NONDESTRUCTIVE TESTING OF SPACE VEHICLE LIQUID PROPELLANT ROCKET ENGINES

by

D. Hagemaier

Rocketdyne
A Division of North American Aviation, Inc.
Canoga Park, California

Presented at the
Western Metals Congress
Los Angeles, California
15 March 1967

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ABSTRACT

This report describes the various nondestructive test methods employed to evaluate materials and processes used in the manufacture of large liquid propellant rocket engines at the Rocketdyne Division of North American Aviation, Inc. The contents of the paper were purposely oriented for an audience of aerospace, design and materials engineers.

A brief description of liquid propellant rocket engine reliability is presented. The relationship of standards and specifications to nondestructive testing is discussed and various test methods are described along with a discussion of their applications and limitations. The sequence of events leading up to the use of nondestructive testing in production inspection is presented. Finally, the organization of labor directly related to nondestructive testing is given.

The author is associated with the Materials and Processes Group at Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California. This paper is scheduled for the Western Metals Congress, 15 March 1967, Los Angeles, California.

INTRODUCTION

Nondestructive testing (NDT) encompasses the entire electromagnetic spectrum (except for cosmic rays) and also includes other tests such as liquid penetrant, ultrasonic, magnetic particle, leak testing, etc. Basically, we might say that NDT includes any test method which can yield qualitative or quantitative evaluation of a material or process without harm to the part being tested. Although a vast array of test methods have been developed for use in NDT, I will confine my discussion to only those tests used at Rocketdyne for inspection of large liquid rocket engine components.

The selection of useful and economical nondestructive techniques requires an understanding of the comparative capabilities, advantages, and limitations of all basic nondestructive test methods. Evaluations presented in this paper are based upon the experience of the author and the successful application of the specified nondestructive tests for inspection of production hardware.

LARGE LIQUID ROCKET ENGINES

Throughout the modern era of rocketry, liquid propellant rocket engines have demonstrated their capability to provide high performance, high reliability and operational flexibility. It has always been desirable to have high launch vehicle reliability. With the advent of manned missions, high reliability became mandatory. A summary of the space launch record (1) shows there have been 378 launches of vehicles using liquid propellant engines since the first United States satellite was launched. Over 410 major propulsion systems involving more than 1600 engines have been used. Including all the propulsion systems used in space launches, a propulsion system flight reliability of 0.965 has been demonstrated. The Rocketdyne engines which participated in some of these space launches are listed in Table 1.

Table 1. Rocketdyne Liquid Propellant Rocket Engines

Engine Designation	Thrust (sea level), pounds	Thrust (vacuum), pounds	Oxidizer	Fuel	Vehicle Application	Stage Prime Contractor
LR89-NA-7	154,500	177,300	LO_2	RP-1	Atlas	GDC
LR105-NA-7	57,000	80,500	↓	RP-1	Atlas	GDC
LR79-NA-11	170,000	195,100		RP-1	Thor	Douglas
LR3-NA-18	150,000	174,500		RP-1	Jupiter	Chrysler
LR43-NA-1	78,000	87,700		Alcohol	Redstone	Chrysler
H-1	205,000	230,500		RP-1	S-I	Chrysler
J-2	--	230,000		LH_2	S-II	S&ID
J-2	--	230,000		LH_2	S-IVB	Douglas
F-1	1,522,000	1,748,000		RP-1	S-IC	Boeing

The engine reliability program begins with design and manufacturing to ensure accurate, high-strength, failure-free hardware. Extensive inspection procedures further assist this phase. Engine component testing follows inspection, and finally the liquid propellant rocket engine can be subjected to extensive testing in the development phase to uncover any potential weakness. This extensive test effort provides a high degree of confidence in the engine reliability. Liquid rocket engines also provide the capability of testing the article that will be used during the actual launch. Also, each engine is tested before it is delivered to the customer and later each stage and engine is tested as a unit and completely checked out prior to the launch. Figure 1 shows a completed Rocketdyne F-1 engine. Five of these 1,500,000-pound-thrust engines will be used on the manned Saturn moon rocket booster stage.

Small hypergolic ablative engines used for descent and maneuvering of the Gemini and Apollo command modules were manufactured by the Rocketdyne Small Engine Division. A complete discussion concerning nondestructive testing of these small ablative engines is given in Ref. 2.

RELATIONSHIP OF STANDARDS AND SPECIFICATIONS TO NDT

Much attention has been given to NDT during recent years. Its favor or disfavor usually ensues from arguments over the variation in test results from different test methods or from variation in interpretation of specific test results. Nondestructive tests are not "tests," but rather measurements, in that the size of defect is usually indicated rather than the performance capabilities of the material or device. In a testing or measuring operation, it is necessary to have a comparative or reference standard which is generally accepted by other people in order that the results be meaningful. If the results of a measurement or test are to be meaningful, the conditions or method of testing must be known. If the test results are to be reproducible, then the method of test must be uniform. Hence, standards control the test sensitivity and specifications specify the method of test or test conditions (3).

What should be included in a specification which deals with nondestructive testing? The answer is somewhat difficult and accounts for some of the problems surrounding NDT specifications. Frequently used working in quality specifications is: "The part shall be free of detrimental defects." This rather conservative attitude is convenient for specification writers, but unfortunately, an X-ray machine or X-ray film reader is not able to determine whether a defect is detrimental or not. It seems rather obvious that the specification must include a description of an acceptable quality level. This quality level must be defined in terms or related to reference standards which can be understood by persons performing the inspection, or by persons who are responsible for interpreting test results.

There is an explanation for the general and noncommittal definition of acceptable quality levels in specifications. Nondestructive tests only indicate the defect size rather than measure the defect size absolutely. For example, in a surface inspection test, such as penetrant or magnetic particle inspection, the length of a defect on the surface is fairly well

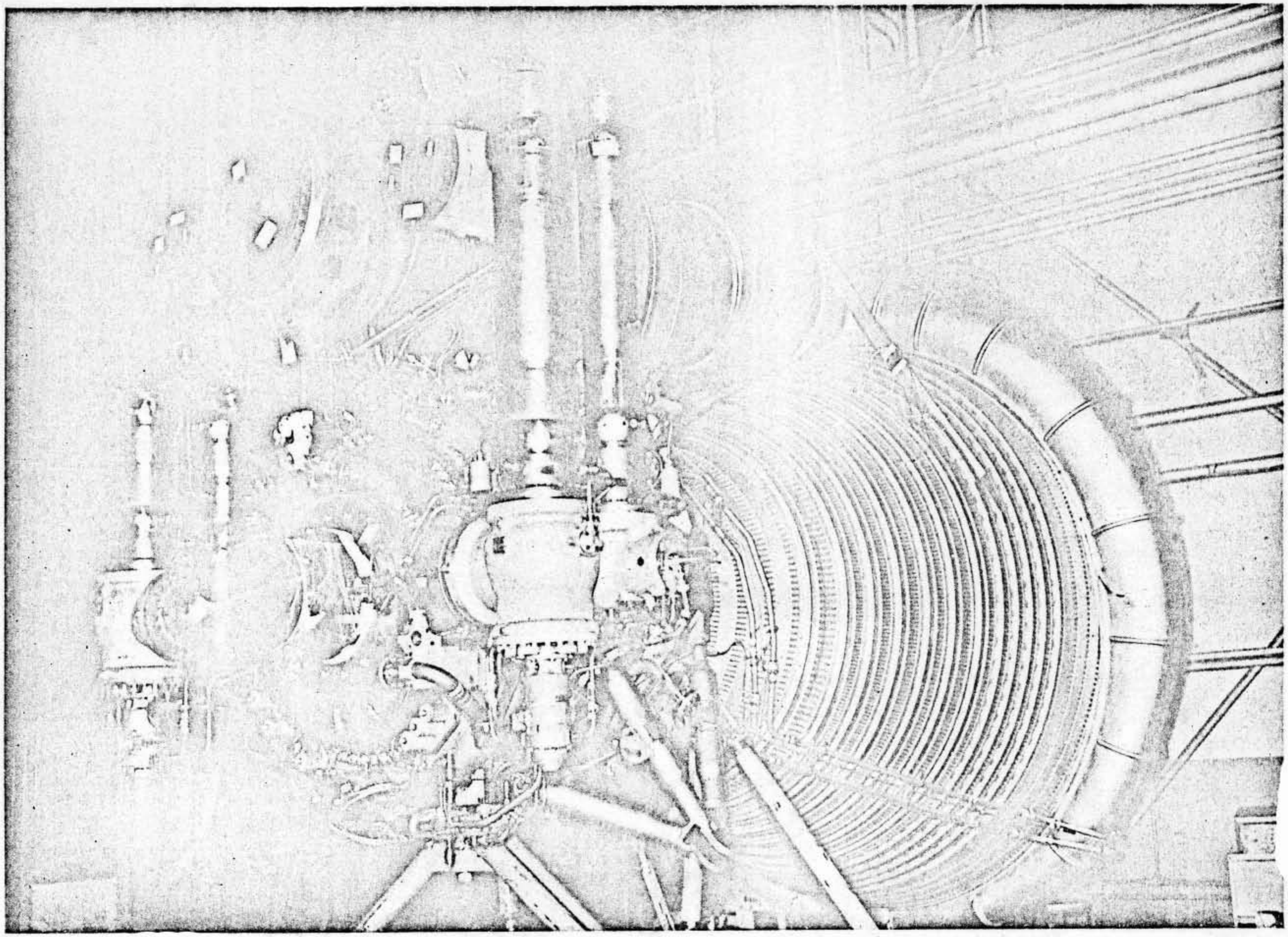


Figure 1. Apollo Space Vehicle Booster Engine, The Rocketdyne 1,500,000 Pound Thrust F-1

defined, however, the depth of the defect can only be estimated. The actual defect size in X-ray and ultrasonic testing is not absolute even with the best techniques and taking into account all of the variables which may influence test results. An even more difficult problem is that of determining the effect of a defect on the service life of a part or piece of material even if the absolute defect size and location is known. Considering the variables involved then, such as size, shape, orientation of defect, complex stress distribution, variation in properties of materials, etc., it is no small wonder that NDT test specifications do not describe acceptable quality levels in definitive terms.

There are less obvious reasons why nondestructive test specifications lack specific acceptance criteria. Persons specifying materials frequently believe materials are homogeneous and in every way perfect unless they are obviously defective. In reality, our materials possess discontinuities which may vary in size from the dimension of the atomic lattice up to visually apparent defects. Also, the nondestructive testing tools used possess sufficient sensitivity to detect discontinuities that would not be harmful to the part or material.

Recognizing the difficulties in specifying acceptable quality limits for materials, it is an inescapable necessity that the specification requiring NDT must define the limits of acceptable quality. Failing to do so is like asking an inspector to check a part to a drawing which does not have dimensional tolerances specified. When engineering problems defy theoretical solutions, then empirical or cut-and-try methods are used. Correlations of service performance, fatigue life, etc., to NDT results are desirable. The number of variables involved, however, necessitate vast quantities of correlative tests and much work is yet to be done in this regard.

There are three major sources of information which can aid in the establishment of acceptable quality levels: (1) theoretical considerations and/or stress analysis, (2) correlation of nondestructive test results with mechanical properties, destructive tests, or service life results, and (3) quality level of similar parts used in the past successfully. In view of the difficulties of using information from theoretical analysis or empirical test correlation results, one of the best sources of information for establishing acceptance levels is the basis of past experience.

An inspection acceptance level arrived at on this basis not only gives reasonable assurance that the material or parts will serve their purpose satisfactorily, but also permits an acceptance level which is economical. Naturally, materials producers' quality level cannot determine design requirements, but on the other hand, it is extravagant to establish a quality acceptance level beyond that which has existed for similar parts that past experience has shown to have performed satisfactorily. The best nondestructive test specifications or specifications incorporating nondestructive test requirements are for specific parts. The more general the specification, the more worthless it becomes. A complete listing of current specifications and standards for NDT can be found in Ref. 4.

