found extensive application in the examination of green (unfired) ceramics, such as clay ware, porcelain insulators, and pottery. Experience indicates that cracks shown by this method in green ware always result in cracks in the fired ware. Rejection prior to firing reduces the costs which would be involved in handling and firing pieces which would be rejected ultimately. The nature of both liquid and particles is such that they "fire off" at low temperatures, without damage to the finished ware.

Brittle-Coating Tests:

Brittle-coating ("Stress-Coat") tests also depend primarily upon mass transport as a medium for probing the test object. In this method, the surface of the test object is cleaned, and a brittle lacquer is applied and allowed to dry and harden under controlled environmental conditions. When hard, these coatings are so brittle that they elongate very little before cracking, the cracks generally being transverse to the direction of strain. If the brittle-lacquer-coated test object is now subjected to mechanical stress (such as in proof loading) which strains it, the coatings cannot elongate as much as the base material of the test object. Where stress concentrations exist, the brittle coating cracks in a distinctive pattern as the base material is strained. The range of strains at which the brittle coatings can be made to just start cracking is 0.0005 to 0.003 in. per in. under normal operating conditions. The coatings can be further sensitized down to 0.0001 in. per in. strain by cooling them while the static load is applied. They respond equally well to dynamic loads and show by increasing patterns of cracking the increase of strain as loads are gradually applied.

A variety of brittle-coating materials is available, for use in different temperature or humidity environmental conditions, as well as for different stress levels required to fracture the coating. In practice, the test objects are cleaned and an aluminum-pigmented undercoating is sprayed on the surface, to provide a uniform bright working background for the brittle coatings. The brittle-coating material is then sprayed on and allowed to dry overnight at room temperature or slightly above. More rapid drying can be attained at 130 F. Calibration strips are coated simultaneously and dried under the same conditions as the part under test. These may be evaluated by applying known strains. Quantitative accuracy is possible only at those strain levels at which cracks start to form.

The test object is subjected to the desired stress loading, and the incidence and patterns of cracks in the brittle coatings observed carefully. This establishes stress magnitudes (at start of cracking) and stress distribution or concentrations (by the pattern of cracks). Suitable dyes are available to stain the cracks for easier observation and recording. The brittle-lacquer technique has found wide application in experimental design and stress analysis, in measuring assembly stresses and residual stresses resulting from fabrication, in measuring strain due to impact and other dynamic loads, as an adjunct to proof tests, and in measuring stresses applied in service. In these applications, it can predict the locations of stress concentration and the probable locations of failures due to such stresses. It has also found use in establishing the nature of service conditions which produced unexpected service failures, to guide redesign or reinforcement of the test objects.

NONDESTRUCTIVE TEST METHODS BASED UPON RELATED PHENOMENA INVOLVING BOTH TRANSPORT OF MATTER AND CORRESPONDING TRANSFER OF ENERGY

In some phenomena, the transport of matter is dependent upon a corresponding transfer of significant quantities of energy intimately linked with and essential to the transport of matter. For example, the motion of high-energy charged particles, such as electrons, transfers energy which may be released if the particle is stopped suddenly (as electrons are stopped when they strike the target of an X-ray tube). In the same sense, the transfer of energy often requires motion of matter, as in heat transfer, ultrasonic mechanical vibrations, or triboelectric phenomena. Many powerful nondestructive test methods depend upon these more complex media for probing the test object (Table VII).

TABLE VII.—TYPICAL NONDESTRUCTIVE TEST METHODS BASED UPON RELATED PHENOMENA OF TRANSPORT OF MATTER AND CORRESPONDING TRANSFER OF ENERGY.

Test Method	Form of Matter Transported	Form of Energy Transferred	Mechanism of Detection of Material Properties and Discontinuities	Forms of External Test Indications
Neutral particle beam tests	Neutrons, atoms, molecules, etc.	Gamma rays, kinetic energy, chemical, atomic, molecular energy, etc.	Absorption, scattering, deflection, attenuation of particles, etc.	Gamma ray image on films, ionization gage indications, crystal or Geiger counter indications, etc.
Charged particle beam tests	Electrons, alpha particles, ions, etc.	Electric field energy, kinetic energy, etc.	Absorption, deflection, scattering, etc.	Geiger or crystal counter indications, ionization gage indications, images on films, etc.
Electric current conduction tests	Electrons (in metallic conductors), electrons and "holes" in semiconductors, electrons and ions in liquids and gases, etc.	Electric field energy, magnetic field energy, heat, etc.	Distortion of current distributions, heat, magnetic fields of currents etc.	Resistance indications, potential drops, magnetic fields, heating, ohmic losses, etc.
Electromagnetic induction tests	Electrons, ions, magnetic domains, dielectric polarization, etc.	Electromagnetic field	Interruption or distortion of eddy current paths, magnetic field distortion, hysteresis loss, resistance loss, etc.	Amplitude of primary (source) or secondary (probe) oscillations, total losses, circuit resonance frequency, Q measurements, induced magnetic field strength, etc.
Sonic and ultrasonic mechanical vibration tests	Solid, liquid, or gaseous matter. Compressional, shear, or surface waves in solids, etc.	Mechanical vibrations	Reflection, refraction, scattering, transmission, transit time, phase shifts of sound waves, etc.	Waves or vibrations (displacements of matter) at exposed surfaces of test objects, piezoelectric or magnetostrictive probe signals, powder patterns, Pohlman patterns, cavitation, etc.
Thermal conduction tests	Solid, liquid or gaseous matter in random oscillations of impacts	Heat	Distortion of temperature distributions	Temperature, distribution at exposed surfaces, electrical resistivity, Curie point, chemical changes, solvent evaporation, thermocouple signals, etc.
Triboelectric and thermoelectric tests	Electrons	Electric field energy	Potentials arising at contacts or upon separation of contacts, etc.	Electric potentials or currents in electric circuits or electrometers, etc.
Chemical and electrochemical tests	Atoms, ions, etc.	Chemical binding energy, heat, etc.	Products of chemical reactions	Visible markings or deposits, images on electrographic paper, etc.

The range of application of these phenomena depends greatly upon limitations both of transport of matter and of transfer of energy. For example, beams of charged high-energy particles, such as electrons and alpha particles, are rapidly attenuated when they pass through dense, solid materials. Consequently, tests using these particles as probing media are usually suitable only for examination of thin sheets or surface layers of thick materials, as in electron diffraction or in the electron microscope. Neutrons, on the other hand, have significantly greater ranges in some solid materials, but react with hydrogen-bearing materials so as to produce gamma rays and are attentuated accordingly. Ultrasonic vibrations of metallic materials with low damping losses may penetrate great distances; such waves have been reported to have penetrated up to 50 ft of steel or concrete with adequate strength of transmitted or reflected signal to be useful in nondestructive testing.

Neutron and Other Uncharged-Particle Beam Tests:

Test methods in which neutrons, atoms, and other uncharged particles moving at high velocities in beams are used to probe the test objects fall into this class. To date, such test methods have found few applications because of the relative difficulties of producing and controlling beams of such neutral particles and of detecting their intensities after modification by test objects.

Neutron beams have been produced by means of radioactive sources whose gamma emanations pass through beryllium to create the neutron flux. Such sources have found applications in atomic energy research and in neutron logging of oil wells. In the latter application, the neutrons react with hydrogen-bearing fluids in earth formations, producing secondary gamma rays which give the logging signal.

A neutron image converter has been proposed, in which a neutron beam transmitted through the material of a test object would be recorded by means of an image tube, somewhat similar to those used to reproduce X-ray images. With narrow neutron beams, the detector might consist of a suitable gamma-radiation detector in a hydrocarbon enclosure. In addition to direct neutron gaging of material thicknesses, it has also been proposed that a neutron beam might be employed to detect the presence of a hydrocarbon within a metallic enclosure, as with petroleum products in steel pipes or tanks, or rosin cores in solder. To date, however, no practical nondestructive tests based upon neutral particle beam inspection have been commercially developed for wide use in industry.

Electron and Other Charged-Particle Beam Tests:

Several valuable test methods based upon the use of beams of electrons or other charged particles have found important industrial applications in nondestructive testing. In these tests, the charged particles impinge upon the test objects, being diffracted, or transmitted with attenuation, to produce images suitable for detection and interpretation. Diffraction of electrons and other charged particles has proved useful for surface inspection and identification of materials. Transmission of electron beams through thin layers of test materials provides remarkably detailed information concerning their structures.

The beams of electrons may be produced with an electron gun, such as is commonly used in cathode ray and X-ray tubes. Or they may be produced by the irradiation of materials with gamma rays or other high-energy photons or particles, as is well known in the use of lead screens to intensify X-ray images in film radiography. Other means of producing beams of high-energy charged particles have been developed in mass spectroscopy and induction accelerator applications.

The production of images by passing electron beams through test materials has found many valuable applications. In the electron microscope, such particle beams transmitted through thin replicas of material surfaces are focused magnetically to produce greatly enlarged electron radiographs upon films or fluorescent screens. In electron radiography, the electron flux produced by irradiation of an intermediate material (such as lead) with X-rays or gamma rays is passed through a test object in intimate contact with both the electron source and the recording film, to produce useful electron radiographs. Similar autoradiographs are produced with electrons (beta particles) emitted from radioactive isotope sources to reveal structure or distribution of radioactive constituents in the test object.

In electron-diffraction techniques, a beam of electrons is directed at a glancing angle of incidence upon the test object to produce diffraction patterns characteristic of thin surface films of contaminants or of the test object itself. In the mass spectroscope, charged particles (atoms, molecules, etc.) are magnetically separated in terms of mass and charge, to produce characteristic patterns for identification purposes or for sorting or separation. Cathodic etching takes advantage of the selective etching of electrons impinging upon test objects in vacuum chambers to reveal structure for metallographical purposes.

Electrons and alpha particle beams have found practical industrial applications in "nucleonic" gaging of sheet thicknesses of thin metallic foils, paper, and plastic materials. In these gages (Fig. 31), radioactive sources of beta rays or other probing beams of charged particles are placed on one side of the sheet material to be gaged, and suitable detectors, such as Geiger counters, are placed on the opposite side, to detect the transmitted-particle beam intensities.

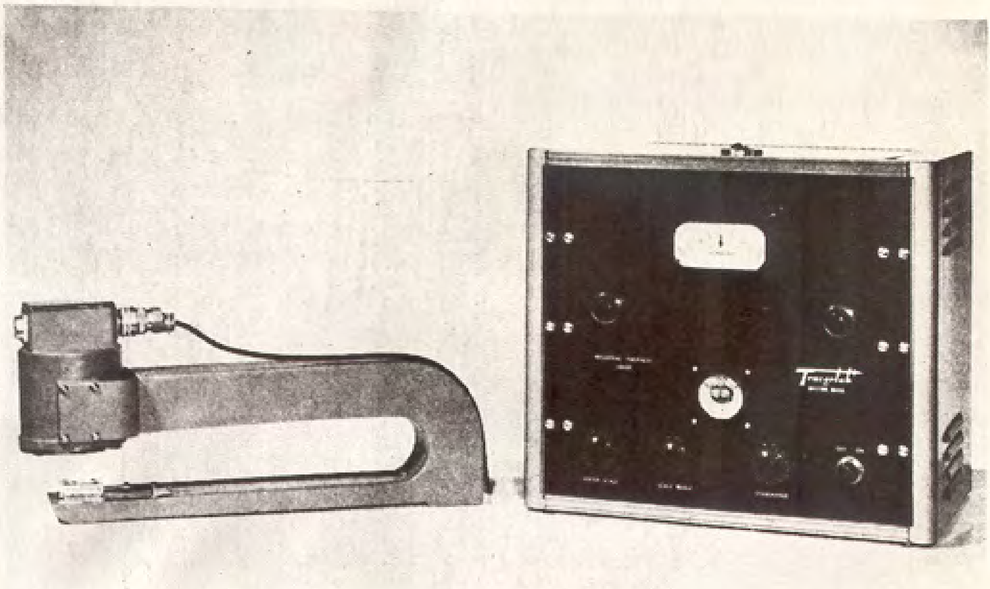


FIG. 31.—Tracerlab Beta-Ray Sheet-Thickness Gage. (Isotope source at bottom of yoke; detector in housing at top of yoke.) (Courtesy Tracerlab, Inc., Boston, Mass.)

Electric Current Conduction Tests:

Tests based on electric current conduction are characterized by a flow of heavy electric current from an external source through the test object by means of direct contacts or electrical connections. (Tests in which electric currents are induced in the test object by varying electromagnetic fields are discussed in the next section of this paper.) Clean, scale-free bare metal surfaces and contacts under considerable pressure are usually required to avoid contact overheating or burning of the test object. The current flow in the test object produces differences in electric potential, magnetic fields, and heat or temperature gradients which may be influenced by defects or variations in the material.

The flow of electric currents in conducting materials is a matter of mass transport of charged particles. (These consist of electrons in metallic conductors, positive or negative charges or "holes" in semiconductors, and ions in liquids or gases.) Because of electric field conditions, however, this transport of charged particles of matter often transmits considerable energy. It may often be readily detected by the changes in the electromagnetic field which accompany the changes in position of the electric charges.

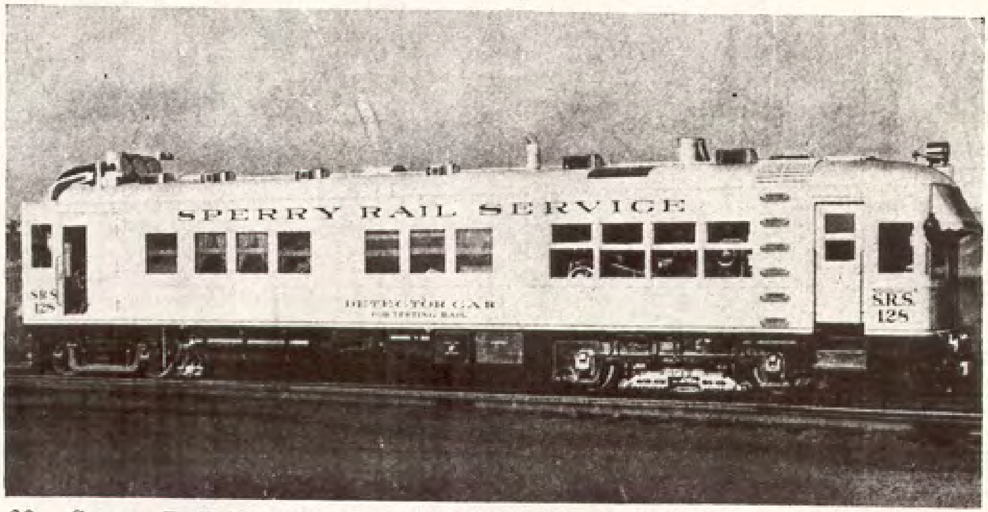


Fig. 32.—Sperry Rail Detector Car. (Courtesy Sperry Rail Service, Sperry Products Corp., Danbury, Conn.)

At low frequencies, *the flow of electric charges* may be readily detected by the static magnetic fields they produce. In the case of a conducting material containing a discontinuity, the interruption or deformation of the flow of current produces a corresponding deformation in the static magnetic field, which might be detectable outside the test object. When electric currents flow through *ferromagnetic* materials, they induce magnetic fields which may be far more sensitive to discontinuities in permeability than were the electric currents themselves. Here, the *magnetic field* now becomes the primary means of sensing material properties and discontinuities and of relaying the desired information to detection points outside the test objects.

The electric current used as the probing medium in these nondestructive tests is usually supplied from an external battery, welding generator, or other source of low-voltage, high-current electric power. The reaction of the test object upon the probing current is detected by means of potential-drop measurements, thermal effects, or (generally most successfully) by pickup coil measurements of the magnetic field produced at the surface of the test object as a consequence of the flow of electric currents and their interruption or deformation by discontuinities. Obviously, electric current conduction tests are usually limited to conducting materials, such as metallic parts, or to other materials with sufficient electrical conductivity to permit the flow of a detectable current.

The most outstanding industrial application of the electric current conduction type of test is in the electrical testing of steel rails. The Sperry rail car (Fig. 32) is designed to pass a heavy electric current through the rail and to explore the magnetic field produced by this current by means of induction pickup coils. This method replaces an earlier, less successful attempt to use potential-drop pickups. To date, such rail cars have inspected over two million miles of track, and more than one million defective rails (Fig. 33) have been detected and removed from service.

FIG. 33.—Transverse Fracture in Rail. (Courtesy Sperry Rail Service, Sperry Products Corp., Danbury, Conn.)

Special applications of electric current conduction tests include methods of measuring the wall thickness of plates, sheets, and tubes, from one side only. The probing electric current is introduced into the test object by means of a pair of current electrodes. The potential drop in the plate (an inverse function of its thickness) is measured by means of an independent set of potential electrodes. To avoid errors due to thermoelectric effects, or to ohmic potential drops at the potential electrodes, use is often made of potentiometer detection circuits which, when balanced, require no flow of electric current through the potential probes. Figure 34 shows a typical relation between material wall thickness and test indications.

Electromagnetic Induction Tests:

Electromagnetic induction tests are

characterized by the induction of varying electrical currents in the test object by means of repeated variations in an electromagnetic field. This method contrasts with the electric current conduction tests in which current flows into the test object through direct electrical contacts from an external source. No input contacts are required with induction-type tests. The induced current in the test object produces differences in electrical potential, magnetic fields, and heat or temperature gradients. When alternating or varying currents are induced in ferromagnetic materials, heat is produced not only by ohmic losses proportional to the square of the current density, but also by hysteresis losses in the magnetic material. The total "iron" losses, composed of both eddy current losses and hysteresis losses, are sometimes employed to indicate material properties. The pickup may detect variations in electrical potential distribution, in magnetic field strengths, in high-frequency electromagnetic wave properties, in temperature, in mechanical force or torque, or in losses in the material of the test object, or combinations of these factors. The complex nature of the probing medium in electromagnetic induction tests is apparent. Energy is transferred through the electromagnetic field. The flow of electrons in the test material also transfers energy and absorbs energy, as do the variations in the state of magnetization of the materials.

Dynamic electromagnetic fields provide an unusual combination of energy transfer through space, and related local movements of matter within test objects

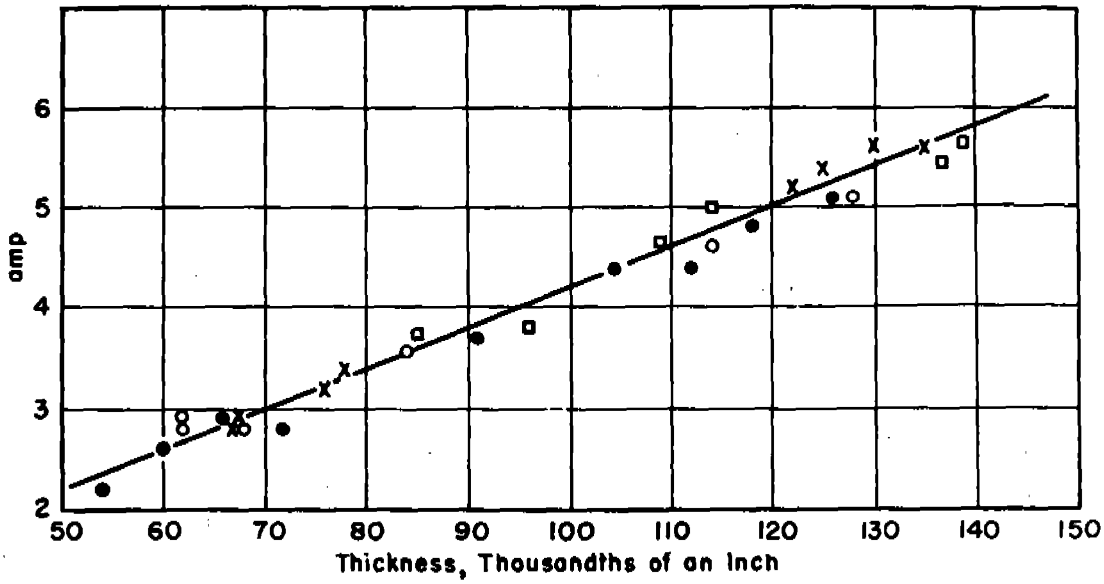
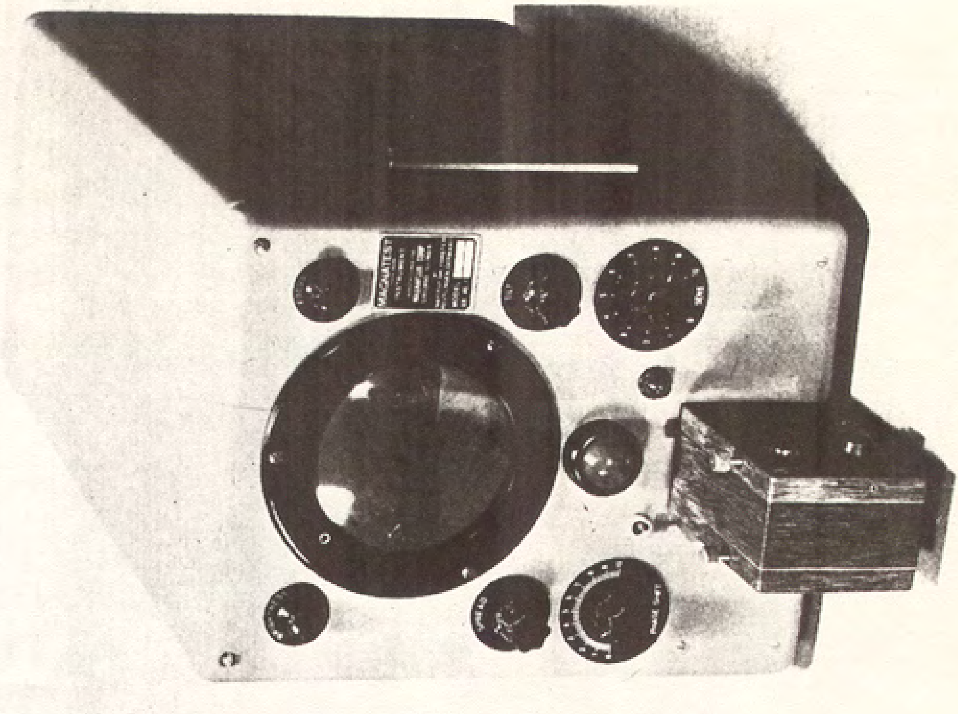
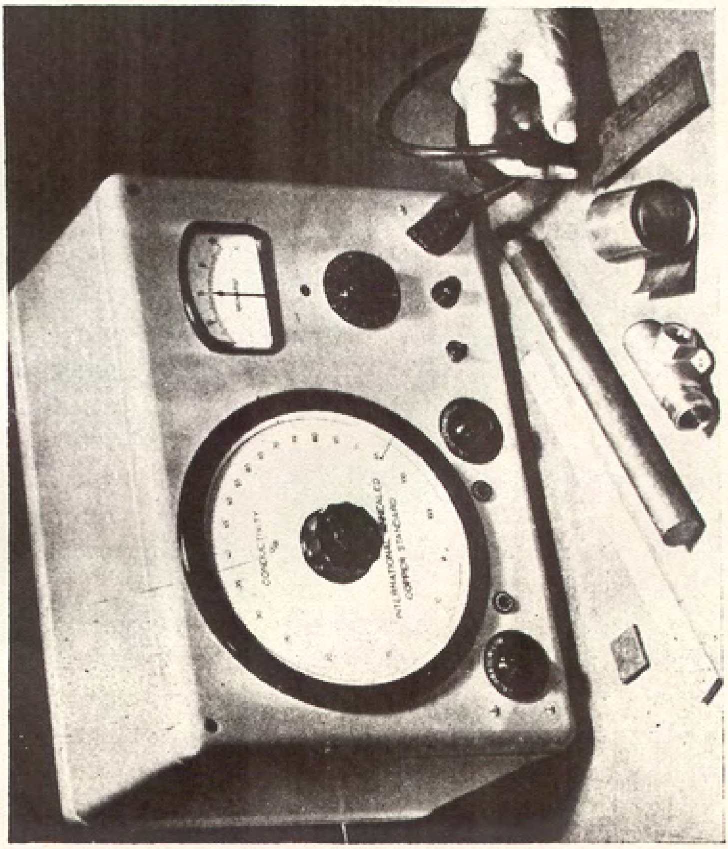


Fig. 34.—Correlation of Electric Current Conduction Test Indications with Wall Thickness of 4-in. OD Boiler Tubes. (Adapted from Thornton and Thornton, "The Measurement of the Thickness of Metal Walls from One Surface Only," *Proceedings*, Inst. Mechanical Engrs., Vol. 140, pp. 349–399.)

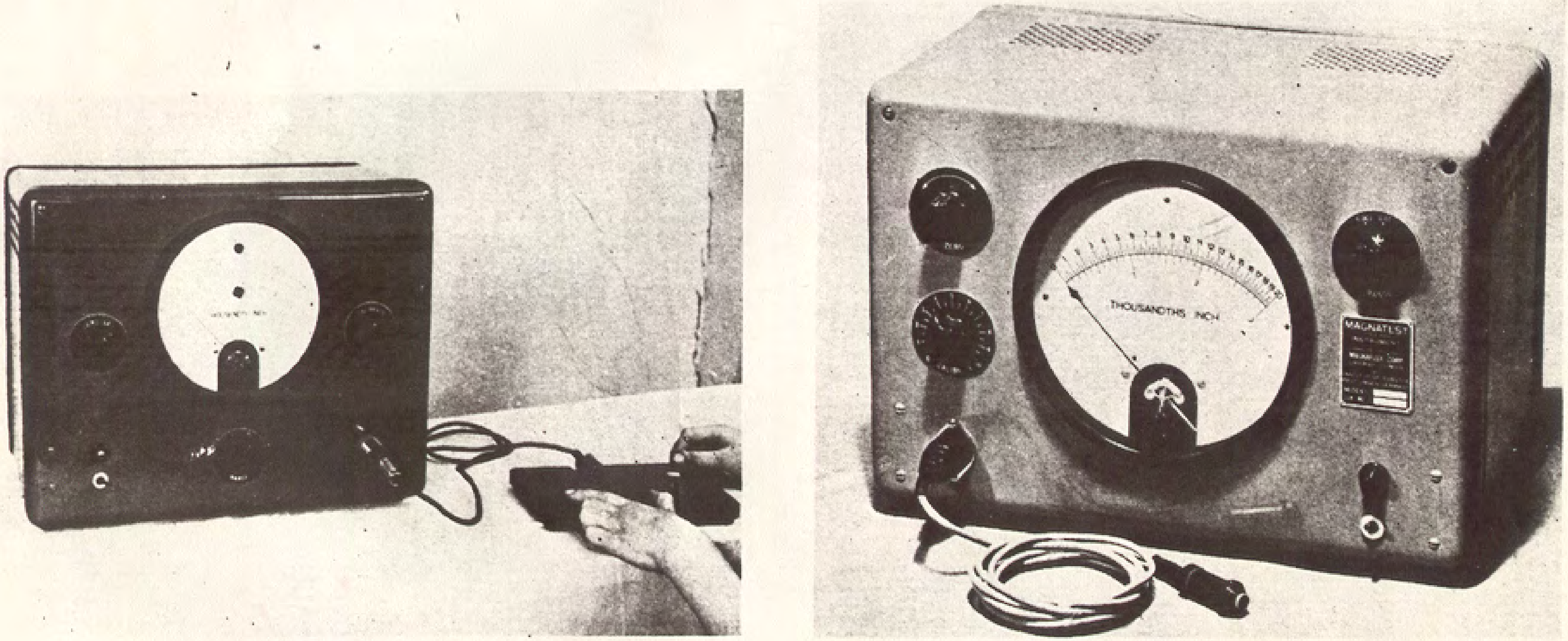
The electromagnetic field, like light or X-rays, may be transmitted through vacuum, in the complete absence of matter. It penetrates materials to varying degrees, depending upon their properties. And it induces local movements of matter within the materials, depending upon their nature. In electrically conducting materials, the electromagnetic field induces the movement of electrons or electric currents (such as the eddy currents in magnetic analysis). In magnetic materials, the dynamic electromagnetic field induces local oscillations of the elementary magnetic domains and, in some cases, magnetostrictive effects. In dielec-



(b) Multitester (for rods).



(a) Conductivity tester.



(*c*)Wall-thickness tester.

(*d*) Coating-thickness tester.

Fig. 35.—Typical Electromagnetic Induction Testing Instruments of Institut Dr Förster. (Courtesy Institut Dr. Förster, Reutlingen, Germany, and Magnaflux Corp., Chicago, Ill.)

tric materials, applied dynamic fields may induce similar oscillations in polarization of local regions, or piezoelectric (electrostrictive) effects. These movements of matter within the test object absorb energy from the applied electromagnetic field. This energy may be converted into heat by resistance, hysteresis, and dielectric losses. The extent of each possible reaction is influenced by material properties such as electrical resistivity, magnetic permeability and retentivity, dielectric susceptibility, and hysteresis. These properties, in turn, are complex functions of material properties such as composition, structure, stress, and many other variables. Thus, the reactions of the test object to the electromagnetic field often produce indications from many different internal causes, so that interpretation requires extensive experience and selective instrumentation. Electromagnetic induction provides a versatile probing medium with several possibilities of reaction with test objects and with good information transfer capabilities.

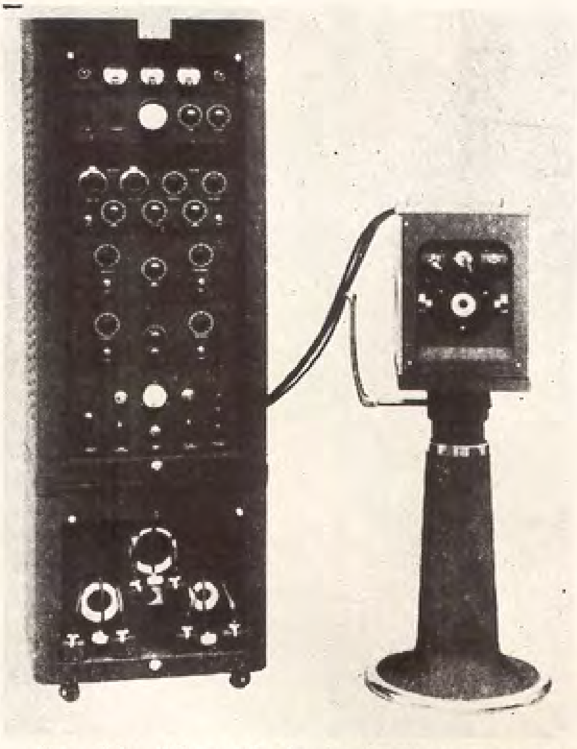


FIG. 36.—Magnetic-Analysis Equipment for Nondestructive Testing of Tubes and Bars. (Courtesy Magnetic Analysis Corp., Long Island City, N. Y.)

Very intensive research on electromagnetic induction methods of nondestructive testing in Germany during the past twenty years has resulted in a particularly effective and successful line of electromagnetic induction testing instruments (Fig. 35). Various electromagnetic induction instruments provide simple production testers for locating cracks, sorting by composition and heat treatment, thickness testing, and other tests, for both ferrous and non-ferrous materials, parts, tubes, bars, wires, and special applications. These have been adopted in German industry for many uses, including evaluation of light-metal-alloy materials.