Now that you are aware of some of the problems in interpretation of test results, let us look at the test methods themselves and see how and why they are used.

TEST METHOD DESCRIPTION AND APPLICATION

RADIOGRAPHIC INSPECTION

X-ray absorption is a function of the atomic number and thickness of the absorber, therefore the selection of energy is dependent upon the part being inspected. For section thickness of 2 to 8 inches, 1- or 2-mev equipment, located at the Los Angeles Cancer Clinic, is employed. Sections ranging in thickness from 8 to 20 inches can be penetrated using 15- to 25-mev Betatrons or Linear Accelerators. The radioactive isotope of Iridium-192 fills the energy gap between 300-kv and 1-mev X-rays. Iridium emits gamma rays of average energy equivalent to approximately 450-kv X-rays and is used for steel equivalent specimens of 1/2 to 2-1/2 inches thick. Radioactive Cobalt-60 emits gamma rays of approximately 1.2-mev-equivalent X-ray energy and is used for steel equivalent sections of 1 to 8 inches thick. Cobalt-60 has a half-life of 5.5 years and Iridium-192, 75 days.

To make a radiograph: (1) film is placed in a light-tight holder and placed close to the part to be inspected, (2) the radiation is passed through the part and exposes the film, (3) the film is processed and dried, and (4) the negative film image is interpreted (Fig. 2). Radiographic emission from different sources is illustrated in Fig. 3.

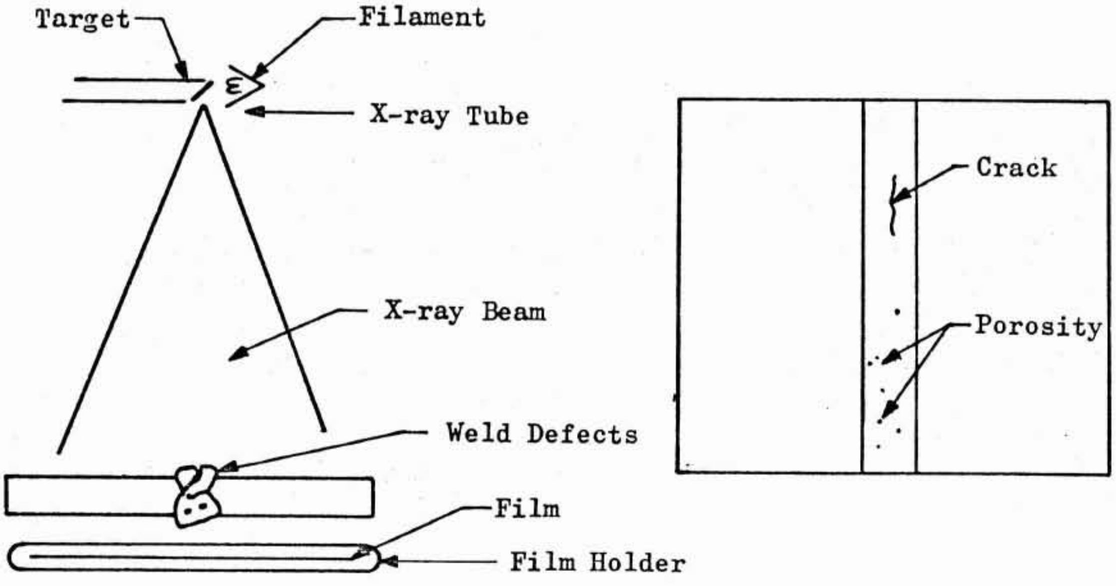
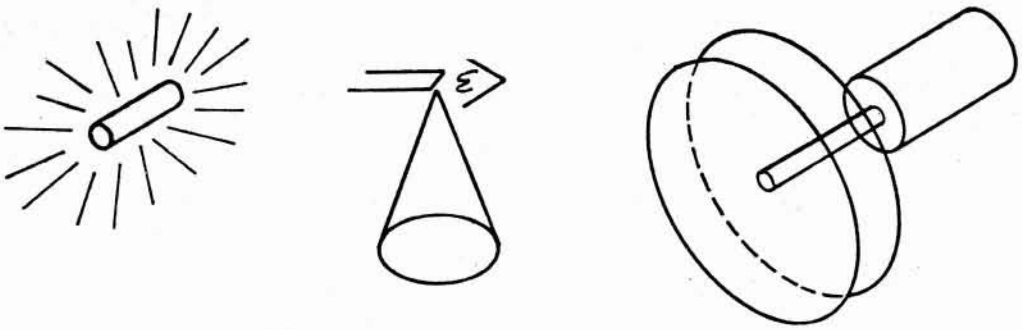


Figure 2. Radiographic Inspection Method



Radioactive Isotope Gamma Ray Emission in all Directions

Standard Conical X-ray Beam

Rod-Anode X-ray Beam 360 x 30 Degrees

Figure 3. Radiation Emission From Different Sources

Radiography is used to detect internal defects in all Class-I weldments and high-strength castings, to determine braze alloy distribution in brazed thrust chambers or components, and to internally inspect electrical assemblies for missing or broken components. Laboratories are located in each of four manufacturing buildings and the Santa Susana Field Laboratory. The X-ray machines range in energy from approximately 50 to 300 kv. Typical radiographic inspection enclosures are shown in Fig. 4.

LIQUID PENETRANT INSPECTION

When the surface of a test object has been wetted with liquid penetrants, capillary action causes the fluid to flow into interstices and cracks which are open to exposed surfaces. A period of time is required to permit the penetrant to migrate into very fine cracks. When penetration is complete, the surface is quickly washed clean of the penetrating fluid, without greatly disturbing the penetrant which is deep in discontinuities. To develop clear surface indications, the exposed areas are next coated with a suitable porous material. This developer provides a contrasting surface against which the indications are clearly revealed, and the coating also acts as a blotter by supplying capillary channels through which the penetrant fluid can flow outward. After a short period of time, the penetrants flow to the surface where they are: (1) evident as wet spots, (2) dye the coating with brilliant color, or (3) fluoresce brilliantly when illuminated with ultraviolet (black) light (Fig. 5).

Penetrants are applied by dipping, spraying, or brushing. They differ in sensitivity and are selected for a particular inspection. There are dye or fluorescent types consisting of oil- or water-base constituents. The water-base penetrants are used on parts which will be in contact with liquid oxygen or other active oxidizers.

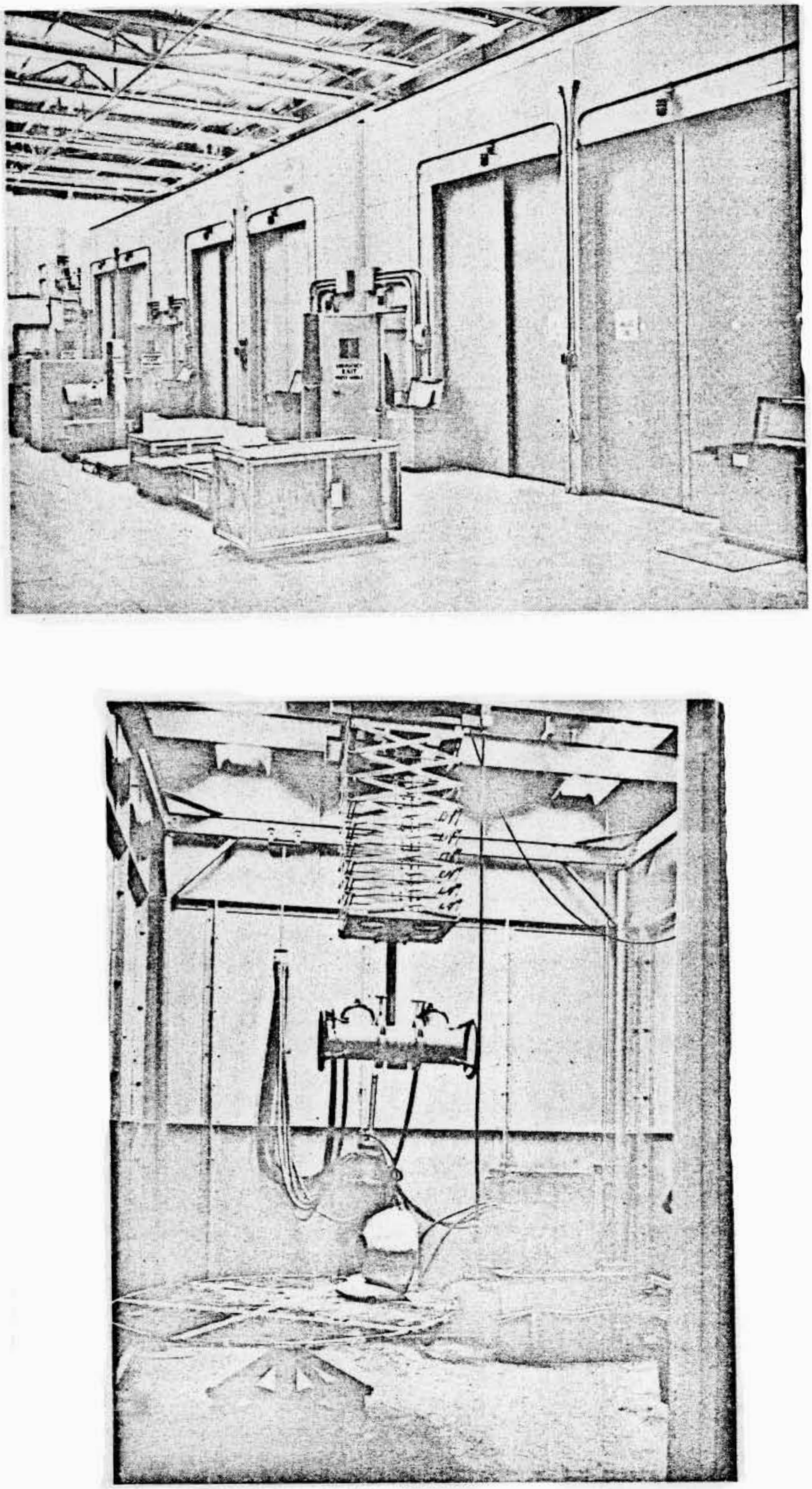
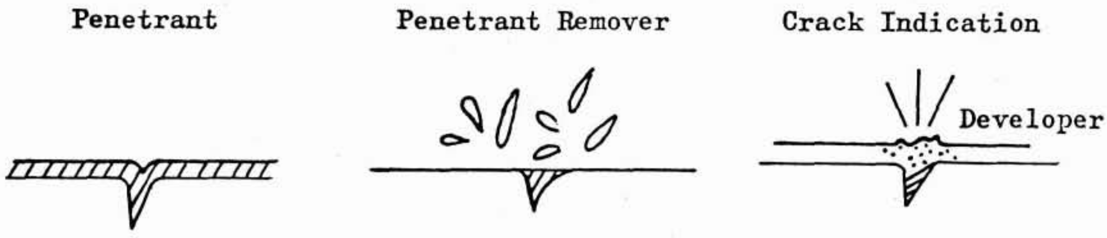


Figure 4. Radiographic Enclosures for Production Inspection



Penetrant Soak Time

Solvent Cleaned or Water Sprayed

Crack Indication, Penetrant Wets Developer

Figure 5. Penetrant Inspection

Before parts can be penetrant inspected, they must be cleaned of scale, dirt, oil, paint, or similar materials and in many cases the parts require an acid descale to remove smeared metal. Leak testing is accomplished by applying penetrant on the inner surface and developer on the outer surface. The penetrant leak time is based on part thickness and desired sensitivity. The penetrant leak test is used to detect unbonds in many brazed assemblies at Rocketdyne. All Class-I and Class-II weldments, tubing (5), all castings, forgings, and in general all nonmagnetic-finished machined parts require penetrant inspection.

Penetrant inspection areas are located in each of the four manufacturing buildings and portable inspection kits are located in all manufacturing areas conducting welding. A typical fluorescent penetrant inspection system is shown in Fig. 6.