Magnetic-analysis equipment (Fig. 36) provides a unique combination of several sensitive magnetic measurements, each analyzed and evaluated separately by electronic discriminating circuits. The magnetizing coils are supplied with 60-cycle alternating current carefully isolated from line fluctuations by voltage and current regulators. The sinusoidal magnetizing coils induce varying magnetic conditions in different metallic materials placed in the test unit. These magnetic variations induce changes in phase and amplitude of fundamental frequency, as well as wave form distortions, in the emf signals induced in the detector coils. The changes in phase and amplitude of fundamental frequency are determined with circuits which include balancing, filtering, amplifying, and indicating electronic networks for the small a-c voltages. To select the optimum points in the distorted wave forms for analysis, special "point inspection" gating circuits are used. These select any desired short interval, of only 50 microseconds duration, or one electrical degree, out of each cycle of 360 electrical degrees. Selecting these points permits elimination of many magnetic variables of no significance from the inspection. Each specimen is subjected to two such "electronic point inspections," to sort materials by grade, structure, hardness, and processing conditions.

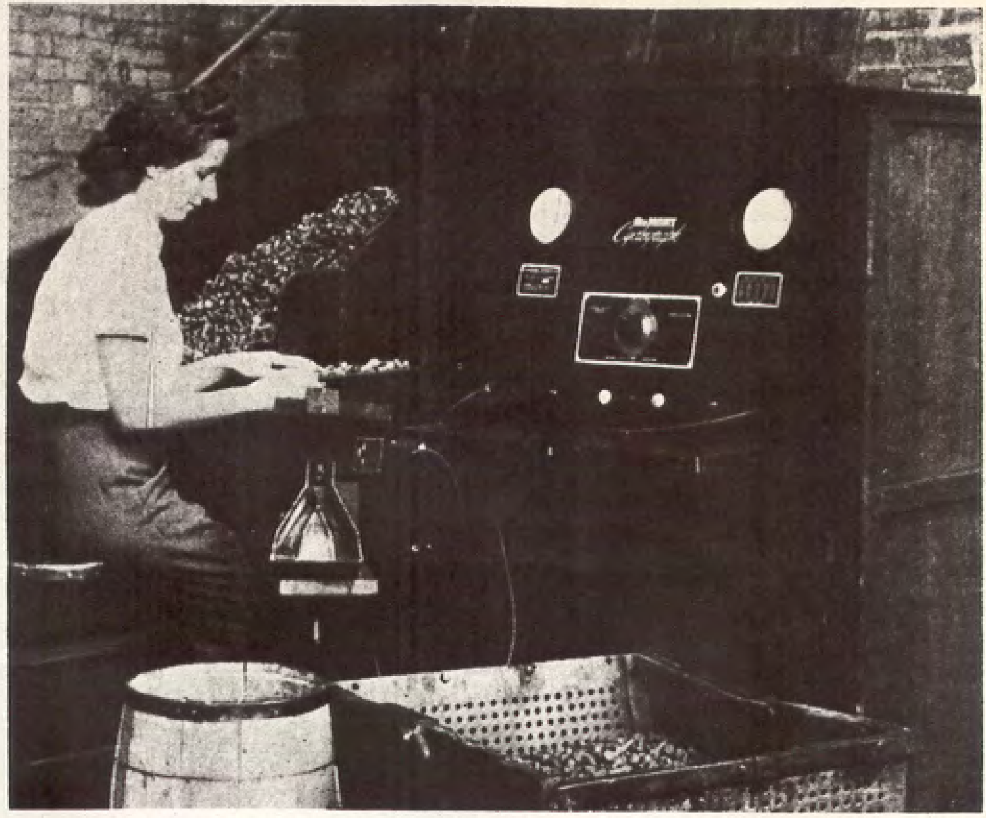
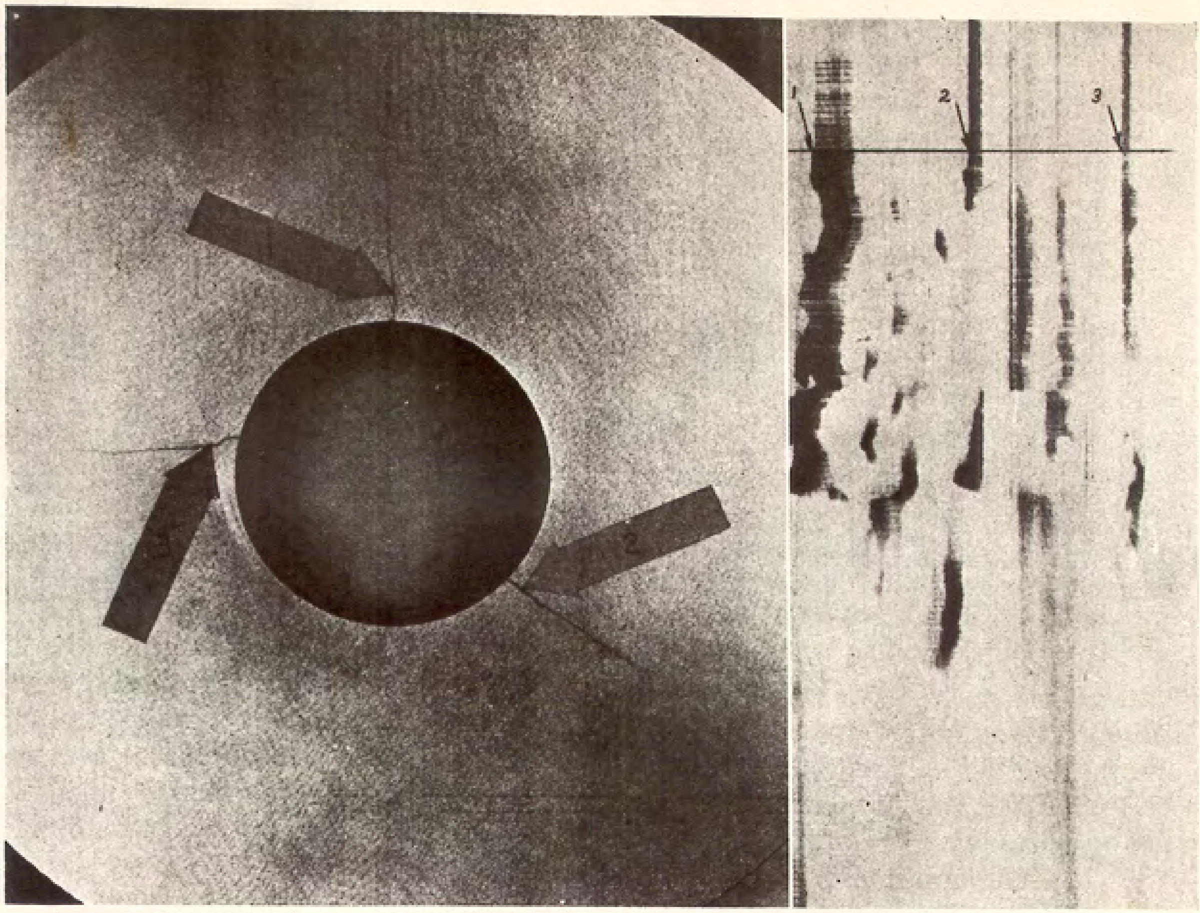


FIG. 37.—Rapid Electromagnetic Induction Sorting of Production Parts with Original Dumont Cyclograph (Model 244). (Courtesy J. W. Dice Co., Englewood, N. J.)

In addition to sorting the materials, the magnetic-analysis equipment detects flaws such as cracks, seams, laps, slivers, and other surface defects with depths not less than 0.001 in. for each $\frac{1}{16}$ in. of specimen diameter. In addition, internal defects such as cupping and pipe in smaller diameter material are located. These defects are located by the differential pickup coil method. Two adjacent portions of the specimen are scanned by pickup coils connected in series opposition. In this way, the average properties of the material cancel out, and only local variations are detected. These differential signals are also analyzed electronically to indicate significant flaws in the materials tested.

Magnetic-analysis inspection is presently used in the cold-drawn steel industry for production testing of hot-rolled, cold-drawn, heat-treated, stress-relieved and annealed machine-straightened bars, tubes, and wires of all shapes and sizes up to $5\frac{1}{2}$ in. in diameter. Seamless tubing is inspected for outside diameter and inside diameter flaws and to identify grade and structure. Butt-welded tubing is tested for open and weak welds, as well as for inclusions and burned sections. Small parts are usually inspected with comparators only for structure and analysis, but normally not for defects. During the past twenty years, the method has developed into a valuable tonnage pro-

(*a*) Installation at Borescope Inspection Station.



(*b*) Section of cracked gun tube.

(*c*) Facsimile recording of cracks (shown in (*b*)) from Magnetic Borescope.

FIG. 38.—Watertown Arsenal Laboratory Magnetic Recording Borescope Used in Gun-Tube Inspection. (Courtesy Carleton ~~R.~~ Hastings, Watertown Arsenal Laboratory, Watertown, Mass.)

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duction test method which is used daily in a number of major steel mills.

The Cyclograph (Fig. 37) provides a wide-frequency-range oscillator in which the test coil is part of the tuning circuit. Regenerative feed-back control allows adjustment of the initial energy output of the oscillator to any desired level. The test frequency is selected by choosing the test coil and by adjusting capacitors in the control unit. Core losses occurring in the metal specimens inserted into the field of the test coil decrease the output of the oscillator. This output of the oscillator is viewed on a cathode-ray tube screen, whose pattern can be correlated with the metallurgical characteristics of the test pieces. At low frequencies (of 2 to 10 kc), these core losses are mainly governed by the magnetic properties of the material of the test object, if it is of iron or steel (ferromagnetic). At higher frequencies, the core losses consist mainly of eddy current losses. These higher frequencies are generally used for inspection of uniformity or analysis of non-ferrous metals. At very high frequencies, the electromagnetic field of the test coil is confined to the surface layers of the test object, due to skin effect. These frequencies are used for tests such as case depth of carburized parts, decarburization, plating thickness, and surface stresses. Cyclograph indications have been correlated with applied and residual stresses, with fatigue damage, as well as with material analysis, structure, hardness, brittleness (stress gradients), degree of cold working, and various sorting applications. The Cyclograph, in measuring these magnetic losses, is not designed to be sensitive to defects or local discontinuities and does not detect them.

The Ferrograph provides a magnetic-analysis method in which the response of a ferromagnetic sample to a *low*-frequency (23 cps) alternating magnetization, and to its third harmonic (69 cps) are compared with each other. In the Ferrograph, the relative amplitudes and phase angles between the fundamental and third harmonic signals are displayed on the fluorescent screen of a cathode-ray oscilloscope (similar to a television viewing tube). The instrument can correlate carbon content in samples of similar chemical analysis. It can also distinguish between high- and low-alloy content samples and separate high- and low-alloy samples with the same carbon content.

A particularly outstanding recent application is a method for recording defects on the interior surface of gun barrels, which produces facsimile records of the entire surface and the location of the defects, such as seams, laps, and cracks (Fig. 38). This method is now being subjected to development into a production testing device.

Electromagnetic induction principles have been applied in an inspection device for nonmagnetic tubes. The device includes an electromagnetic induction probe which is pushed or pulled through tubes by a cable. As the probe moves through the tube, a strip recorder charts or indicates the position of defects. Since the probe can be passed through tubes without removing them from the equipment in which they are installed, it permits quick inspection. The device has been particularly applied to inspection of tubes in heat exchangers, condensers, and similar tubular equipment. It is reported to detect dezincification, eroded and corroded pits, cracks, strained areas, changes in alloy or chemical composition, and abnormal changes in physical dimensions.

Ultrasonic and Other Mechanical Vibration Tests:

Mechanical vibration tests are characterized by the establishing of mechanical vibrations in the test object, and their detection by suitable means. The vibrations may be natural frequency vibrations (as when the test object is excited by a hammer blow) or forced sonic or ultrasonic vibrations. At the higher frequencies, the vibrations tend to travel in beams, which may be transmitted, scattered, or reflected locally by discontinuities.

FIG. 39.—Sperry Ultrasonic Reflectoscope Used to Show Indications of Internal Defects in Portion of Railway Car Axle. (Courtesy Sperry Products, Inc., Danbury, Conn.)

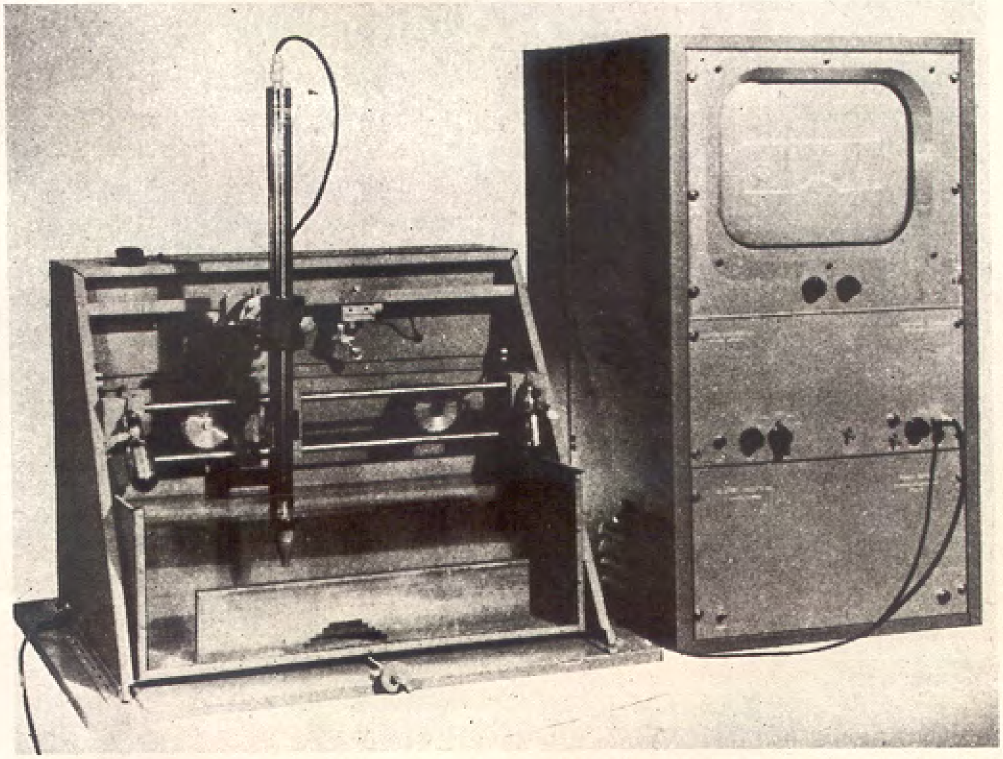


FIG. 40.—Electrocircuits, Inc., Ultrasonic Immersion Scanning Inspection Unit Reproducing B-scan presentation of discontinuities in aluminum alloy test block. (Courtesy Electrocircuits, Inc. Pasedena, Calif.)

The vibrations are usually established in the test objects by means of transducers operating from electronic power supplies. For lower frequency applications, the transducers may be electrodynamic (as in radio loud speakers) or magnetostrictive types. For higher frequencies (in the range of megacycles), quartz crystal transducers are most widely used. Most such transducers have only a limited frequency range through which they operate efficiently. Fluids, such as oil or water, are usually needed in order to couple the transducers to the test objects so as to transfer the vibratory energy efficiently.

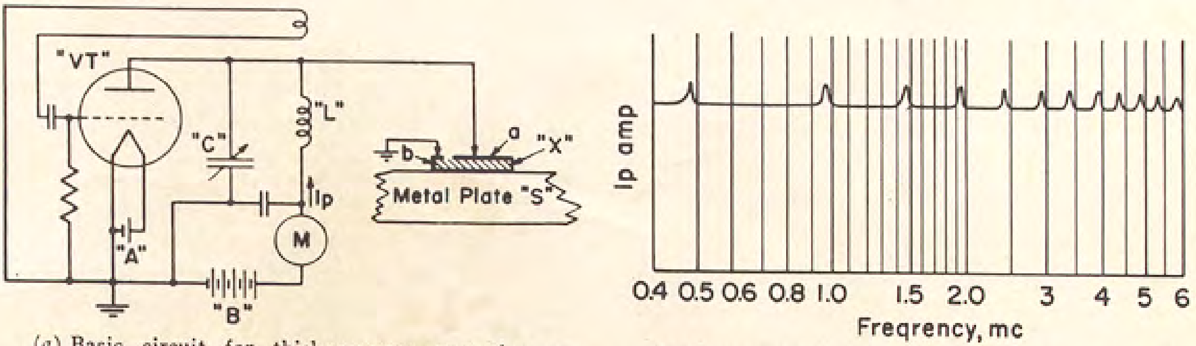
Fig. 41.—"B-Scan" Television-Type Presentation of Surfaces and Laminations in ¾-in. Aluminum Plate Detected with Immersion Ultrasonic Scanner. (Courtesy Electrocircuits, Inc., Pasadena Calif.)

The transmitted or reflected ultrasonic beams are usually detected by means of similar quartz crystal transducers (in many cases the same transducer as was used to establish the vibrations). With immersion techniques, limited success has been obtained by the use of a cell containing small particles in a liquid suspension, to present an image of the ultrasonic beam. At low frequencies, the vibrations may be readily detected with microphonic devices or crystal cartridges such as are used in phonograph reproduction. The use of small particles, such as sand, sprinkled onto the test object, has proved useful in establishing the modes of natural vibration at sonic frequencies.

Pulse-reflection techniques, such as are used in sonar detection of submarines, have been developed to a high degree for inspection of metallic materials for discontinuities. The ultrasonic reflectoscope uses a quartz crystal to introduce short (5 microsecond) pulses of ultrasonic frequency (0.5 to 5 mc) vibrations as a probing medium into the test object (Fig. 39). These high-frequency pulses travel great distances (up to 50 ft) in steel and some other metallic materials; however, large grain size introduces scatter and attenuation of such beams. The pulses are reflected from discontinuities, such as voids or cracks, and return to the transmitting (or receiver) quartz crystal transducers as echoes. The time from initial pulse to their return measures the distance of the discontinuity from the transducer, so that when the pulses are displayed upon a cathode-ray oscilloscope, the discontinuities can be readily located.

More recently, the pulse-reflection technique has been extended to higher frequencies and immersion techniques, which permit automatic scanning of the test object with the transducer (Fig. 40). The information obtained from the ultrasonic probe is displayed upon a "B-scan" cathode-ray picture tube (Fig. 41), so as to present a cross-section of the entire test object and a graphic picture of the discontinuities within it. Three dimensional probing, with electronic computation, has also been developed experimentally, with equipment based upon these principles.

Ultrasonic resonance has also been applied to thickness gaging with similar quartz crystal probes (Fig. 6). The oscillator which energizes the transducer is continuously tuned throughout a range of frequencies, including those at which resonance occurs (Fig. 42). At each resonant frequency, the mechanical impedance or amplitude conditions are reflected into the electronic circuit and produce "pips" or detectable deflections on the screen of a cathode-ray tube. An alternative form of equipment, designed for portable operation from batteries, indicates the thickness or resonant conditions by changes in an audible tone in headphones worn by the operator (Fig. 43).



(*a*) Basic circuit for thickness-gage operating on ultrasonic-resonance principle.

(*b*) Plate current as a function of frequency for ¼-in. steel thickness.

FIG. 42.—Ultrasonic-Resonance Testing. (Courtesy Branson Instrument Co., Stamford, Conn.)

The sonic resonant frequency of entire test objects is used for comparison of similar test objects with a standard known to be sound, in the sonic comparator (Fig. 44). It is assumed that identical bodies will have identical natural frequencies of vibration. The test object is vibrated by means of a transducer and stylus excited from a calibrated electronic oscillator. A wide-range microphone is used to detect resonant frequencies. Frequencies of vibration in the range from 100 to 10,000 cps are measured to an accuracy of the order of 1 per cent. Resonance is detected by a characteristic pattern upon the cathode-ray oscilloscope indicator. This method has been applied particularly to the nondestructive testing of grinding wheels, but conceivably could be used upon a variety of test objects.

FIG. 43.—Branson Audigage Ultrasonic Measurement of Corrosion Wall Thinning of Storage Tank in Service. (Courtesy Branson Instrument Co., Stamford, Conn.)

Triboelectric and Thermoelectric-Power Tests:

Triboelectric and thermoelectric-power tests are based upon the use of potentials developed through contacts with the materials of test objects. In triboelectric tests, use is made of the phenomenon which occurs when two dissimilar materials are brought into intimate contact with each other (as with rubbing friction) and then separated. Usually one material receives an excess of electrons (tribute) from the other, so that it is negatively charged, while the other material is left positively charged. The magnitude and polarity of such triboelectrification vary for different material combinations and have been evaluated in the "triboelectric series." In thermoelectric-power tests, use is made of the thermoelectromotive forces developed at junctions between dissimilar metallic materials, which can cause a flow of current in external circuits when such circuits are closed through two junctions held at different temperatures. This principle is well known in the use of thermocouples to measure temperatures. The magnitude of the net voltage, for given differences in junction temperatures, can be established for given combinations of two materials at the junctions. Both triboelectric and thermoelectric nondestructive tests involve the transport of electrons through potential barriers (at the surfaces between unlike materials) as their probing medium. Only the triboelectric method of nondestructive testing has been fully developed into a commercially available nondestructive testing instrument to date.

Fig. 44.—Saturn Sonic Comparator Used in Mechanical Vibration Tests of Grinding wheels. (Courtesy Saturn Electronics Co., Niagara Falls, N. Y.)

The Metalsorter (Fig. 45) employs a circuit which will detect minute quantities of electrical current generated when two metallurgically or chemically unlike materials are moved in frictional contact. If both conductors are metallurgically identical, no current will be generated. Occasionally, two unlike conductors will not generate a current of measurable magnitude. However, such conductors can almost always be distinguished from one another by comparing each to a third conductor and using the differential current value as a basis for separation. It should be noted that triboelectric polarity is a function of the metallurgical nature of the conductors and their connection with respect to the measuring circuit; however, the magnitude of the effect is not necessarily a function of the degree of unlikeness. Therefore, the triboelectric magnitudes and polarities of various conductors are obtained empirically. Since these values are all relative with respect to one another, the Metalsorter has been provided with controls for calibrating the instrument to fixed standard values.

The Metalsorter is designed for the sorting or identification of metal parts where not more than four chemically or metallurgically different alloy types are involved. Where more than four types are involved, it may be necessary to make two or three sorts with as many different selective test rods in order to accomplish complete separation. The test can be made on any metal part wherever a small area of clean, scale-free metal surface is available. It can be applied to slabs and billets as well as semifinished and finished parts.

Sorting can be done on either a basis of composition or structural differences. It is often possible to determine, in a relative sense, the differences in degree of cold work in sheet and wire products. A production testing fixture allows the sorting of small parts at a rate of 15 to 20 per minute.

Essentially, the equipment consists of a control unit and a portable sorting head which is connected to the control unit by means of a cable. The sorting head contains all the main controls for actuating the test and is designed for one-handed operation. A standard rod in the form of a bar of known alloy, $\frac{1}{4}$ by 3 in. long, is fastened into the sorting-head chuck. When the standard rod is placed on the piece to be tested, it completes an electrical circuit. Actuation of the test switch on the head energizes a solenoid which causes the standard rod to be reciprocated against the test piece, and a large electrical meter indicates the character of triboelectric effect produced. Both the sorting head and the control

FIG. 45.—Doschek Metalsorter for Triboelectric Sorting and Classifying of Metallic Materials (Courtesy Doschek Associates, Inc., Crafton, Pa.)

unit contain signal lamps which also indicate the character of the test and eliminate the necessity of the operator having to view the meter after each test.

Present applications of the Metalsorter include sorting, inspection, and quality control in a wide variety of metal-producing and fabricating industries.

Spot Test and Other Chemical Tests:

Methods in which the test objects are subjected to any type of nondestructive chemical action are included in this class. Tests which are purely chemical analysis (and possibly destructive of the samples) and metallurgical etching procedures fall outside the scope of nondestructive testing, in most cases.

The two most widely used chemical tests are (1) chemical spot tests used to identify or measure some inherent characteristic of the material, and (2) chemical and electrochemical tests used, for example, to detect processing or material defects such as pinholes in protective coatings. In such tests, the chemical reactions involve transport of matter as well as the chemical energy of reaction.

Common examples of chemical types of tests include the well known sulfur-print technique which records the sulfur distribution in steel, and similar tests for revealing the distribution of phosphorus, nickel, lead, etc., in steels. These tests are used for sorting or quality inspection of steel blooms or billets. The corrosion resistance of stainless-steel welds has been chemically evaluated, as has the distribution of oxygen near the faying plane of pressure welds in steels.

Coating porosity tests include several which detect pinholes by chemical reactions with the base material beneath the coatings. Ferroxyl paper prints and electrographic printing have both been used successfully for this purpose.

SELECTING AND SPECIFYING THE PROPER NONDESTRUCTIVE TEST METHODS AND PROGRAMS IN INDUSTRIAL APPLICATIONS

The preceding examples and the basic principles which underlie them illustrate the nature and limitations of the available nondestructive test methods. Each method has specific limitations and specific application advantages for certain materials and inspection needs. There is no such thing as a general nondestructive test applicable to every kind of material, part, or structure, nor to all their functions or operating conditions. Instead, each nondestructive-test design must be based upon a thorough understanding of the nature and function of the part being tested and of the conditions of its service.

The engineer requires full information concerning the service loads and conditions of use to which a part is to be subjected in order to specify a useful nondestructive test. He also needs, from operating experience or destructive tests upon the part, clearly established limits of acceptability or rejectability, or at least a statement of the accuracy to which service performance must be predicted in order that the tests be useful. Furthermore, it is necessary to prove that the property which is to be measured by the nondestructive test is, in itself, a reliable measure of the strength or serviceability property to be predicted. In absence of such necessary data, it is not possible to specify intelligently a reliable nondestructive test.

The necessary data on service loads and conditions and the acceptability limits should be provided by the *designer* of the part or material to be tested and by the *stress engineer*. They are presumably fully informed as to the nature of the service conditions and the probable stress distribution. They may know the probable points of initial failure with the given design under operational loads.

very pertinent!!

The knowledge of the designer may be supplemented by destructive tests upon critical materials and components. The determination of the correlation between the strength or serviceability, and the defects or correlated properties to be measured by the nondestructive test, is usually a matter for a *materials or process engineer*. Often an extensive series of controlled destructive tests is required in order to prove that the correlation is a complete and reliable indication of serviceability.

Finally, the job of finding a sensitive and reliable method of measuring the correlated property nondestructively is the job of the *nondestructive-test engineer*. Unfortunately, it has been the practice all too frequently to assume that the engineer developing the nondestructive test would take on the functions of the designer, the stress engineer, and the materials or process engineer, in addition to the job of designing and developing suitable nondestructive tests. Many fine nondestructive-test developments have eventually proven worthless in industry because the designer and the materials engineer failed to contribute reliable data. The nondestructive test may have been developed to be a reliable and sensitive measurement of the property it was designed to measure. However, it would be unreliable if that property were not proved by previous destructive tests to be a good measure of strength or serviceability.

Even the well-established methods of nondestructive testing now widely used in industry are subject to limitations. Radiography, for example, may reliably reveal porosity, shrinkage, inclusions, dross, and misruns in castings, lack of penetration in welds, and similar defects. Few indeed, however, are the cases in which the actual load for failure under service conditions or the service life can be predicted quantitatively from the X-ray examination. This would be difficult to do even by destructively sectioning the parts.

Similarly, magnetic-particle inspection of ferrous materials reveals cracks and surface defects reliably. However, there are not very many cases in which the fatigue strength, or the load necessary to produce static failure, can be predicted from these data. It is generally sufficient, however, that the inspector know that a fatigue crack or stress concentration will lead to premature failure under repeated stressing, in order to reject the part for such service.

The engineer specifying or designing nondestructive tests should recognize certain geometric limitations in their scope and sensitivity. Some test methods require access to *both sides* of the part, material, or specimen which is under test. Other methods can be modified for use as "*one-side*" tests. Some test methods can be applied to parts of almost any shape or size. Others are limited to areas with reasonably flat surfaces or with constant thickness section. A few types of nondestructive tests are applicable only to specimens of exactly identical geometry. Other tests are limited, at present, to certain kinds of materials or to parts with definite thickness limits. Some nondestructive tests allow large areas or volumes to be inspected in a single operation. Other test methods require *scanning* of each small area suspected of being defective.

Especial care should be exercised in specifying the limits of sensitivity and accuracy required or expected in a nondestructive test. The sensitivity of every type of nondestructive test is limited. Sensitivity adequate for excellent testing on one part may be totally inadequate for another test object. In general, more sensitive tests require more elaborate equipment and cost more. The cost of developing a suitable nondestructive test, as well as the cost of the actual inspection with that test, must be considered in every application. Nondestructive tests which cannot be applied economically in the specific application will usually be abandoned.

A simple rule to guide the specification of nondestructive tests might be the assumption that it is not economical to require the nondestructive-test sensitivity to exceed the accuracy with which the magnitude and number of service loads are known, or the accuracy within which the design assumptions predict true stresses or performance. Alternatively, it might be reasonable to limit the sensitivity specified for the nondestructive test to a reasonable fraction of the variations in strength or serviceability corresponding to the tolerance limits acceptable in the production of the sound parts.

It is desirable to limit the number of functions or properties to be measured by the nondestructive tests to those of practical importance in production or service. For example, a particular part might be weakened for service by any one or by a combination of several possible causes. These might include improper material, wrong heat treatment, internal defects such as porosity, shrinkage, segregation, dross, inclusions, or external defects such as cracks, surface notches, defects in plating, and so on. No single nondestructive test should be expected to measure reliably all of these properties. Often a separate type of nondestructive test is required for each general type of defect or cause of weakening.

The same reasoning holds true for service damage. Corrosion, repeated stressing, wear, impact, surface destruction, and many other factors may contribute to service failures of parts which were originally sound. Usually a separate method of inspection may be required for each of the types or locations of service defects.

The interval between nondestructive tests for service damage may vary with the types of defects. If specific nondestructive tests for each of the causes of failure are pyramided into large, complex nondestructive tests, the costs would ordinarily be unreasonably high. The designer, process engineer, and operating engineer should determine which properties are of practical limiting importance in production or service. The nondestuctive test engineer should reserve for nondestructive testing only those properties which cannot be more economically or reliably controlled through other methods of process control or inspection.

Often, many causes might produce weakening of the part. If only a few of these particular types of defects have been selected for nondestructive testing, the correlations obtained between these nondestructive tests and the service performance of the parts may be poor (unless the other causes for weakening are controlled or accounted for). Suppose that a choice exists between alternative methods of nondestructive testing, one of which measures only one cause of weakening while a second measures several important causes of weakening. The latter test may be more reliable on the whole, even though it is less accurate or sensitive in certain measurements than the former test.

EVALUATING THE RELIABILITY OF NONDESTRUCTIVE TESTS

Most nondestructive tests, as illustrated in the preceding examples, detect and evaluate flaws or defects, or determine strength and serviceability, by *indirect procedures*. These usually involve the measurement of a different but correlated property. Nondestructive proof of the existence of a flaw or defect is one thing. Measuring the influence of that flaw or defect upon the strength or serviceability of the test object is quite another. This latter determination must ordinarily be made by destructive tests on specimens both free of flaws and containing flaws, of each basic type, in each critical location. In nearly all fields of engineering materials, there is a serious lack of specific information on the influence of material and fabrication defects upon strength or serviceability. The nondestructive test cannot supply this knowledge. Such information should be obtained from destructive tests or from operating experience.