The "penestrip" process was developed by North American Aviation, Inc. in Inglewood, California. This particular penetrant is solvent base and has demonstrated the ability to enter very tight cracks in periods less than 5 minutes (6). The excess penetrant is removed with a detergent-type remover and a final wipe with a water-dampened rag. The part is then sprayed with a white lacquer whose solvent is the same as that used in the penetrant. Defect indications appear immediately and the part is continually sprayed until a clear indication is obtained. If a record of the inspection is desired, the part is sprayed with a clear lacquer which aids further development and provides body to the coating which can be stripped off in 15 to 30 minutes. Because of the sensitivity of the "Hy-Rez"* inspection, it is only used to find very fine cracks such as shown in Fig. 7. It is used in the engieering NDT Laboratory for failure analysis and process development.

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*Magnaflux Corporation

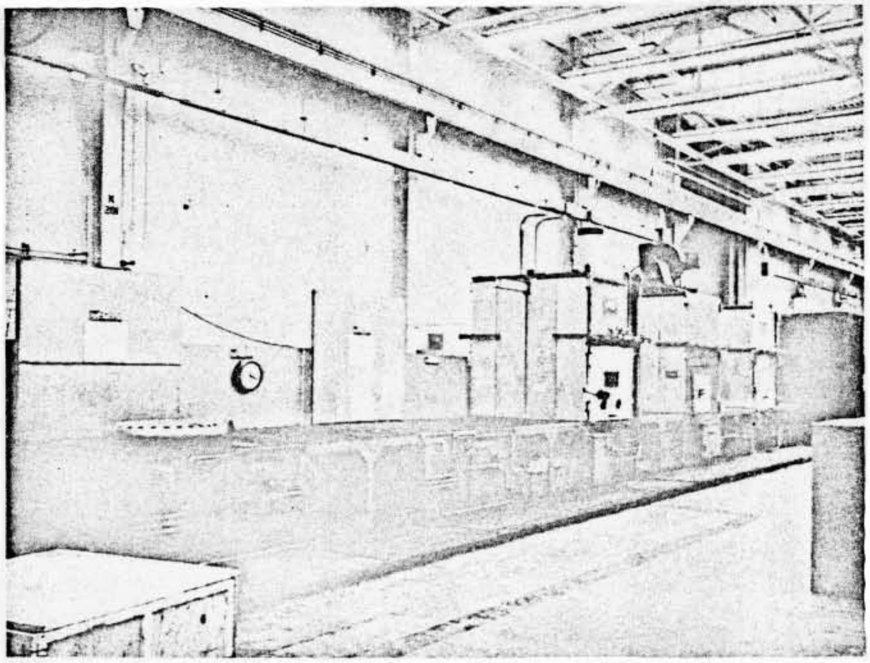


Figure 6. Fluorescent Penetrant Inspection Facility

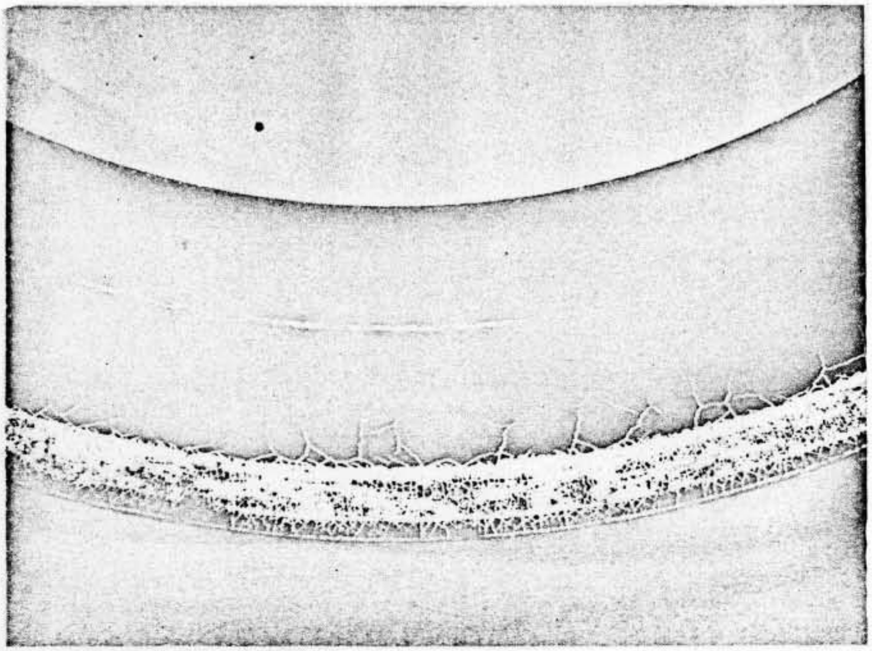


Figure 7. Fluorescent Hy-Rez Indications of Cracks in Chromium Plating on 440C Material

MAGNETIC PARTICLE TESTING

Magnetic particle inspection is a nondestructive means of detecting discontinuities in ferromagnetic materials. It consists of three basic operations:

1. Establishing a suitable magnetic field in the test object
2. Applying magnetic particles to the surface of the test object
3. Examining the test object surface for accumulation of the particles (indications), and evaluating the test object

The method can detect all discontinuities at the surface and under certain conditions, those which lie completely under the surface. Nonferromagnetic materials, which cannot be strongly magnetized, cannot be inspected by this method.

The sensitivity of the test is usually controlled by the applied current and the density of the magnetic particles employed. The magnetic particles vary from a red or black dust only, to similar particles suspended in a nontoxic oil base. Fluorescent particles suspended in a nonfluorescent oil base have proved to be a very sensitive indicator.

The use of a longitudinal or circumferencial magnetic field is determined by possible defect orientation as illustrated in Fig. 8. Parts inspected by this method are demagnetized before subsequent processing or use. Test equipment is located in each of the four manufacturing buildings. Inspection is performed on all ferromagnetic materials and parts during processing and after final machining or heat treatment. A fluorescent magnetic particle inspection unit is shown in Fig. 9.

ULTRASONIC TESTING

Ultrasonic inspection is usually performed by one of two basic methods: through transmission or pulse-echo (Fig. 10a and 10b). Inspection is accomplished because the ultrasonic beam travels with little loss through homogeneous material, except when it is intercepted or reflected by discontinuities. Ultrasonic inspection utilizes high-frequency mechanical vibrations for NDT of material. Most industrial testing is done at frequencies between 1 and 25 megacycles per second (megahertz).

Applications of ultrasonic inspection include:

1. Flaw detection in thin or thick plates, bars, rods, forgings, tubing, or weldments
2. Thickness measurement of metals (0.010 inch to 12 feet) from one accessible surface (pipes, tanks, plates, etc.)
3. Evaluation of the influence of processing variables on the specimen

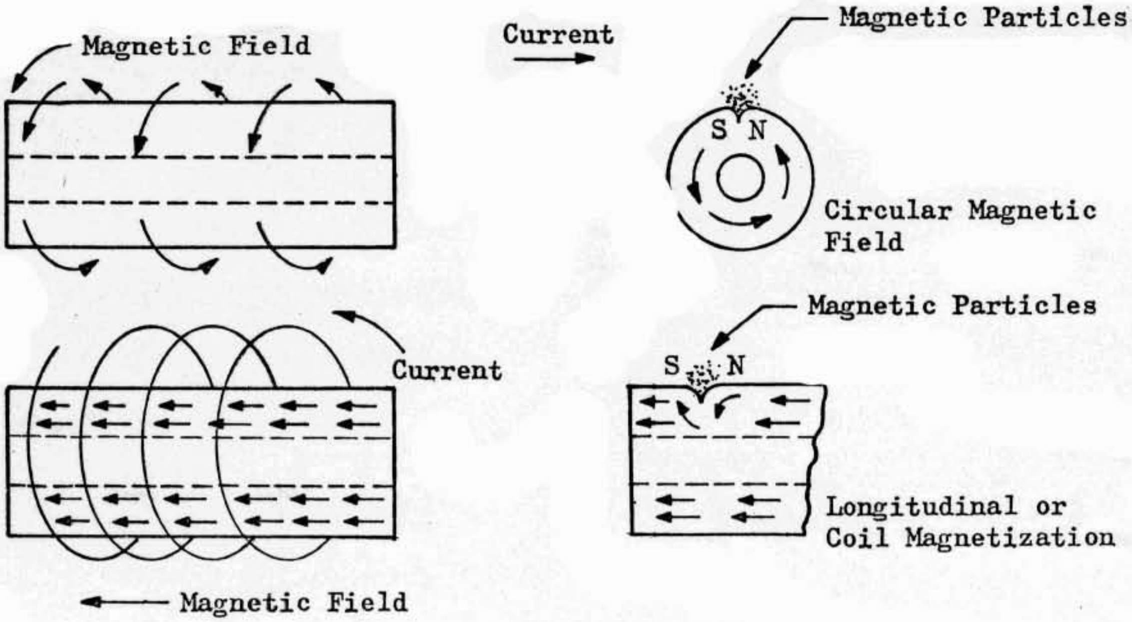


Figure 8. Magnetic Particle Inspection

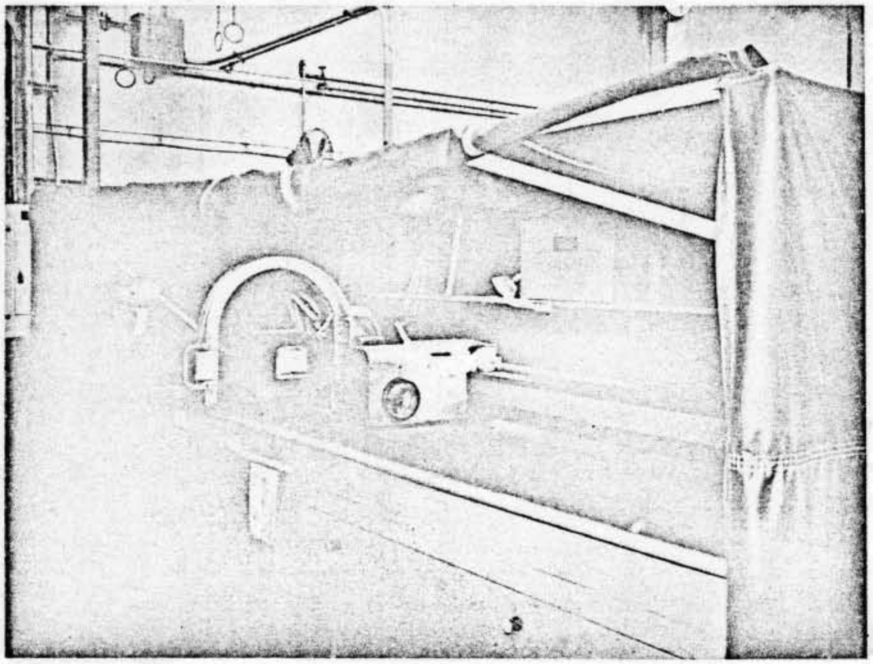
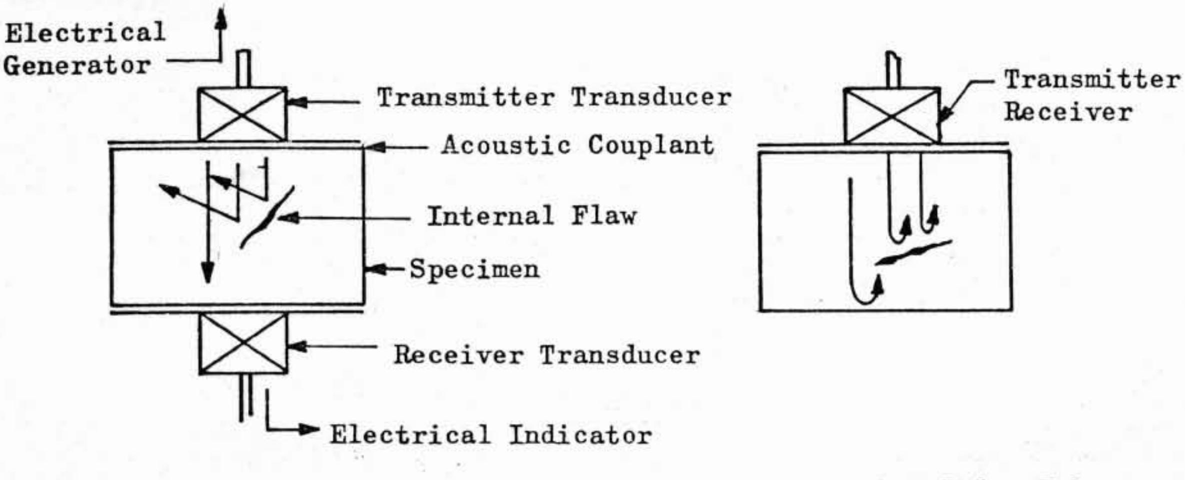
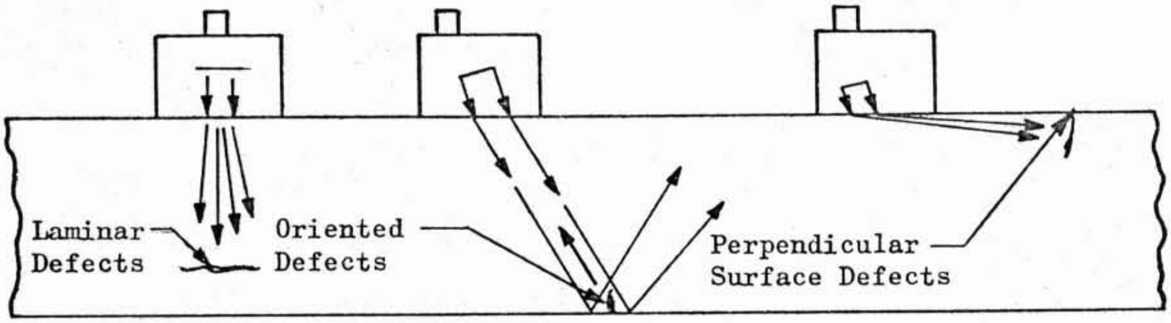