A necessary prerequisite to a reliable nondestructive test is a *proven* correlation between the property actually measured by the nondestructive test and the strength or serviceability property being predicted from the measurement. In situations where such correlations have not been fully established, or where several factors influence the relation between the measured property and the property being predicted, evaluations based upon the experience and judgment of skilled interpreters become a vitally important feature of a nondestructive test method. Such correlations are usually implied, but seldom proved or demonstrated, in patents, advertisements, and some technical articles which provide information to the administrative engineer. To obtain the necessary data to establish these correlations, and then to design and develop a reliable nondestructive test method based upon such correlation, is usually difficult and frequently costly.

Failure to demonstrate the reliability of such correlations before applying and believing nondestructive tests can be far more costly. This element of doubt, based upon lack of specific knowledge, has cost American industry millions of dollars. In most cases of doubt, inspectors using nondestructive test methods tend to be conservative, particularly in the absence of reliable service data. In all too many cases, parts rejected because of defects revealed in the nondestructive tests have shown no weakening because of the defects when subjected to proof tests. Millions of dollars worth of aircraft parts and thousands of man-hours of labor were wasted in the aircraft industry during the last war. This resulted from radiographic rejection of castings and forgings on the basis of arbitrary standards. Such standards were frequently established more by fear than upon careful physical tests. Such misuse of nondestructive tests cannot be justified economically in peacetime industry.

In evaluating nondestructive test methods, it is important to discriminate between the *reliability of the test method* (in revealing flaws or defects and in measuring the physical properties of test objects) and the *reliability of the judgments of the inspectors* (based upon the evidence revealed by the nondestructive method).

Lack of specific data, operating experience, or good judgment, may seriously influence the inspector's conclusions. This may occur even when the nondestructive test method is providing excellent data concerning the condition of the test object. Consequently, it is seldom good economy to place useful nondestructive testing equipment in the hands of unskilled laborers or inspectors with little inspection experience or with poor judgment. The combination of good data concerning the test object, provided by the nondestructive test, and good judgment on the part of the inspector is essential.

The inspector must evaluate the data concerning the test object in the light of the service to which it will be subjected. He must have full regard for experience obtained during operation of similar test objects under this same service condition. It is particularly dangerous to extrapolate conclusions from one service condition to new and completely different service conditions. Each case is specific. Generalizations are hazardous in most applications of nondestructive testing.

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PREVIOUS EDGAR MARBURG LECTURES

First Lecture, June 23, 1926, by Arthur N. Talbot—*Research and Reinforced Concrete as an Engineering Material*

Second Lecture, June 22, 1927, by George L. Clark—*X-rays in Industry*

Third Lecture, June 27, 1928, by Frank B. Jewett—*Some Research Problems in Transoceanic Telephony*

Fourth Lecture, June 26, 1929, by Saul Dushman—*Cohesion and Atomic Structure*

Fifth Lecture, June 25, 1930, by C. E. Kenneth Mees—*Color and Its Measurement*

Sixth Lecture, June 24, 1931, by A. Nadai—*The Phenomenon of Slip in Plastic Materials*

Seventh Lecture, June 22, 1932, by Hugh S. Taylor—*Fundamentals in the Problem of Resistance to Deterioration*

Eighth Lecture, June 27, 1933, by H. J. Gough—*Crystalline Structure in Relation to Failure of Metals, Especially by Fatigue*

Ninth Lecture, June 27, 1934, by Sheppard T. Powell—*Water as an Engineering and Industrial Material*

Tenth Lecture, June 26, 1935, by L. B. Tuckerman—*Aircraft: Materials and Testing*

Eleventh Lecture, July 1, 1936, by Arthur L. Day—*Developing American Glass*

Twelfth Lecture, June 30, 1937, by T. Smith Taylor—*Plastics: Some Applications and Methods of Testing*

Thirteenth Lecture, June 29, 1938, by Albert Sauveur—*The Torsion Test*

Fourteenth Lecture, June 28, 1939, by Herbert Fisher Moore—*Stress, Strain, and Structural Damage*

Fifteenth Lecture, June 26, 1940, by P. H. Bates—*Portland Cement—Theories (Proven and Otherwise) and Specifications*

Sixteenth Lecture, June 25, 1941, by Harry L. Fisher—*Natural and Synthetic Rubbers*

Seventeenth Lecture, June 24, 1942, by Graham Edgar—*Gasoline—Past, Present and Future*

Eighteenth Lecture, June 30, 1943, by L. J. Markwardt—*Wood as an Engineering Material*

Nineteenth Lecture, June 28, 1944, by Harold DeWitt Smith—*Textile Fibers—An Engineering Approach to Their Properties and Utilization*

Twentieth Lecture, June 26, 1946, by Joseph J. Mattiello—*Protective Organic Coatings as Engineering Materials*

Twenty-First Lecture, June 18, 1947, by Walter C. Voss—*Engineering Laminates—Fundamentals Underlying the Problems of their Inhomogeneity*

Twenty-Second Lecture, June 24, 1948, by Paul C. Aebersold—*Isotopes and Their Application in the Field of Industrial Materials*

Twenty-Third Lecture, June 28, 1949, by William Marsh Baldwin, Jr.—*Residual Stresses in Metals*

Twenty-Fourth Lecture, June 27, 1950, by Wallace R. Brode—*Chemical Spectroscopy*

Twenty-Fifth Lecture, June 29, 1951, by Francis L. La Que—*Corrosion Testing*

APPENDIX B

Concentrated effort in the field of nondestructive testing has been expended by Watertown Arsenal Laboratories for over thirty (30) years, during which time virtually all nondestructive methods have been studied with regard to their Ordnance Corps applicability. Much of this effort has been of a pioneer nature and has earned considerable industrial recognition on a national and international scale. Over the past decade the Pitman-Dunn Laboratories at Frankford Arsenal have been markedly successful in applying advanced electronic design concepts to the development of instrumentation for the performance of magnetic and electrical tests of numerous items of Ordnance. The principle direction of effort at both of these cooperating laboratories at the present time is toward the development of testing principles and equipment capable of providing reliable nondestructive evaluation of Ordnance materials and materiel at such testing speeds that bottlenecks in mass production will not occur.

The abstracts which follow present a very brief picture of the accomplishments and work in progress at these laboratories as a result of previous effort.

Radiography: Pioneer work began at Watertown Arsenal Laboratories in 1922, directed at the evaluation of internal flaws in castings. Radiography has been recognized, as a result of this work, as a valuable tool for the development and control of satisfactory foundry and welding procedures. As such, it has been widely employed by Ordnance installations and industry and has resulted in untold savings in dollars and man-hours in the production of all types of Ordnance materiel. During World War II hundreds of Ordnance Corps inspectors were trained at Watertown Arsenal in the use of radiographic and other nondestructive tests. In addition, specifications and standards were written to permit the standardized application of radiography to production inspection. During the course of concentrated effort in the standardization and specification of radiographic procedures, inadequacies in these procedures were recognized. Critical analysis of these inadequacies has led to a program of development which promises marked improvement in the inspection of many items of Ordnance materiel, important among which are weldments of many types, melt loaded ammunition, rockets and propellants, etc. This work is directed at the development of an electronic X-Ray image pick-up system capable of providing instantaneous images of flaws in Ordnance materiel. (See Fig. 1) If successful, it will eliminate the need for photographic film as an image detection material, along with the attendant costs and time consumed in its exposure and processing. Feasibility has already been demonstrated.

Magnetic Methods: General studies of magnetic particle testing techniques in 1940-1942 at Watertown Arsenal Laboratories led to the preparation of the first Ordnance Corps specification covering these procedures. They were subsequently employed widely throughout the industry for Ordnance procurement inspection of castings, weldments, forgings and many items of materiel. The desire to provide more rapid and reliable examination and wider applicability for these important tests lead to a program at Watertown Arsenal Laboratories for the development of sensitive seach-coil flow detectors. In addition, the Pitman-Dunn Laboratories began a study of commercially developed techniques for the magnetic and electrical evaluation of mechanical properties and soundness of metals. Most of these commercially available equipments were believed to be applicable to many Ordnance problems but had been unsuccessful in the past. The Pitman-Dunn studies resulted in a significantly clearer understanding of the magnetic principles involved and has resulted in the design and construction of successful inspection equipments for a variety of Ordnance production inspection problems. Together with the work of Watertown Arsenal Laboratories, the following accomplishments in the field of magnetic and electrical testing may be listed:

1. The development and construction of a nondestructive hardness test equipment for caliber .30 and caliber .50 AP cores; fully automatic, inspection rate 100 cores per minute. (See Fig. 2)

2. The design and construction of an equipment for the 100% nondestructive acceptance testing of M52A3 electric primers. (See Fig. 3)

3. The design and construction of equipment for nondestructive evaluation of stress relief in caliber .50 brass cartridge cases; inspection rate 9000 cases per light hour day. Previous inspection rate - 1000 cases per day by a less reliable method. (See Fig. 4)

4. The development and construction of a nondestructive hardness test equipment for caliber .50 M9 Belt Links for machine gun ammunition

belts; fully automatic, inspection rate 100 links per minute. (See Figs. 5 and 6)

5. The design and manufacture of a nondestructive hardness test equipment for caliber .50 steel cartridge cases. (See Fig. 7)

6. The development of a high reliability, semiautomatic crack detector for the bore surface of artillery tubes; eight of these Magnetic Recording Borescopes are being constructed for use at Watertown and Watervliet Arsenals, Jefferson, Erie, Aberdeen, and Naval Proving Grounds, Naval Gun Factory, and Dickson Gun Plant. (See Figs. 8 and 9)

In addition to the above past accomplishments, the applied research and evaluation studies in the general field of Magnetic and Electrical testing at Pitman-Dunn Laboratories and Watertown Arsenal Laboratory has led to the following projects which are now in progress and for which work a successful conclusion is visualized.

1. The development of nondestructive test equipment for the detection of heat treating cracks and for the evaluation of hardness of artillery ammunition (AP shot and HE shell); fully automatic, rate of inspection 600 projectiles per hour. (See Figs. 9 and 10)

2. The development of nondestructive test equipment for the field and proving ground evaluation of progressive stress damage in the chamber of 155 mm. artillery tubes. (See Fig. 11)

3. The development of nondestructive equipment for measuring the hardness of steel cartridge cases for artillery ammunition. (See Fig. 12

4. The development of equipment for the nondestructive hardness measurement of 30 mm. high explosive projectiles.

5. The development of equipment for the automatic detection of heat treating cracks in 20 mm. AP shot; inspection rate, approximately 80 shot per minute. (See Figs. 13 and 14)

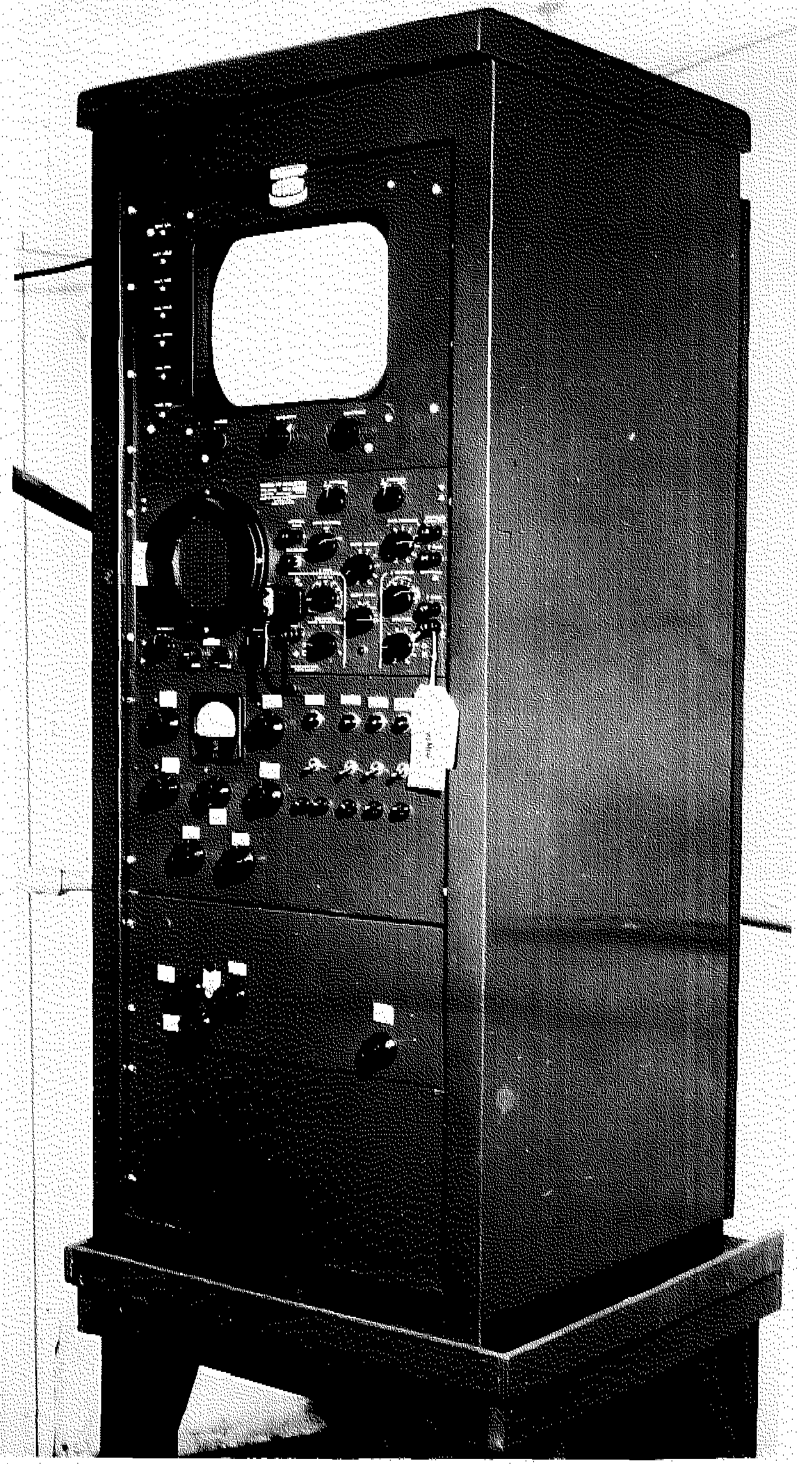
6. The development of equipment for the nondestructive detection of seams, laps, and inclusions in 20 mm. and 30 mm. shell.

7. The development of equipment for detection of cracks in caliber .50 APIT cores.

8. Further applied research in the field of magnetics and electrical behavior of materials. Such basic work is directed at increased knowledge which will be applicable to the solution of specific Ordnance Corps testing and inspection problems as they occur.

<u>Ultrasonic Methods</u>: Although ultrasonic testing techniques received a tremendous increase of industrial applicability in 1942 as a result of technical improvements, the method has enjoyed little applicability to Ordnance inspection and testing because of certain definite limitations of the method as practised. However, at the present time work is under way at Watertown Arsenal Laboratory to develop a standardized test procedure for the detection of cracks and other flaws in tungsten carbide bullet cores. In addition, a new equipment, the Ultrasonic Flaw Plotting Machine, has been constructed for the Ordnance Corps under contract by Electro Circuits, Inc. of Pasadena, California, and is now undergoing evaluation. (See Fig. 15) It is hoped that this machine will provide faster and significantly more economical examination of thick weldments and Ordnance castings such as cast armor, artillery breech rings, structural and armor weldments, etc.