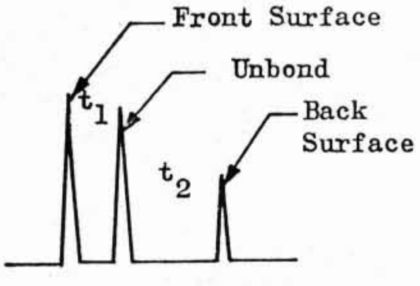
Figure 9. Fluorescent Magnetic Particle Inspection Unit



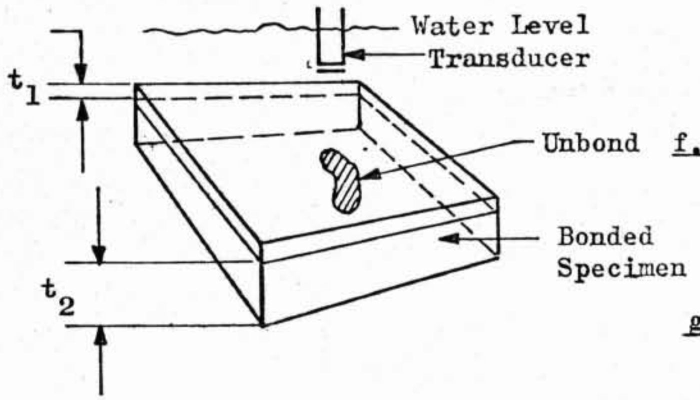
a. Through Transmission b. Pulse-Echo

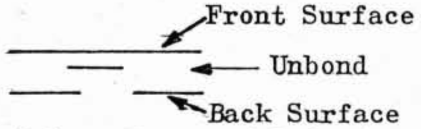


c. Longitudinal d. Shear or Transverse e. Surface of Rayleigh

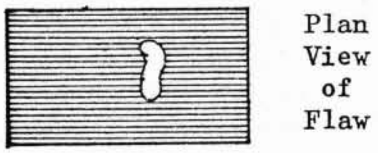


f. A-Scan Indication of Defect





g. B-Scan Trace of Defect



h. C-Scan Trace of Defect (Facsimile Recording

Figure 10. Ultrasonic Inspection Methods

The advantages of this inspection method include:

1. High sensitivity, permitting detection of minute defects
2. Great penetrating power in elastic medium
3. Accuracy in the measurement of flaw position and estimation of flaw size
4. Fast response, permitting rapid and automated inspection
5. Need for access to only one surface of the specimen

The limitations are:

1. Unfavorable sample geometry, i.e., size, contour, and defect orientation
2. Undesirable internal structure, i.e., poor elasticity, porosity, inclusion content, or grain boundary precipitates

Piezoelectric transducers are used for ultrasonic inspection above 200 kc. Piezoelectric materials generate electric charges when mechanically stressed and, conversely, produce mechanical sound waves when electrically excited. The transducers differ in materials, size, shape, sensitivity, application, and wave mode propagation. Basically, only three wave forms are used for ultrasonic inspection each having different velocity (Fig. 10c, 10d, and 10e).

The reflected or indicated pulse from the material being inspected is fed into various electronic systems for presentation and evaluation. The three most popular presentation methods are shown in Fig. 10f, 10g, and 10h. The A-scan presentation is a point-by-point inspection of the part with results indicated on the time baseline oscilloscope. Inspection may be conducted by direct contact or immersed methods and the equipment is portable and can be brought to the job.

Pulser/receiver units, Fig. 11, are located in the Engineering Laboratory, each of the four manufacturing buildings, and in the receiving inspection area. The immersion tanks in the Engineering Laboratory and Manufacturing Building No. 2 are equipped to perform C-scan facsimile recording inspection. Automated immersion C-scan ultrasonic facsimile recording systems are shown in Fig. 12 and 13. B-scan inspection is not available at Rocketdyne.

Thickness testing of metals (0.004 to 3.0 inches) is performed in accordance with ASTM E-113, "Recommended Practice for Ultrasonic Testing by Resonance Method." The Branson Vidigage (Fig. 14) is the instrument employed. Vidigages are located in the ultrasonic inspection area in the main shop building, Receiving Inspection, Manufacturing Building No. 2, and the Engineering Laboratory. Automated recording Vidigages, for measuring the thickness of thrust chamber tubing, are located in Manufacturing Building No. 4 and the Engineering Laboratory.

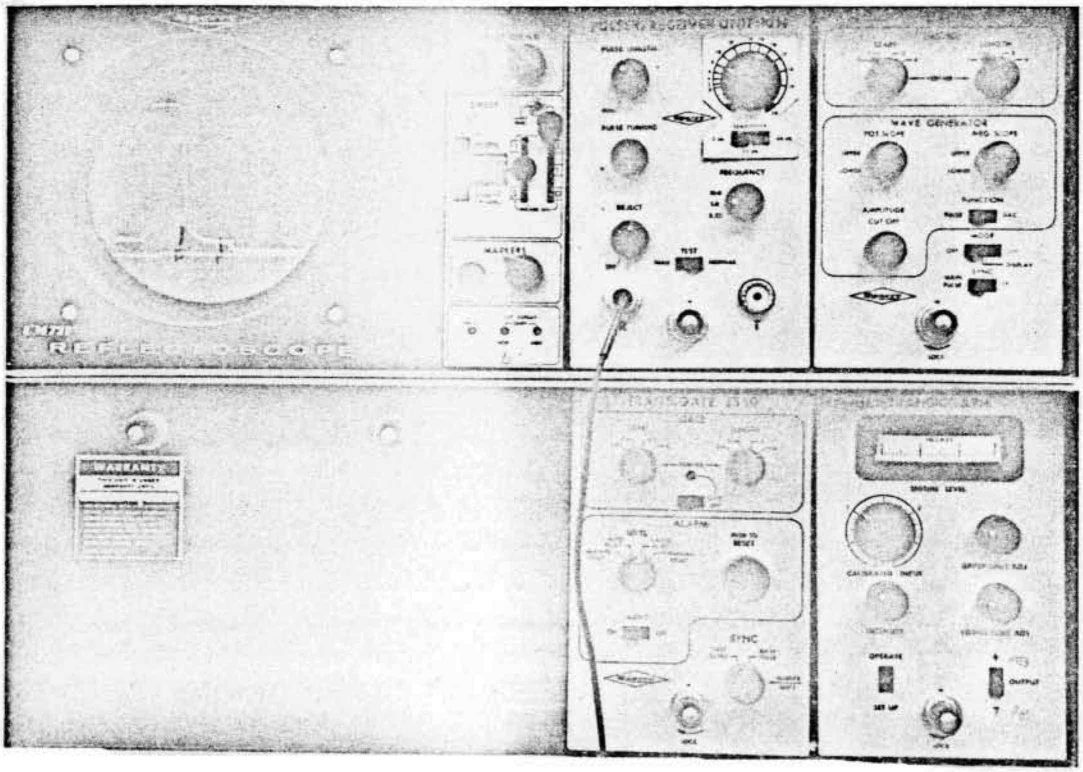


Figure 11. Ultrasonic Pulser-Receiver Inspection Unit

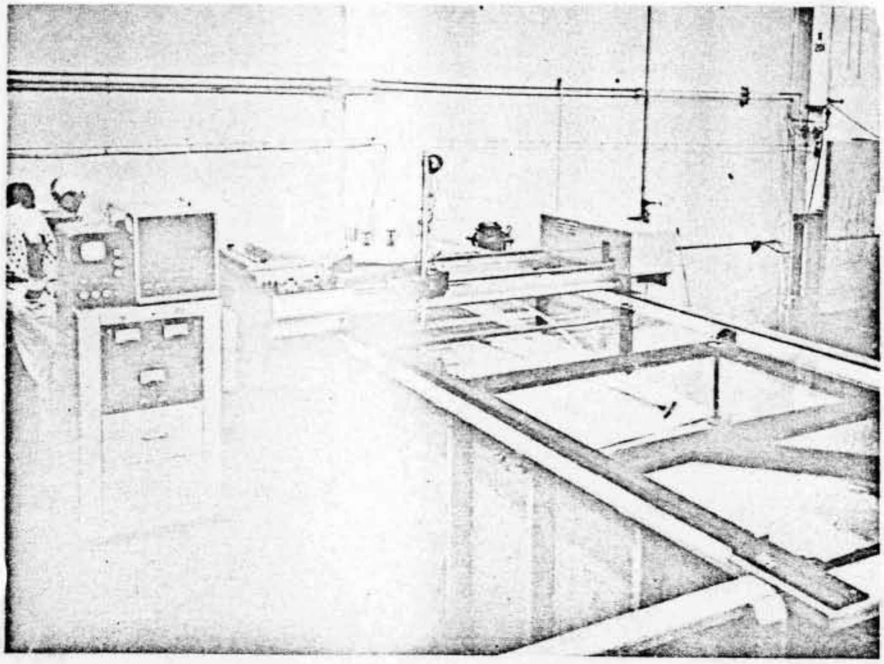


Figure 12. Automated Immersion C-Scan Ultrasonic Facsimile Recording System for Production Inspection