It is believed that ultrasonic attenuation measurements in metals offer considerable promise as a substitute for charpy impact and other destructive tests for determining the mechanical properties. This belief is being followed-up through a research contract with Brown University and additional studies at Watertown Arsenal Laboratory. It has been demonstrated that embrittlement of alloy steels can be detected readily by such ultrasonic measurements. Work is in progress (See Fig. 16) toward the development of practical tests based upon fundamental knowledge of the propagation and scattering of ultrasonic energy in polycrystalline metals. Such work is regarded as having prime potential for future use since most Ordnance items are subject to some form of mechanical loading (tensile, impact, fatigue). It is anticipated that "Ultrasonic Spectroscopy" may hold the key to nondestructive evaluation of the mechanical properties of metals.



WATERTOWN ARSENAL LABORATORY

FLAW IMAGE CONSOLE — PART OF TELEVISION
X — RAY IMAGE PICK-UP SYSTEM

FIGURE 1

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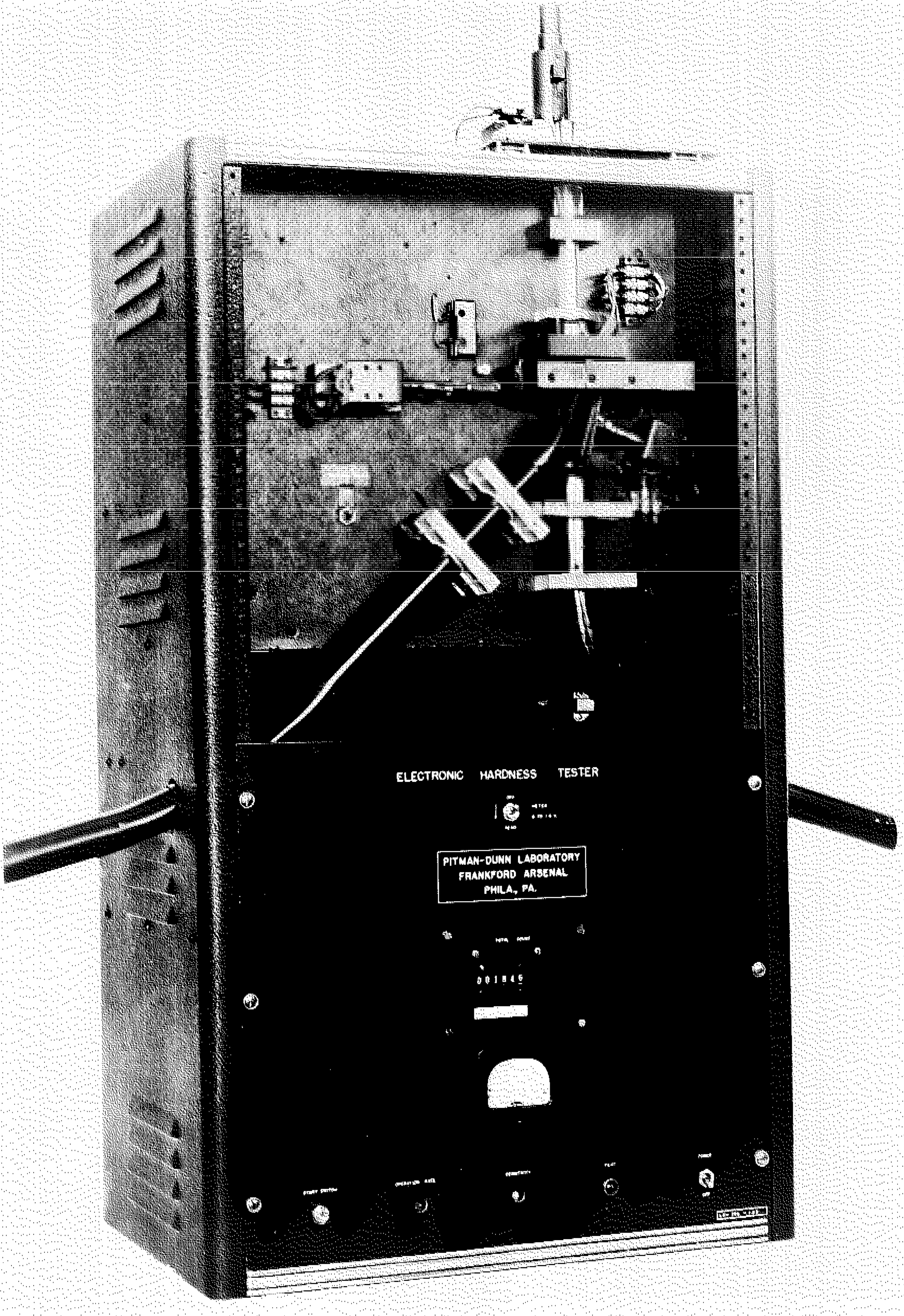
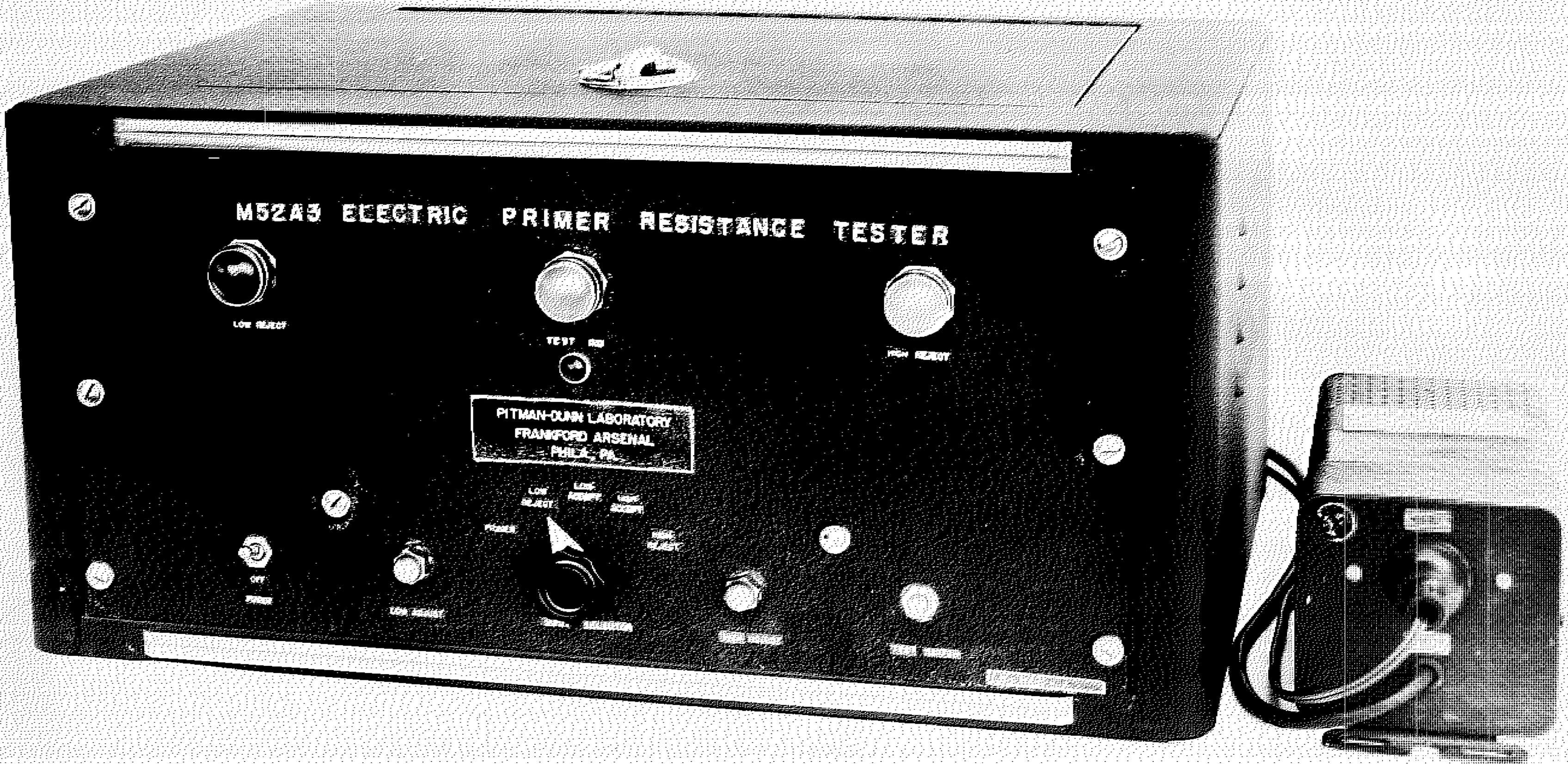
Neg. #24858-1



ELECTRONIC HARDNESS TESTER (Caliber .30 and Caliber .50 Bullet Cores)

Figure 2

Neg. #24858-3



M52A2 ELECTRIC PRIMER RESISTANCE TESTER

Figure 3

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CALIBER .50 BRASS CASE HARDNESS TESTER

Figure 4

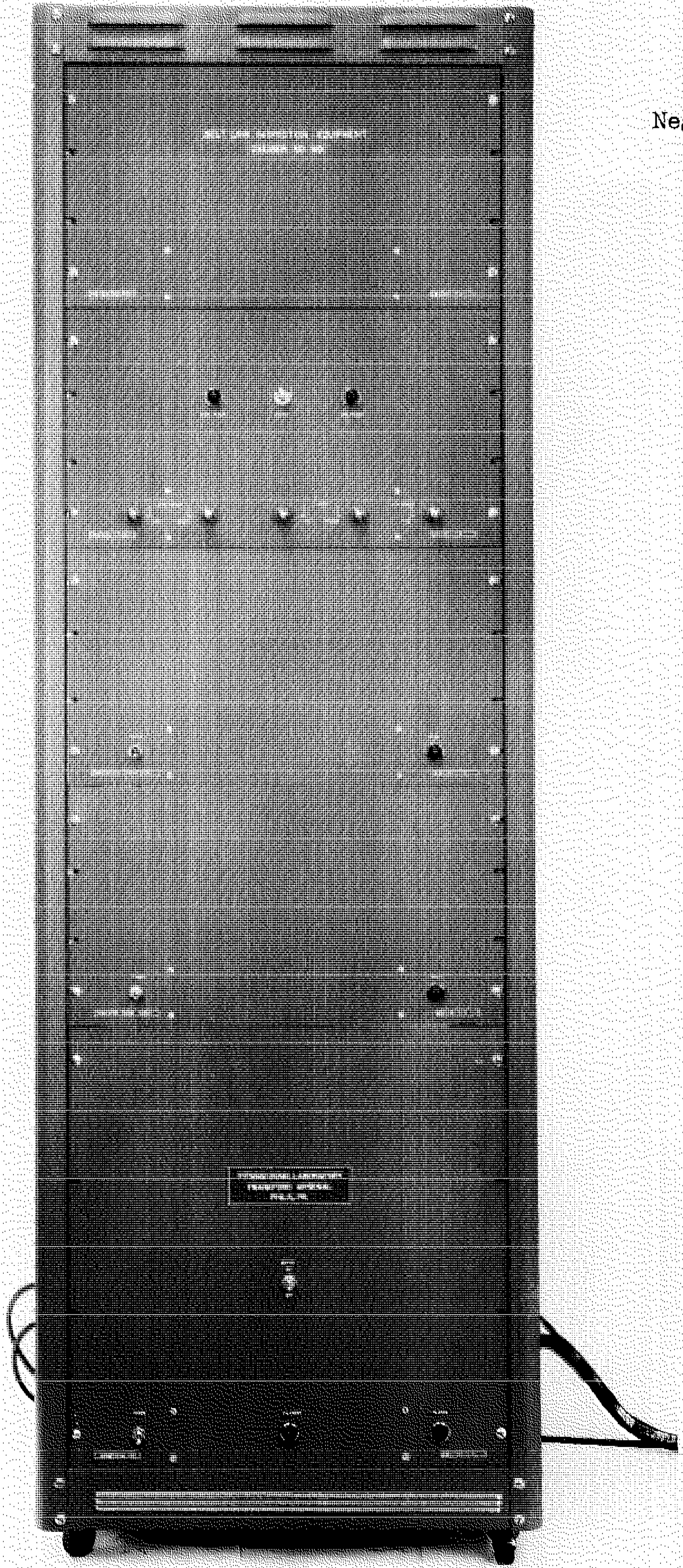

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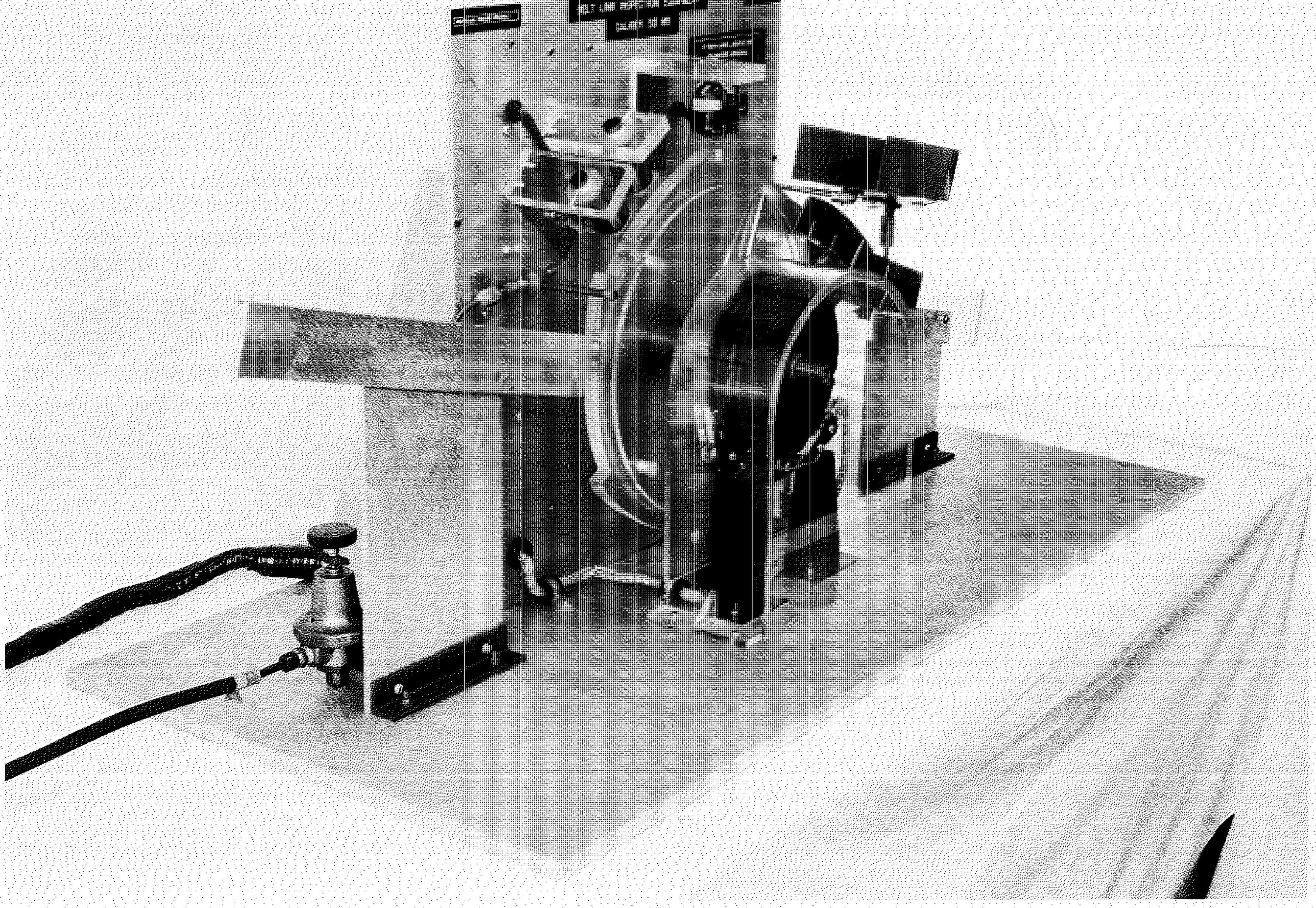
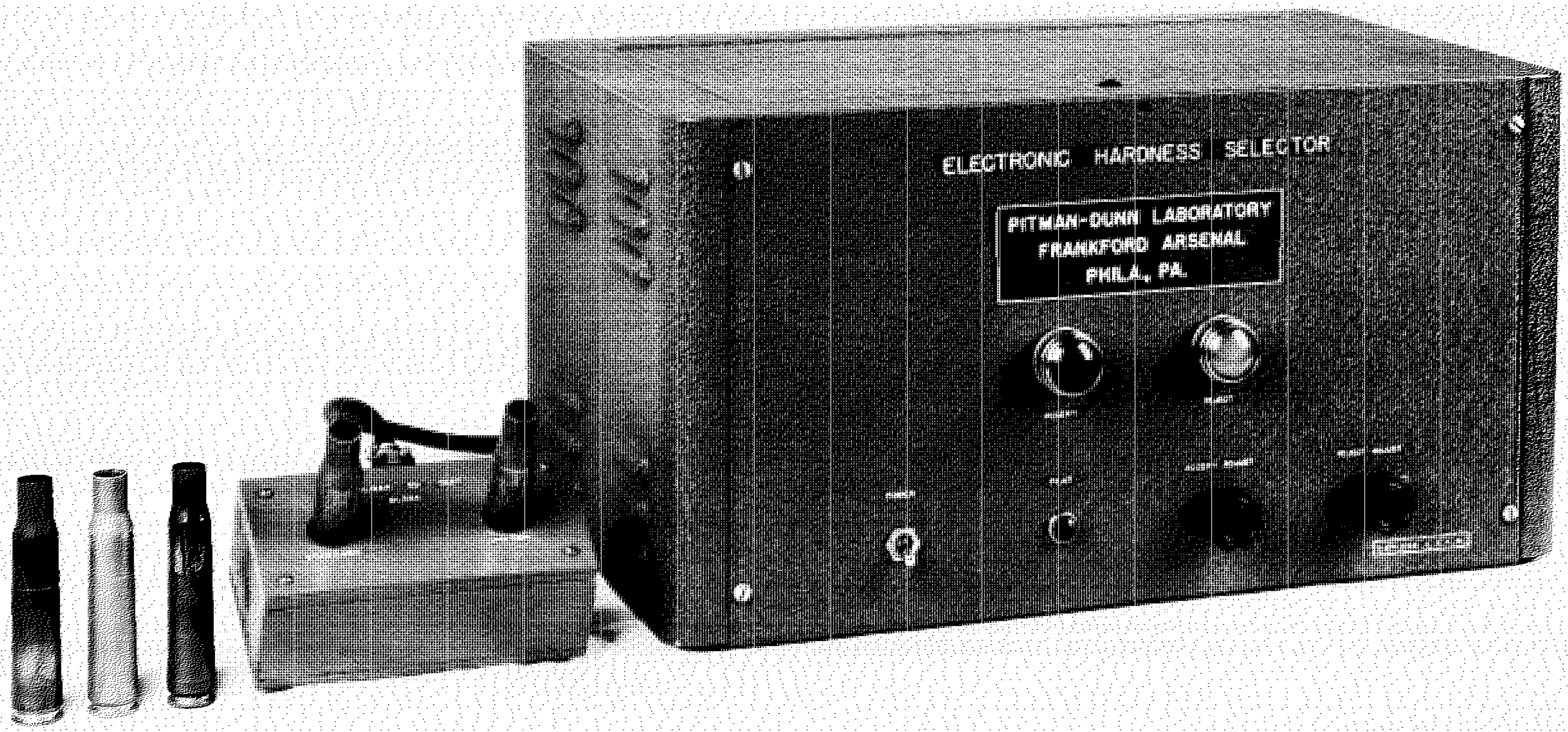
Figure 5 BELT LINK INSPECTION EQUIPMENT (Caliber .50 M9)
ELECTRONIC CONTROL PANEL