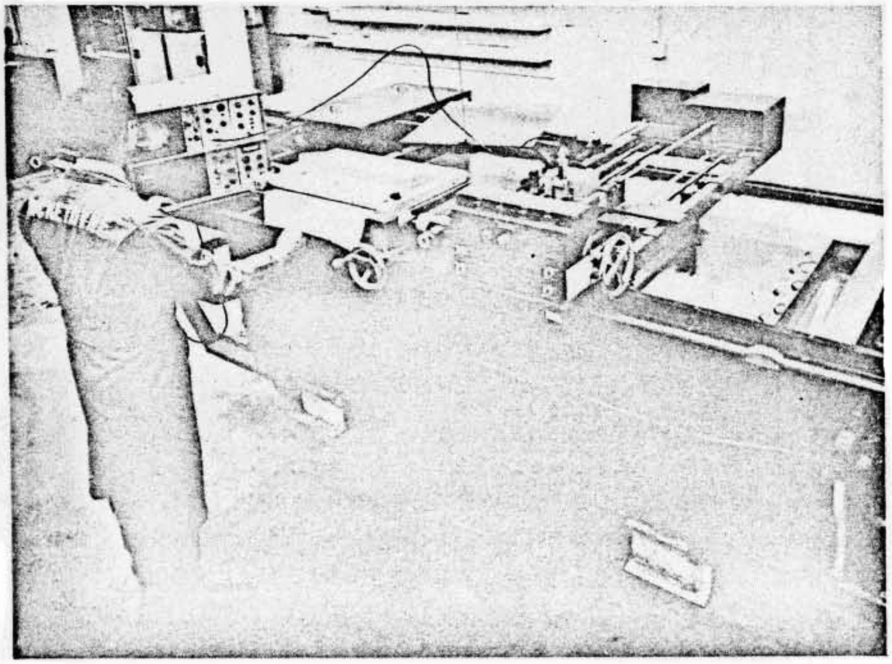


Figure 13. Automated Immersion C-Scan Ultrasonic Facsimile Recording System for Engineering Research and Development

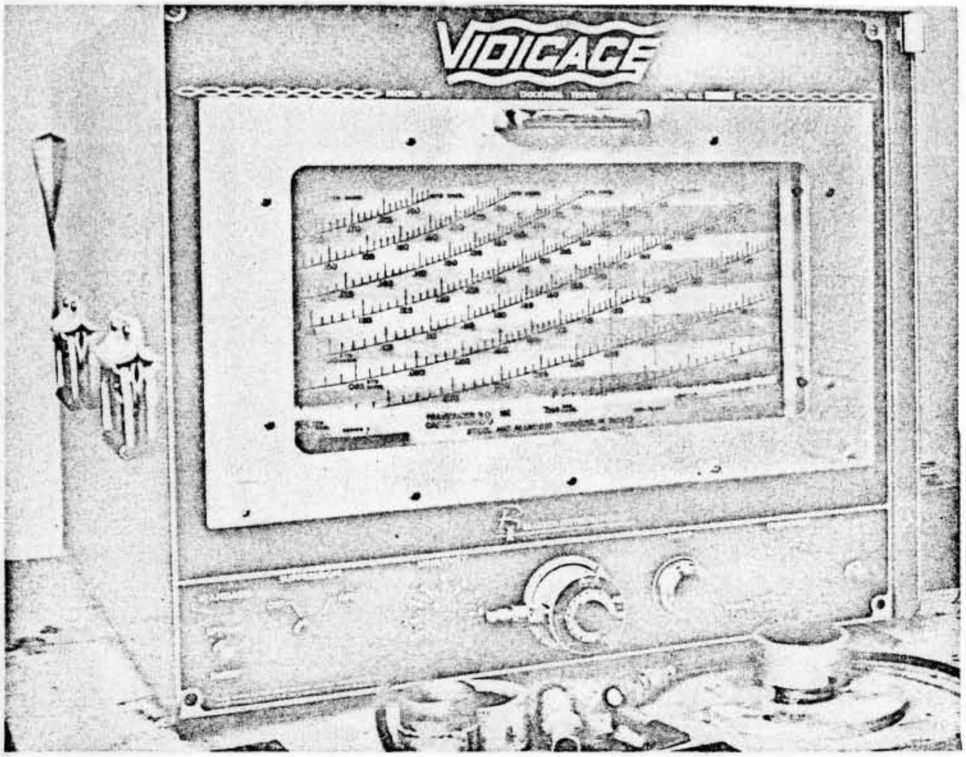


Figure 14. Resonant Ultrasonic Thickness Testing Unit

The application of ultrasonic testing for inspection of weldments and brazed assemblies is rapidly growing at Rocketdyne. Some weld assemblies cannot be inspected by radiography because of thickness or part geometry; in these cases, ultrasonic inspection is employed. It is used extensively to detect disbonds in brazed injectors, hot-gas generators, stators, and thrust chamber tube-to-jacket and tube-to-band braze joints. It is applied to all forgings, OFHC plates and bars, Rene′ 41, Inconel-X, and Hastelloy-C plate stock. All Inconel-X thin-wall, seamless, thrust chamber tubing is inspected for longitudinal defects. An automated system was built for inspecting straight, and straight-tapered tubing. The system is presently being used to evaluate welded, Type 347 CRES, tapered tubes, 0.012 inch thick.

The feasibility for the system was conducted by Bob McClung at Oak Ridge National Laboratory (7).

EDDY CURRENT TESTS

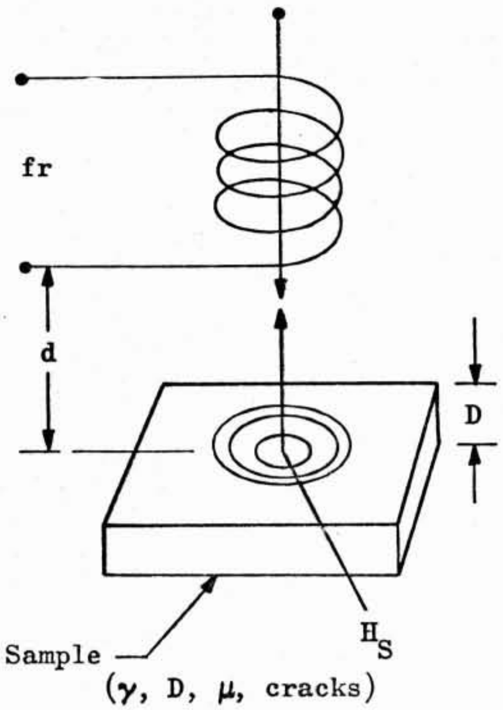
In many eddy current (or electromagnetic induction tests), the object is placed in the varying magnetic field of a coil or probe carrying an alternating current (ac). The a-c magnetic field induces eddy currents in the test object. These eddy currents, in turn, produce a back emf in the vicinity of the test object. Various coil and probe designs are required for specific test objectives. Indications are obtained without electrical contact with the test object, in extremely short-time intervals. Physical properties measured include: alloy variation, heat treatment, hardness, magnitude of defects, dimensional changes, and conductivity or permeability. Eddy current test applications include:

1. Inspection of rods, bars, wires, plates, tubing, and ball bearings for physical properties and defects
2. Thickness measurement of thin nonferrous metal tubing or sheets
3. Thickness of nonconductive coatings on a nonmagnetic substrate (anodize aluminum)
4. Sorting different alloys (347 from 2920) or sorting one material in different tempers (7075-T6 from 7075-T73)

Eddy current test parameters are illustrated in Fig. 15. Test equipment is located in the Engineering and Quality Assurance Laboratories. A general purpose instrument, the Magnatest ED-500 is shown in Fig. 16. The Magnatest FM-110 Conductivity Meter, also shown in Fig. 16, was used to establish a relationship between conductivity-hardness-strength of heat-treatable aluminum alloys. Verification of the 7075-T73 heat treatment (8), proper artificial aging of 2024-T6 to prevent stress corrosion (9), and overaging of 2014-T6 during welding (10) was established.

LEAK TESTING

Leak testing at Rocketdyne is conducted by various departments having the necessary equipment. The subject is very broad and beyond description in this report, except for some basic information given in the following paragraphs.



(H_ρ) = primary field of coil in absence of test object

(H_S) = secondary field created by eddy currents in test object

<u>Significant Instrument Characteristics</u>

(fr) = frequency of a-c field in test coil

(d) = distance of test coil from test object

Size and shape of test coil

<u>Significant Properties of Test Object</u>

(γ) = electrical conductivity

(μ) = magnetic permeability

(D) = dimensional change

Presence of discontinuities, such as cracks

Figure 15. Eddy Current Testing

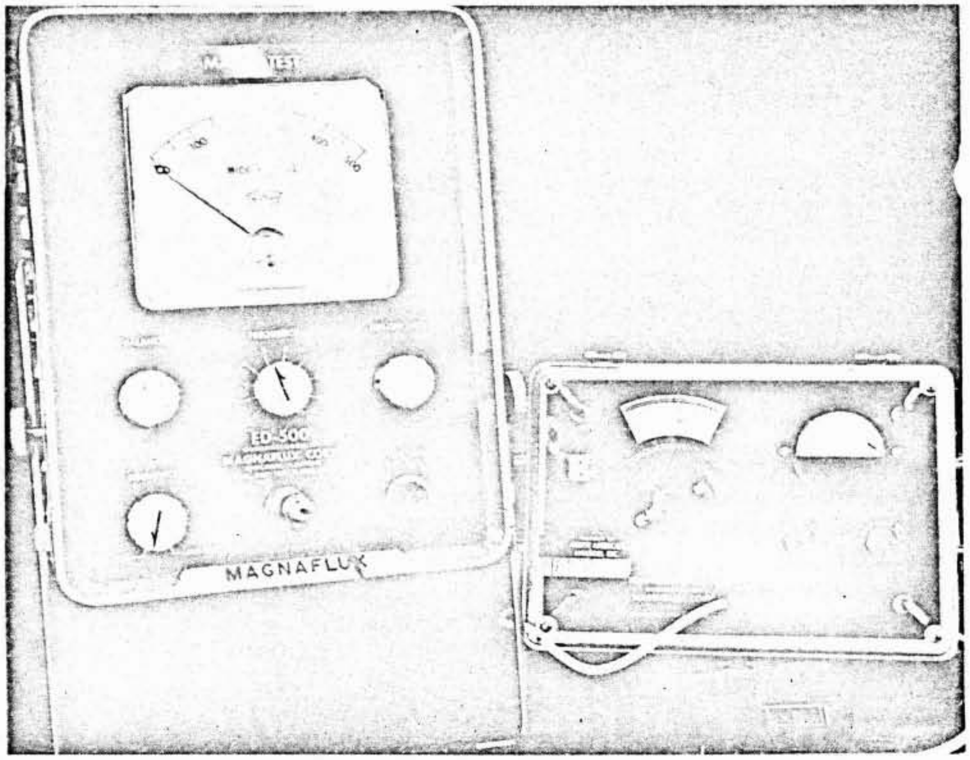


Figure 16. Eddy Current Instruments General Purpose ED-500, and Conductivity Meter FM-110

The expressions, "no leakage allowable" and "zero leakage," have been used in specifications and on drawings to specify the leakage limits of a particlar system or component. This statement indicates a relative, rather than an absolute "zero," since "zero leakage," as an absolute term, would connotate that there is no leakage present which could be detected by any method or instrument whatsoever. For this reason, the specifications and drawings should specify the method by which the system is to be tested. Most specifications cover this area by including the following or equivalent statement:

> "Acceptable leakage rates for this test are confined to those obtained using the equipment and test methods specified herein. When 'no leakage allowed' is expressed or implied, this shall be construed to mean the results obtained under the circumstances of the tests per this specification only."

Usually the engineering drawing will specify the: (1) method of test, (2) pressure, and (3) leakage rate per unit time. A basic breakdown of the various leak tests is shown in Table 2.

Table 2. Comparison of Leak Detection Methods

Method	Practical Limit atm cc/sec	Relative Test Time	Locate Leaks	Quantitative Determination
Sound of Escaping Gas	10^{-1}	Short	X	
Soap Bubbles	10^{-3}	Depends on size	X	
Immersion	10^{-4}	Short to long	X	
Halogen Flame	10^{-3}	Depends on size	X	
Acid Gas + NH_3	10^{-3}	Depends on size	X	
Gel-Reactive Gas	10^{-6}	Long, depends on size	X	X
Liquid Penetrants	10^{-5}	Long, depends on size	X	
Odor	10^{-5}	?	?	
Pressure vs Time	As sensitive as measuring device	Long		X
Ionization (Halogen)	10^{-6}	Rapid	X	X
Mass Spectrometer Probe	10^{-8}	2 ft/min	X	X
Vacuum	10^{-14}	10 to 20 min	X	X
Radioactive Gas	10^{-12}	Depends on size and volume of parts		X

INFRARED OR THERMAL TESTING

Infrared encompasses an area in the electromagnetic spectrum between microwaves and visible, i.e., wavelength 10^{-3} to 10^{-6} meters at a frequency of 10^{12} to 10^{15} cps. Every object emits heat at some intensity and wavelength. When a structure has been altered or a defect is present, the emitted heat will vary on the object's surface. To detect this change, the object may be heated and scanned for variations during the cooling down period, or conversely, as it is being heated.