BELT LINK INSPECTION EQUIPMENT (Caliber .50 M9)
INSPECTION STATION ASSEMBLY

Neg. #24673

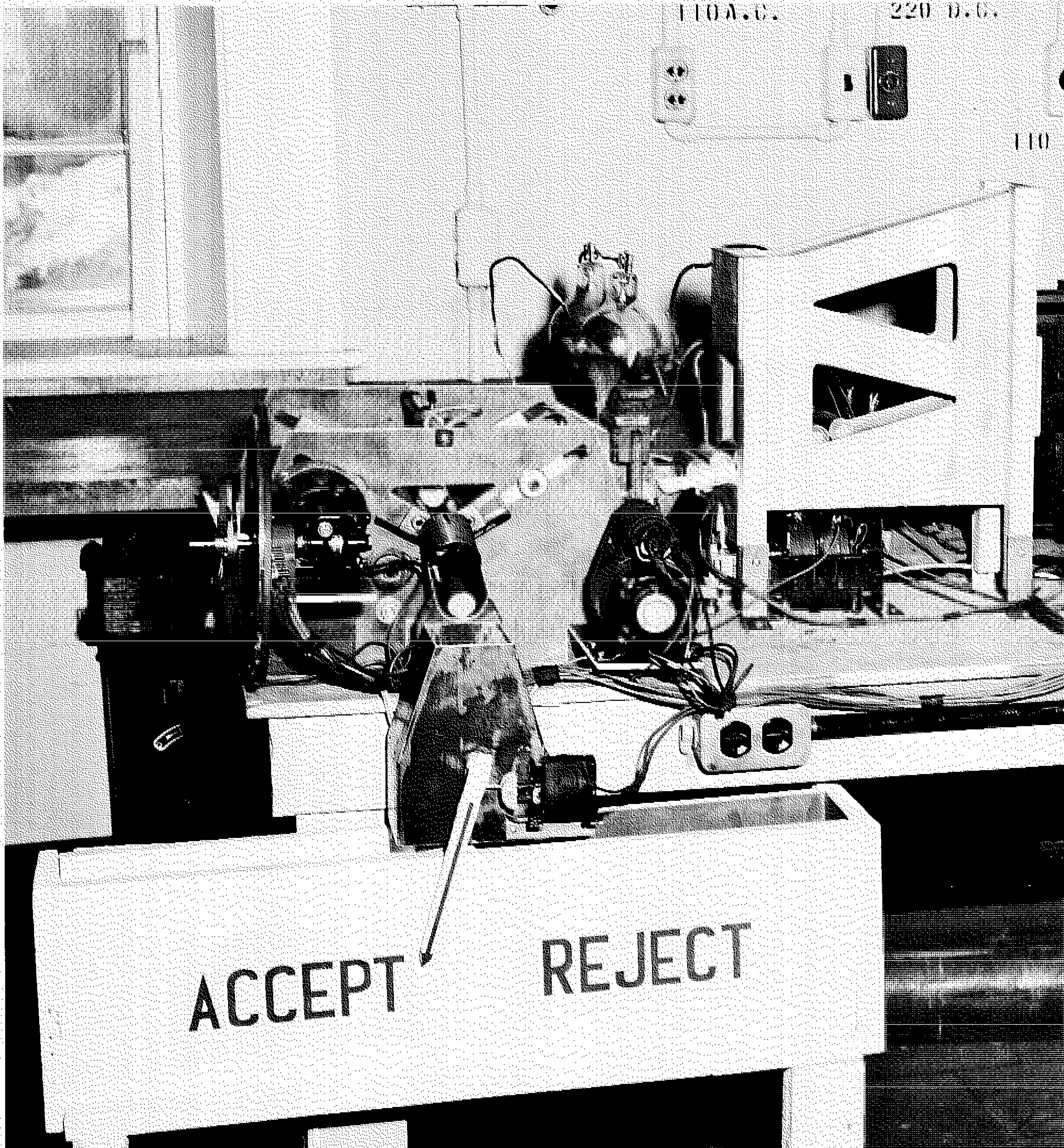


ELECTRONIC HARDNESS TESTER
(Caliber .50 Steel Cartridge Case)

Figure 7

WATERTOWN ARSENAL LABORATORY

FIGURE 8 ——MAGNETIC RECORDING BORESCOPE IN USE AT THE BORESCOPE INSPECTION STATION, WATERTOWN ARSENAL 26 JUNE 1951. WTN.681-452



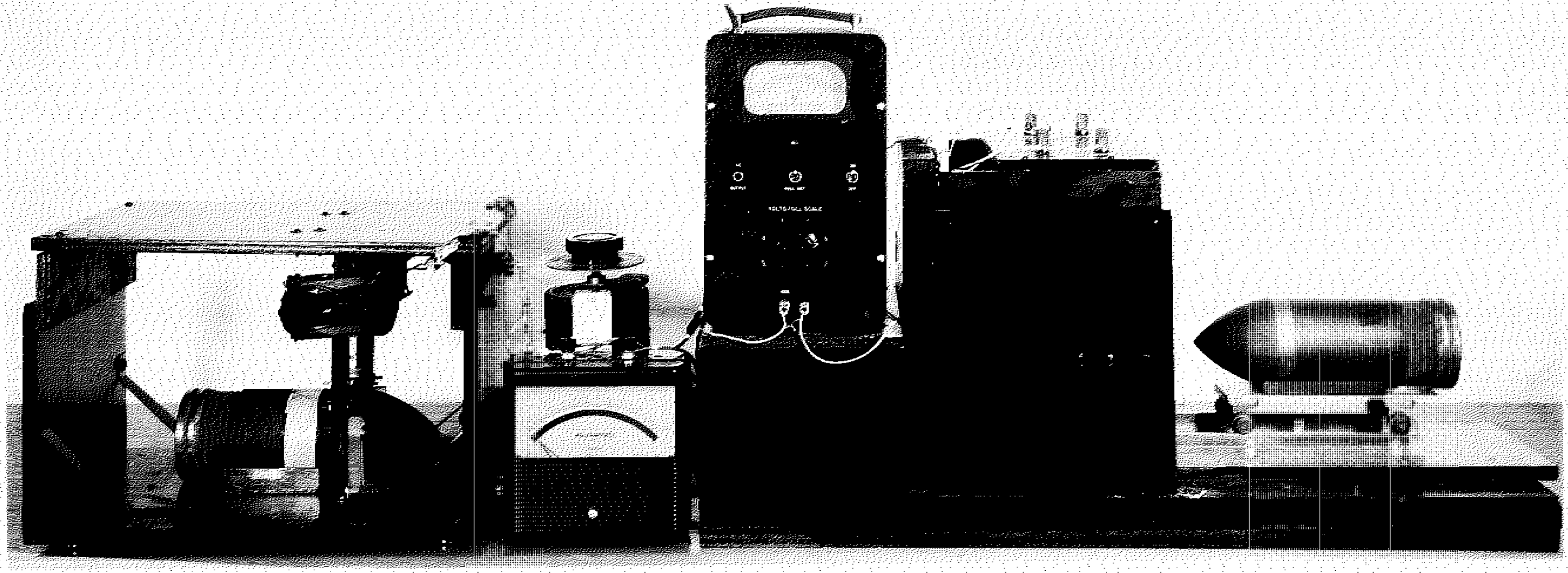
WATERTOWN ARSENAL LABORATORY

LABORATORY MODEL OF AUTOMATIC
CRACK DETEDTER FOR PROJECTILES

FIGURE 9

WTN.681-392

Neg. #24858-5



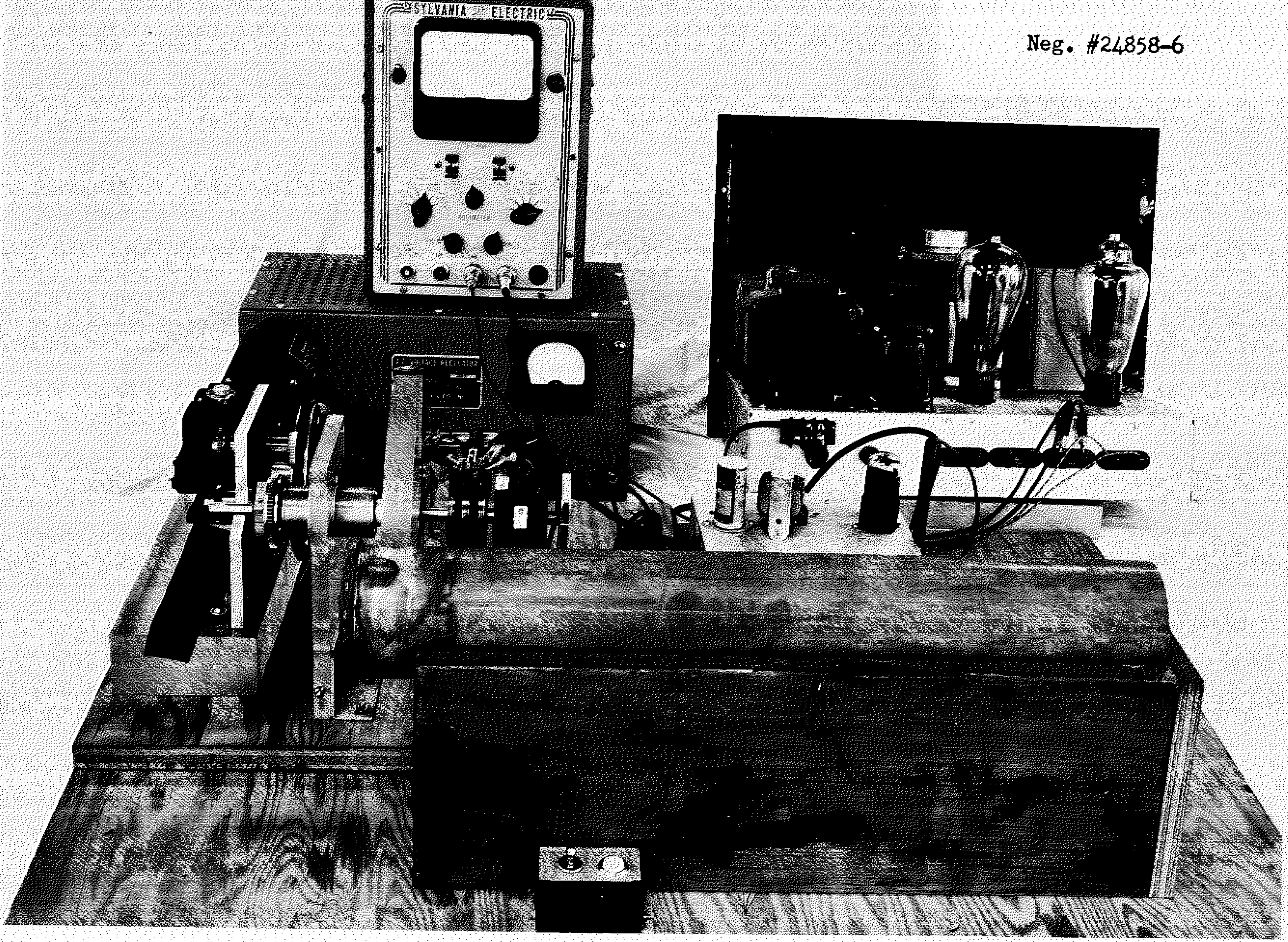
INSPECTION OF ARMOR PIERCING SHOT FOR HARDNESS
Laboratory Model - 90 mm A.P. Shot Tester