A second method is to slave the detector to a moving heat source and record variations in heat absorption or emission while scanning the part's surface. The scanners or detectors used in infrared testing are called radiometers or radiation thermometers. Since scanning and temperature sensing are performed without contact, the observed surface is not disturbed or modified in any way. The scanning system consists of a scanning mirror, mirror position transducer, radiation thermometer, and auxiliary read out or display. The collecting mirror focuses radiation onto the infrared detector which generates an electrical signal exactly proportional to the incident radiant flux. The signal is amplified and serves to modulate the brightness of a glow modulator lamp which is focused onto Polaroid film. The position of the lamp image on the film is controlled by the motion of the scanning mirror, resulting in a recorded thermal pattern having one-to-one correspondence with the infrared scanning pattern. The thermal pattern may also be observed on a cathode ray tube or storage (memory) tube display. Infrared nondestructive testing is a rapidly growing new field. It is obviously used to detect heat transfer problems in thermal or electrical units.

Thermal test equipment is not available at Rocketdyne and R&D studies are conducted under contract with Automation Industries, Boulder, Colorado. A typical thermal test system used for these studies is shown in Fig. 17.

Thermal indicating paints AIRCO Detecto-Temp 915 are being used to evaluate thin-facing sheet braze joints. The pigment is mixed with four parts alcohol and sprayed on the part. After the paint dries (in a few minutes), the part surface is exposed to short-duration heating using quartz lamps. Detecto-Temp 915-0951 turns from light green to vivid blue at 140 F and 915-0950 turns from light violet to vivid blue at 104 F. Unbonded areas heat up first due to a lack of heat sink and are evident by a color change which is semipermanent.

KINEFLUOROGRAPHY AND CINEFLUOROGRAPHY

Operates on passing X-rays through the object and observing the ima on a fluoroscopic image intensifier. In kinefluorography, the image is taken from the output phosphor of the X-ray vidicon and presented on a television monitor. The Norelco Searchray is presently being used to spect (by kinefluorography) electronic components and thermocouples at Atomics Internation Division of North American Aviation, Inc., for Rocketdyne engineering evaluation. Cinefluorographic (motion picture) studies were conducted at Rocketdyne (11), to evaluate failure modes in small ablative thrust chambers during hot firing.

THICKNESS TESTING DEVICES

The following instruments are used at Rocketdyne to measure plating or material thickness:

1. Permascope ES (Twin City Testing Co.): Operates on magnetic attraction through substrate and an a-c coil established magnetic field. Used to measure any nonmagnetic coating on a magnetic substrate, i.e., paint on steel or cadmium on steel (Fig. 18).
2. Dermitron (Unit Process Assemblies): Operates on the eddy current principle. Used to measure anodize on aluminum or other nonconductive coatings on nonmagnetic substrates (Fig. 19).
3. Betascope (Twin City Testing Co.): Operates on the beta-ray backscatter intensity variation from the bare substrate and ultrathin coatings. The coating must be 15 units different from the substrate along the atomic number scale before this method is applicable. We use it to measure gold on copper (0 to 10 mils thick). It is also used to measure chrome on aluminum (Fig. 20).
4. Process Nucleonics Thickness Gage (Giannini Controls Corp.): Operates on the gamma-ray backscatter principle. Photons emitted by a radioisotope source are reflected by material in their path; a detector shielded from the source picks up the reflected photons. The number of reflected photons is proportional to the mass of matter directly in their path; this number is converted into a reading by electronic circuits. Thickness and type of material govern which of the following sources are used: Americium-241 (60 kev), Cesium-137 (660 kev), Cobalt-60 (1.2 mev). We recently purchased a gage for measuring the thickness of small-diameter, tapered, thin-wall thrust chamber tubing.

HARDNESS TESTING

One of the oldest and most familiar NDT methods is the hardness test. Because of its general acceptance, I will not go into detail concerning the methods involved because they are generally understood by most metallurgists. In the engineering metallurgical laboratory is a vast array of standard and portable hardness testers and comparators. In the fabrication inspection areas, the Rockwell tester is used. In the heat-treat areas, standard and superficial Rockwell, Brinell, and Riehle testers are used. Generally stated, all parts which are heat treated are hardness tested for conformance to engineering specifications or drawings (Fig. 21 and 22).

VISUAL

The first nondestructive test was a visual one and it is still necessary for sorting obvious defectives from a lot of parts. Large cracks, pits, scratches, misruns, dimensional errors, color, hue, etc., are quite

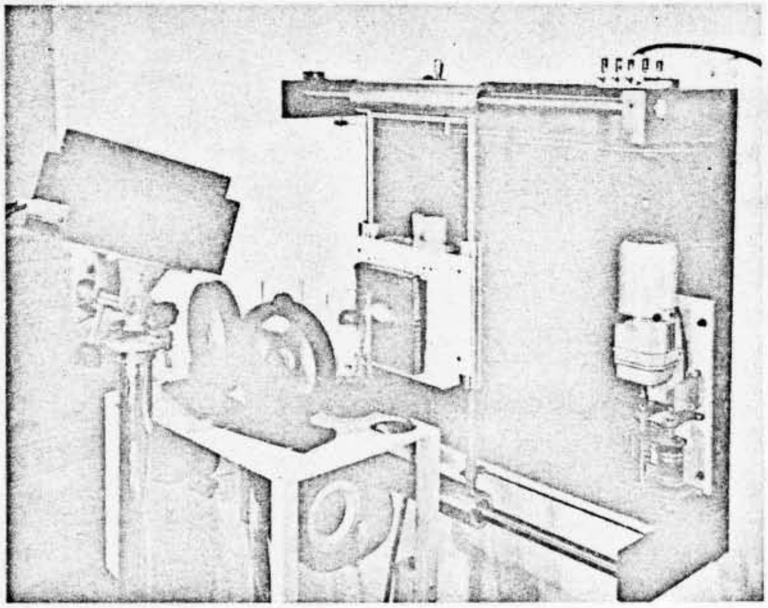


Figure 17. Thermal Nondestructive Test System

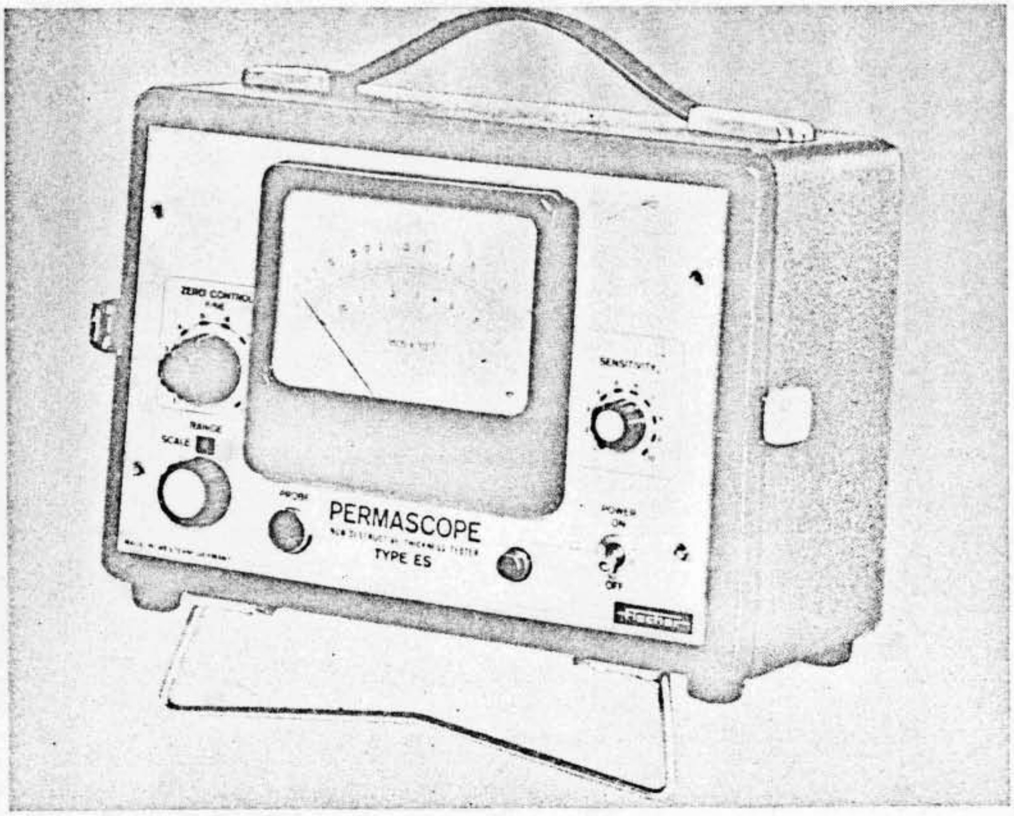


Figure 18. Permascope ES, Used to Measure Thickness of Nonmagnetic Coatings on Steel

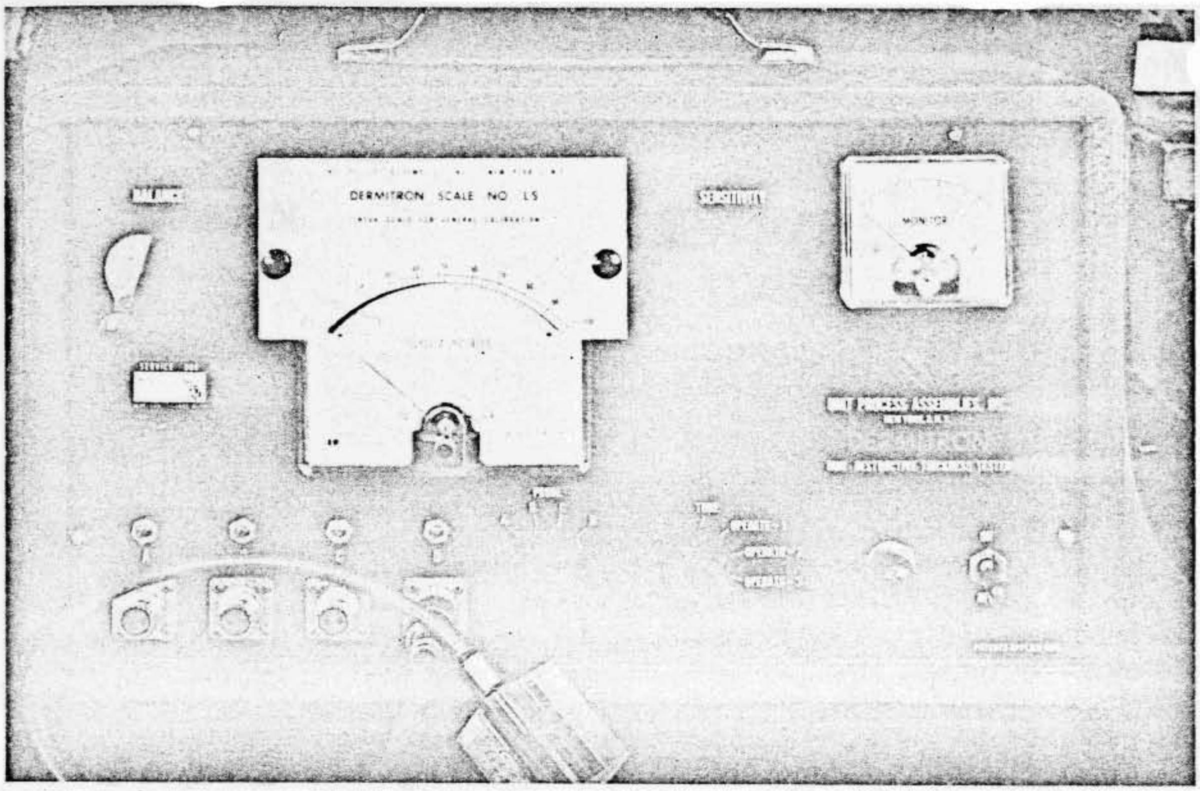


Figure 19. Dermitron, Used to Measure Thickness of Nonconductive Coatings on Nonmagnetic Substrate

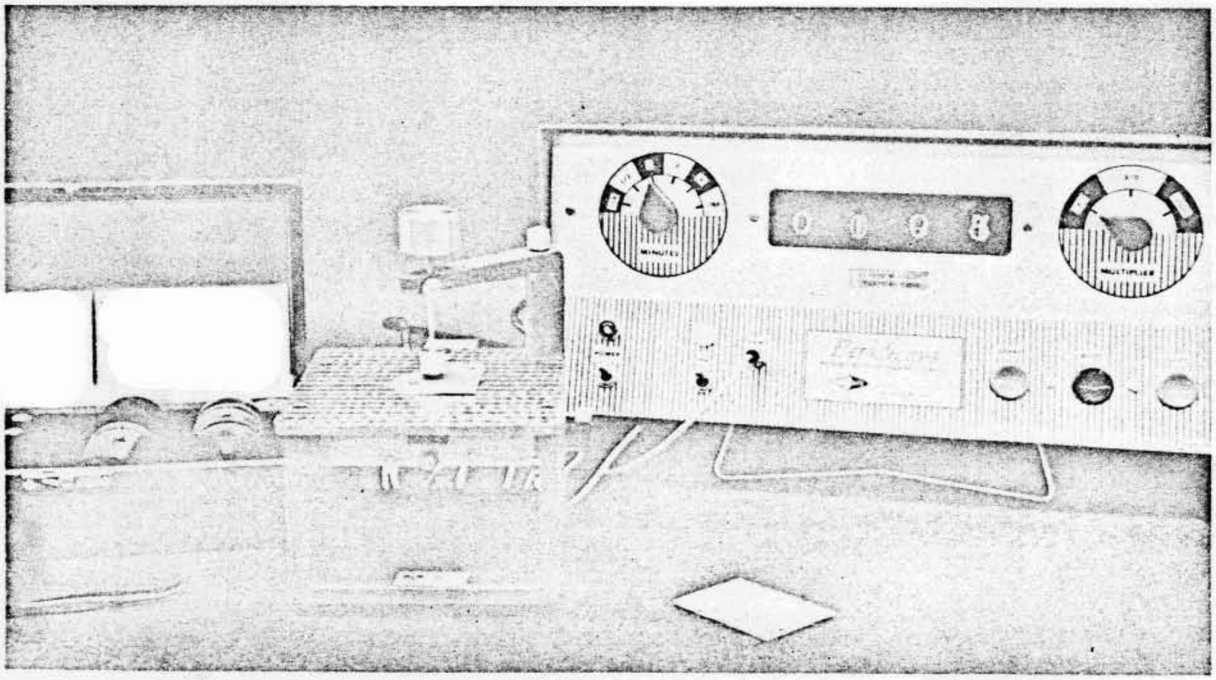


Figure 20. Betascope, Used to Measure Thickness of Ultrathin Coatings

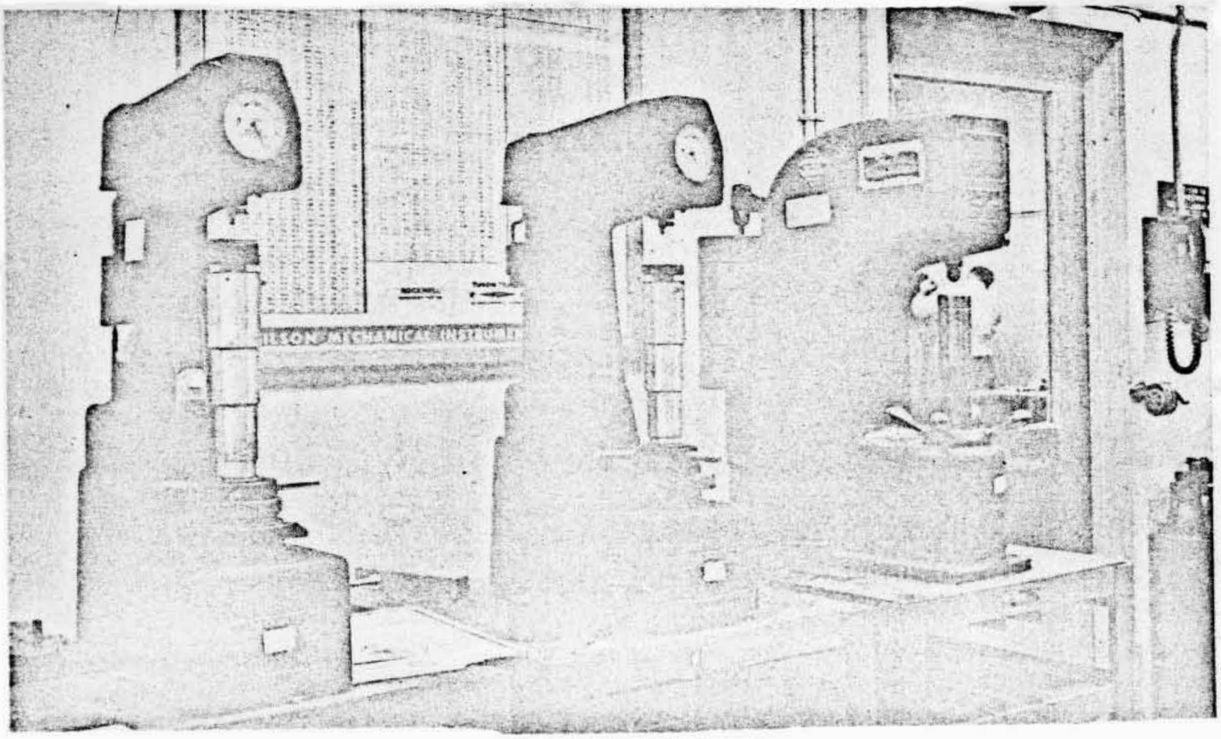


Figure 21. Standard Hardness Testing Machines

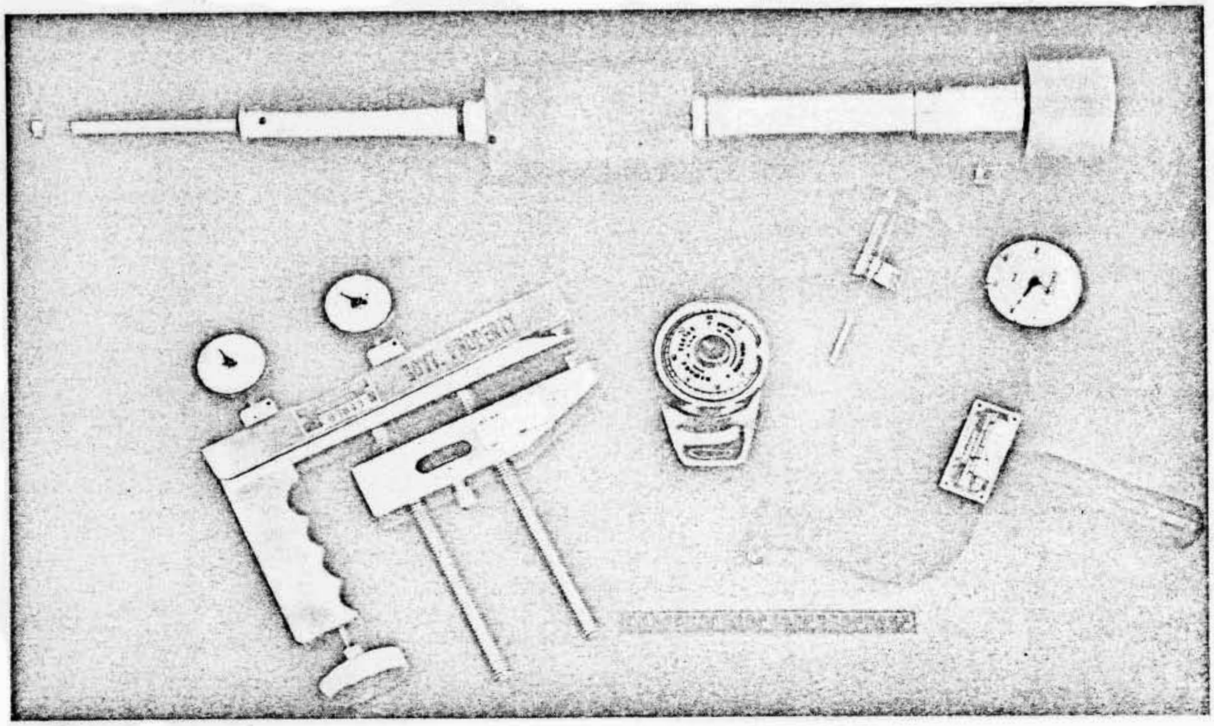


Figure 22. Portable Hardness Testers and Comparators

discernible by visual inspection. Many visual aids and mechanical measuring devices have been added to assist in visual inspection. For defect-detection optical magnifiers, boreoscopes, and fiberoptiscopes are employed. Experience has indicated that parts should receive a 100-percent visual inspection.

All too often, the more exotic inspection methods pass obvious discrepant parts because the discrepancies were outside the measuring or detection capabilities of the exotic inspection methods.

SUMMARY

A general synopsis of the forementioned test methods is outlined in Table 3. A general illustration of results from the majority of test methods previously discussed is shown in Fig. 23, as extracted from Ref. 12.