Figure 10

WATERTOWN ARSENAL LABORATORY

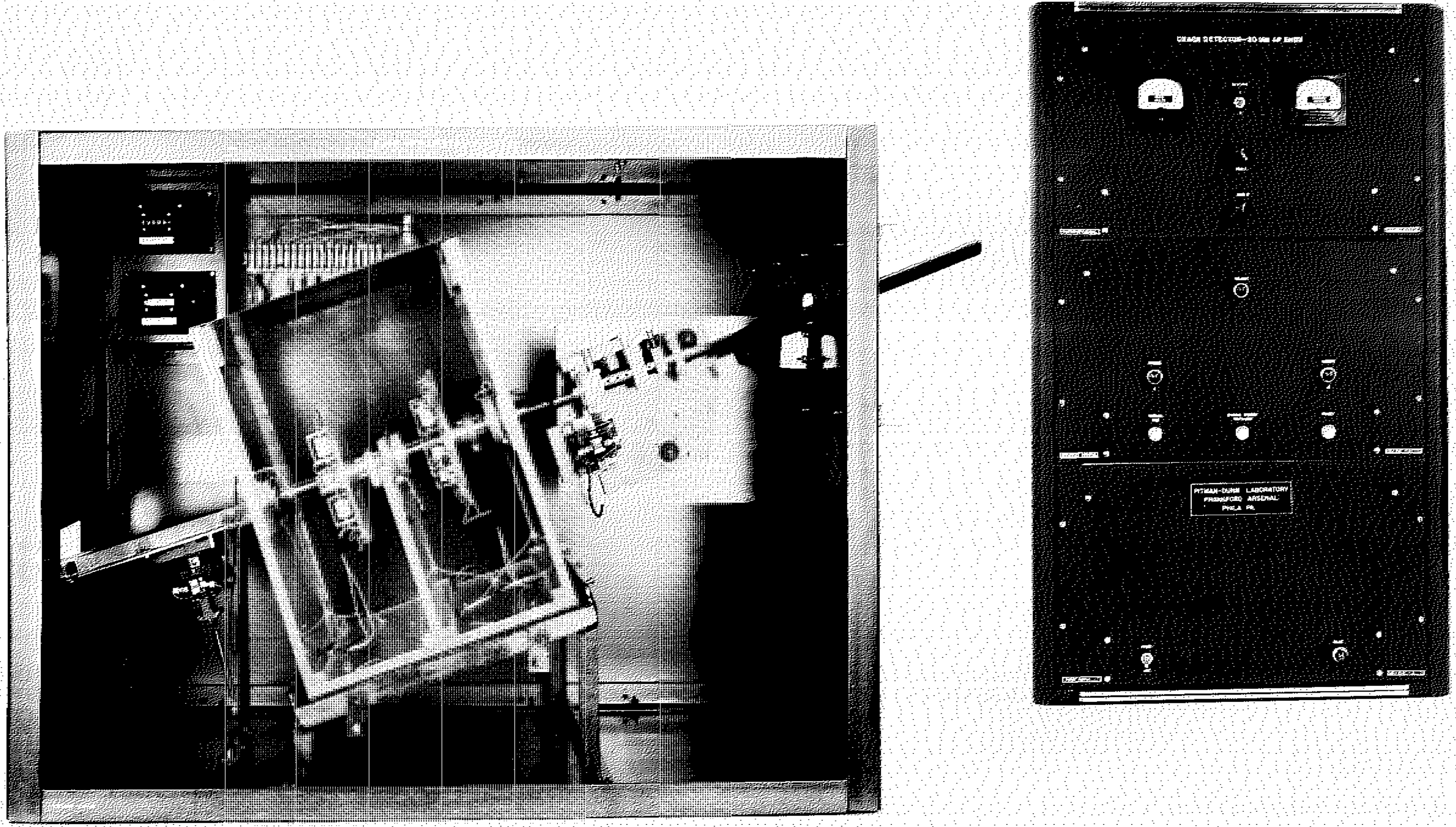
FIGURE 11 —— THE MANETIC RECORDING BORESCOPE.(FIELD MODEL) AN INSTRUMENT DESIGNED FOR THE DETECTION AND MEASUREMENT OF SERVICE INDUCED CHAMBER CRACKS IN THE 155MM HOWITZER AND GUN IN THE FIELD. WTN.681-503

Neg. #24858-6



NONDESTRUCTIVE HARDNESS TESTING OF STEEL CASES
Laboratory Model - Residual Magnetism Technique

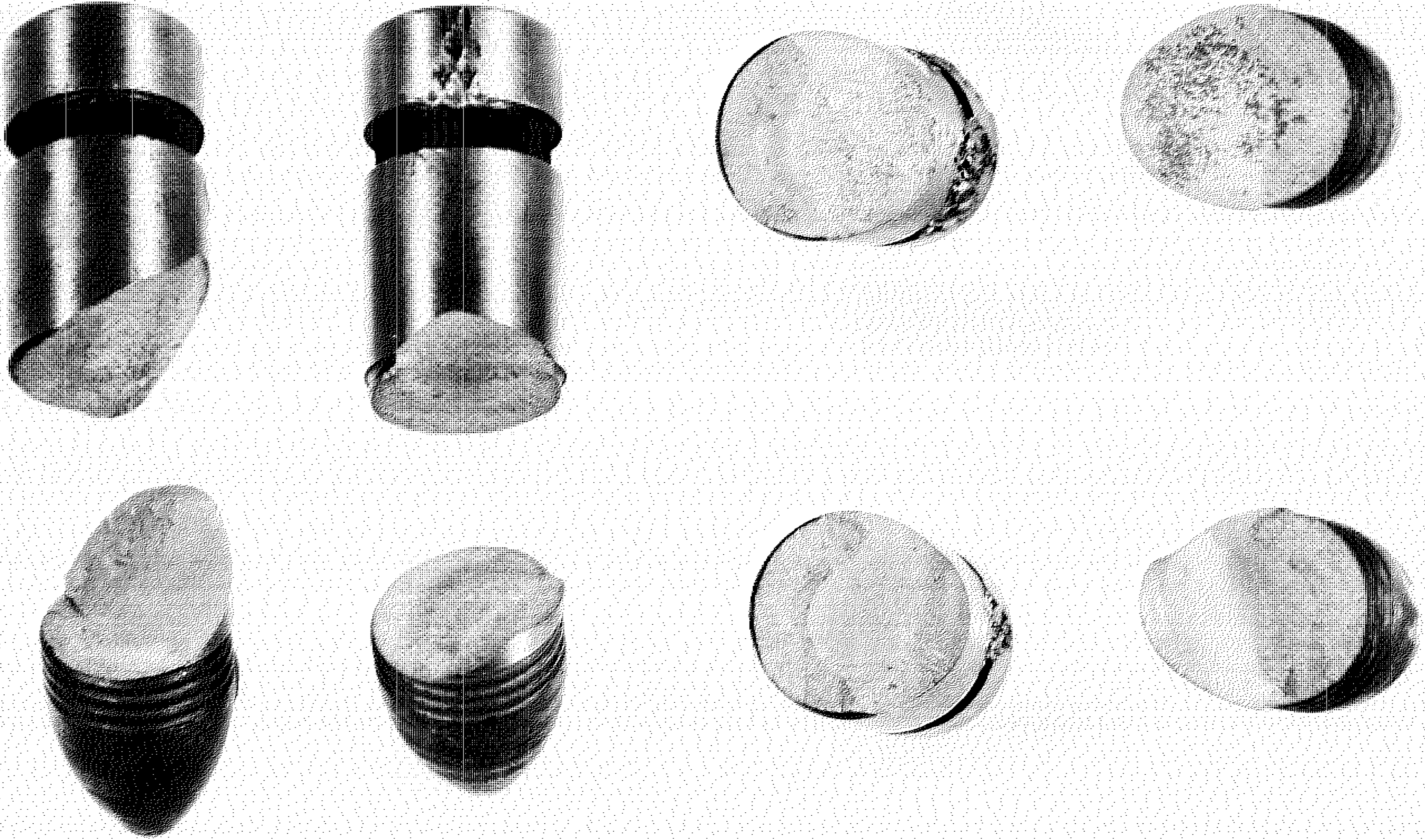
Neg. #24702



CRACK DETECTION FOR 20 mm A.P. SHOT (Front View)

Figure 13

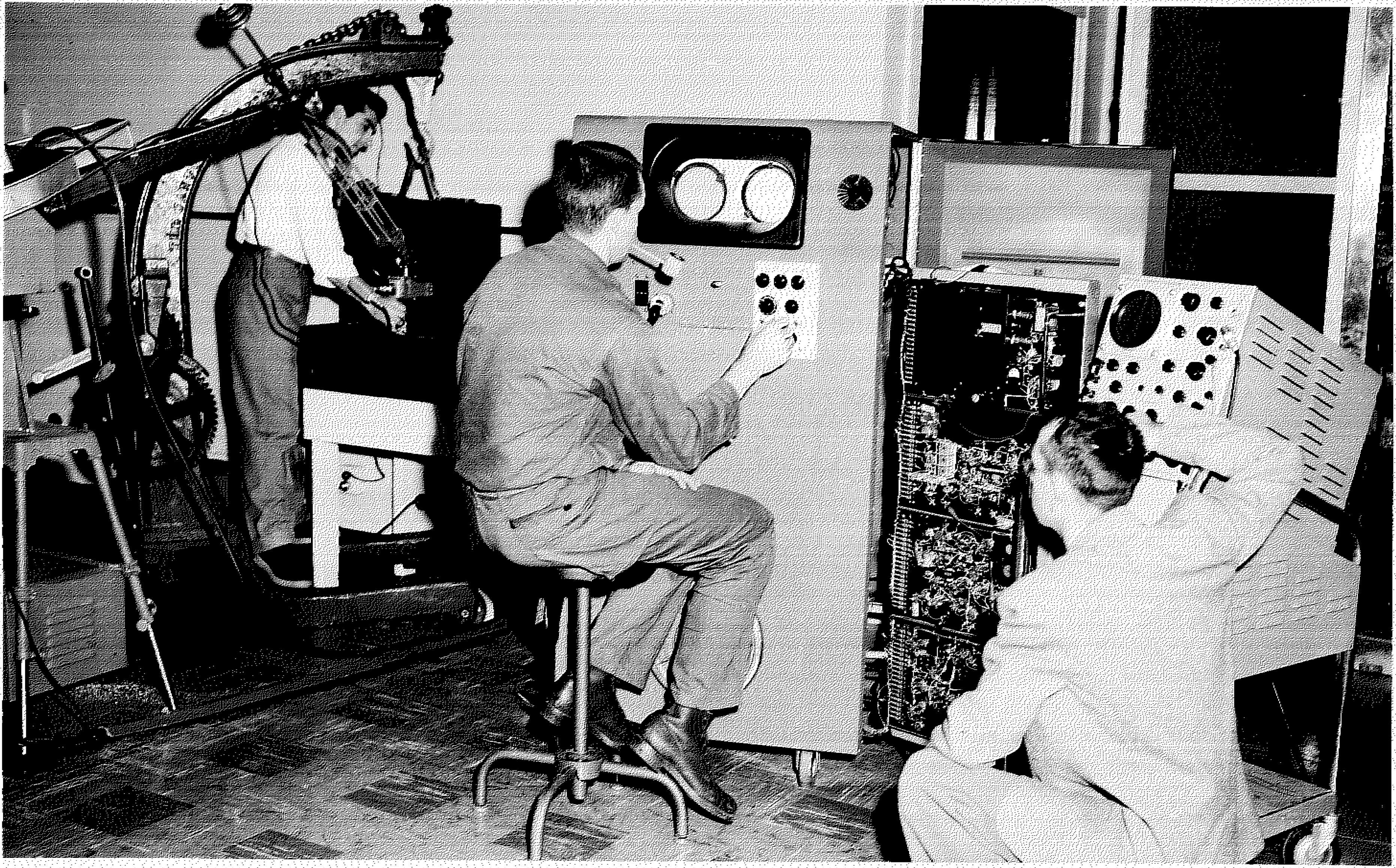
Neg. #



CRACK DETECTION IN 20 mm A.P. SHOT

Shot inspected and accepted by Magnaflux method but rejected by Pitman-Dunn Crack Detector. Broken specimens revealed flaws.

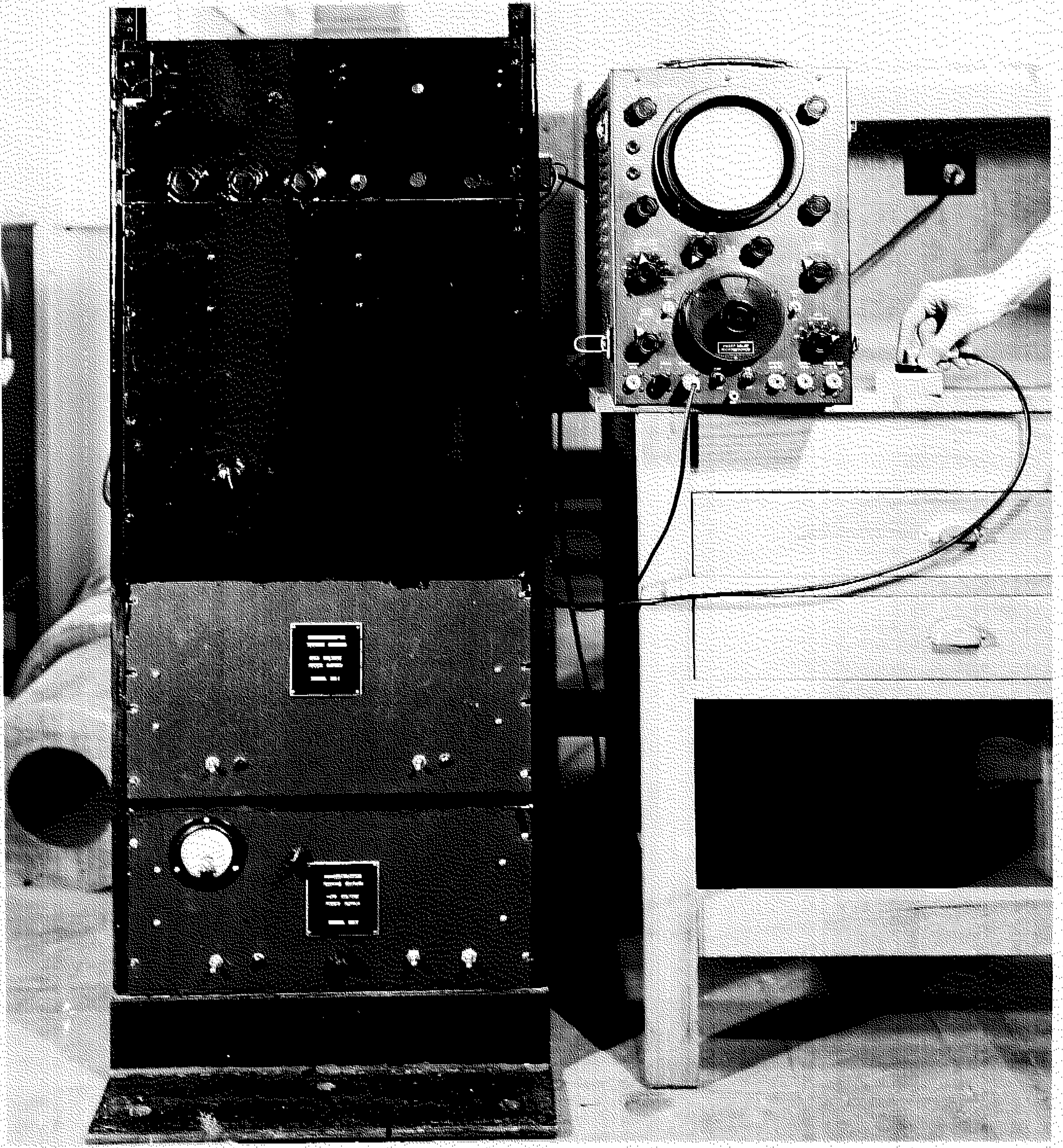
Figure 14



WATERTOWN ARSENAL LABORATORY

FIGURE 15 —— ULTRASONIC FLAW PLOTTING MACHINE UNDERGOING EVALUATION ANALYSIS AT WATERTOWN ARSENAL LABORATORY

WTN.681-582



WATERTOWN ARSENAL LABORATORY

ULTRASONIC ATTENUATION MEASURING EQUIPMENT - FRONT VIEW

WTN.681-495

FIGURE 16