SELECTION OF TEST METHOD

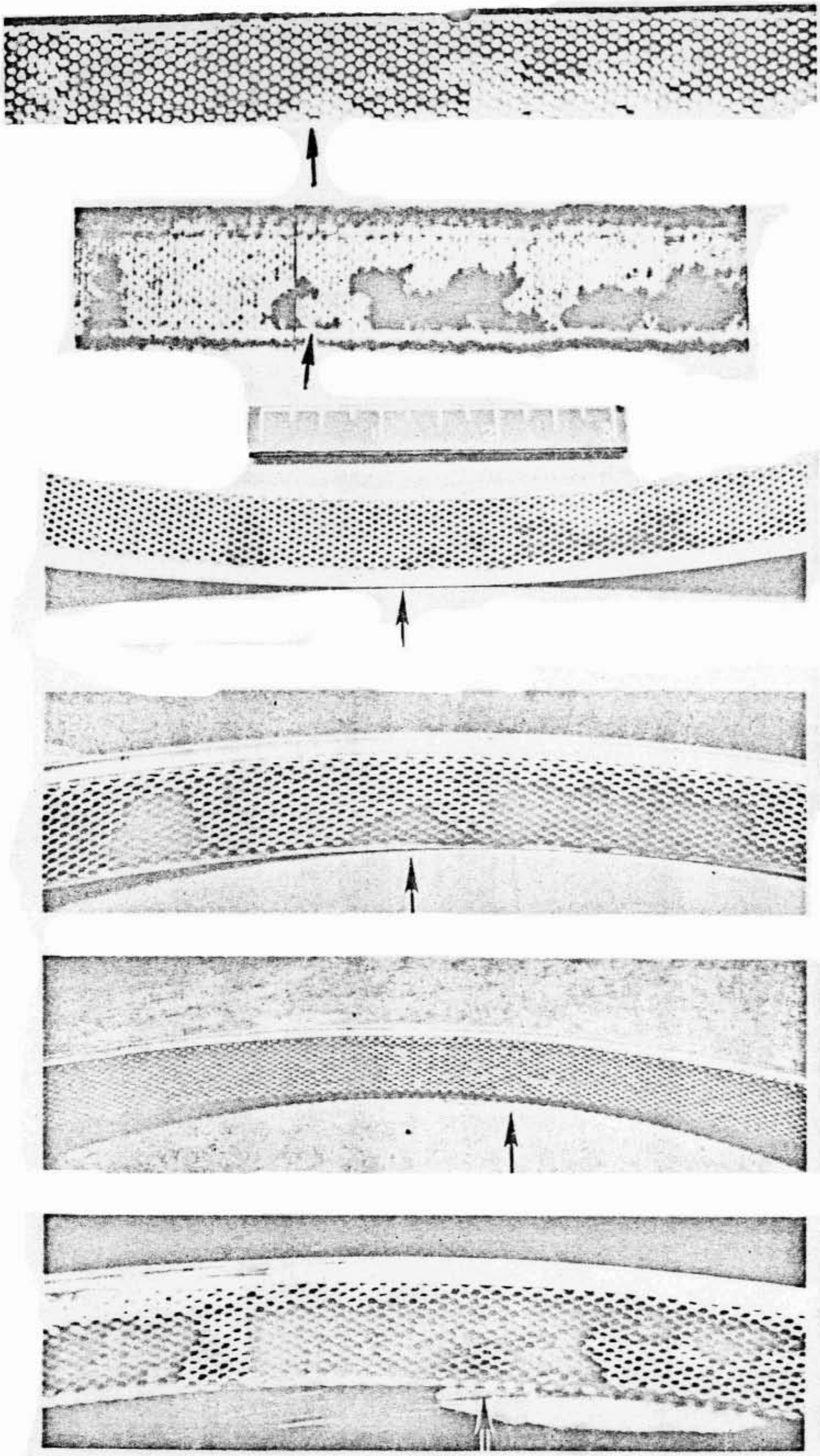
The engineering drawings for R&D and production hardware are reviewed for NDT inspection methods to control the quality of the material or process. In general, all forgings require ultrasonic and penetrant or magnetic particle inspection; all castings require radiographic and penetrant or magnetic particle inspection; all Class-I weldments require radiographic or ultrasonic and penetrant or magnetic particle inspection. A long list of standard callouts could be cited but the few listed above are given as typical examples. If a part cannot be inspected by standard NDT methods then new methods are developed or, as a last resort, the part is redesigned so it can be inspected. This phase of the planning requires good communication between the designer, materials and process engineers, Manufacturing and Quality Control departments.

As the R&D hardware is being fabricated, it is thoroughly inspected using standard, modified or newly developed NDT methods to ensure quality reliability and establishment of quality acceptance standards or a change in material selection, process, or design. Usually, the completed R&D assemblies are statically and dynamically tested for design conformance. During this time, the articles are often periodically inspected to detect weak spots and prevent premature failures. Parts which fail are submitted for failure analysis and metallurgical evaluation in which NDT is used to locate the nonobvious defects or failure mode. Also, failures may indicate the need for additional, or a change in, test methods. It is during this phase that report writing takes place, specifications are prepared, and equipment selected and purchased.

Production inspection requires the establishment of firm techniques and specifications. Shop and supplier surveillance is mandatory until communication is completed and acceptable quality hardware is being fabricated. Additional R&D inputs or design changes are rapidly incorporated to avoid delays in production. Nondestructive testing techniques not covered by a general specification are controlled by an NDT sketch which specifies detail requirements. Figure 24 illustrates typical

Table 3. Nondestructive Testing Methods for Inspection of Liquid Propellant Rocket Engines

Type	Eddy Current	Gamma Rays	X-Rays (Film and Fluoroscopy)	Ultrasonic-Sonic (Pulse-Echo and Resonance)	Magnetic Particle	Penetrants	Thermal	Leak Testing
When to Use	1. Surface and subsurface cracks and seams 2. Alloy 3. Heat treatment 4. Wall thickness 5. Coating thickness 6. Crack depth	Internal defects and variations; porosity, inclusion, cracks, lack of fusion, geometry variations	Internal defects and variations; porosity, inclusion, cracks, lack of fusion, geometry variations	Internal defects and variations; cracks, lack of fusion, porosity, inclusion, delaminations, lack of bond	Surface and slightly subsurface defects	Defects open to surface of parts	Lack of bond	Leaks
Where to Use	1. Tubing 2. Wire 3. Ball bearings 4. "Spot checks" on all types of surfaces	Usually where X-ray machines are not suitable because tubes cannot be placed in parts with small openings and/or power source not available	1. Castings 2. Electrical Assemblies 3. Welds 4. Small, thin, complex wrought products 5. Nonmetallics	1. Wrought metals 2. Welds 3. Brazed joints 4. Adhesive-bonded joints 5. Nonmetallics 6. In-service parts	Ferromagnetic materials	All parts with nonabsorbing surfaces Note: Bleedout from porous surfaces can mask indications from defects	1. Brazed joints 2. Adhesive-bonded joints with metal skins 3. Metallic platings or coatings	Joints 1. Welded 2. Brazed 3. Adhesive-bonded
Why to Use	1. No special operator skills required 2. High speed, low cost 3. Symmetrical parts; may be automated with permenent records 4. No coupling material or contact between probe and part	1. Low initial cost 2. Permanent records; film 3. Small sources can be placed in parts with small openings	1. Permanent records; film 2. Adjustable energy levels 3. High sensitivity to density changes 4. No couplant required 5. Geometry variations do not effect direction of X-ray beam	1. Most sensitive to cracks 2. Test results known immediately 3. Operation can be made simple with automation and permanent records 4. Portable 5. Great penetration	1. Advantage over penetrant in that it indicates subsurface defects; particularly inclusions 2. Relatively fast and low cost 3. May be portable	1. Low cost 2. Portable 3. Indications may be further examined visually 4. Results easily interpreted	1. Very low initial cost 2. Can be readily applied to surfaces which may be difficult to inspect by other methods 3. No special operator skills	High sensitivity to extremely small, tight separations not detectable by other NDT methods
Limitations	1. Conductive materials 2. Depth of penetration; thin walls only 3. Masked or false indications caused by sensitivity to variations, such as part geometry	1. One energy level per source 2. Source decay 3. Radiation hazard 4. Trained operators 5. Unsharpness of image	1. High initial costs 2. Orientation of linear defects in part may not be favorable 3. Radiation hazard 4. Depth of defect not indicated 5. Sensitivity decreases with increase in thickness of part	1. Liquid couplant required 2. Small, thin, complex parts may be difficult 3. Lack of reference standards 4. Trained operators for manual inspection	1. Alignment of magnetic field may be difficult in some complex shapes 2. Demagnetization of parts required after tests 3. Parts must be cleaned after inspection	1. Surface films, such as coatings, scale, and smeared metal may prevent detection of defects 2. Parts must be cleaned after inspection	1. Thin-walled surfaces only 2. Critical time-temperature relationship 3. Image retentivity effected by humidity	Accessibility to both surfaces of part



A. Radiographic Method

B. Reverse Ultrasonic C-Scan Facsimile Recording Inspection Method

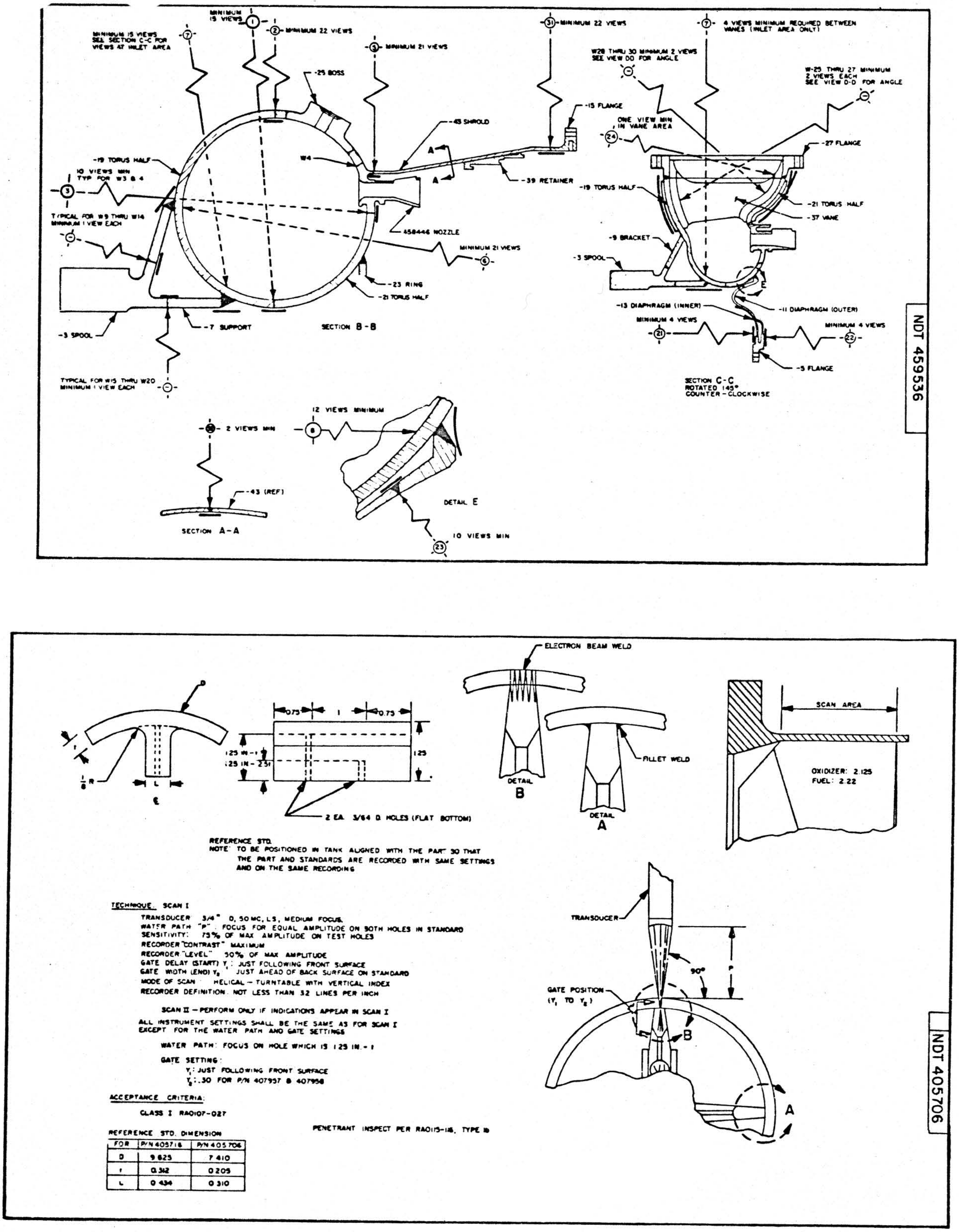
C. Thermographic Method Detecto-Temp Temperature Indicating Paint

D. Inspection With Water-Base Liquid Dye Placed Along Edges of Honeycomb

E. Inspection With Normal White Light Background Using Freon TF Liquid

F. Inspection Using Freon TF and Fluorescent Dye Photographed Under Ultraviolet (Black) Light

Figure 23. Nondestructive Test Results From Inspection of Brazed Open Face Honeycomb Ring Seals (Arrow Denotes Same Defective Area During Each Test Method)



REFERENCE STD.
NOTE: TO BE POSITIONED IN TANK ALIGNED WITH THE PART SO THAT THE PART AND STANDARDS ARE RECORDED WITH SAME SETTINGS AND ON THE SAME RECORDING

TECHNIQUE: SCAN I

TRANSDUCER: 3/4" D, 5.0 MC, L.S., MEDIUM FOCUS.
WATER PATH "P": FOCUS FOR EQUAL AMPLITUDE ON BOTH HOLES IN STANDARD
SENSITIVITY: 75% OF MAX AMPLITUDE ON TEST HOLES
RECORDER "CONTRAST" MAXIMUM
RECORDER "LEVEL" 30% OF MAX AMPLITUDE
GATE DELAY (START) Y_1: JUST FOLLOWING FRONT SURFACE
GATE WIDTH (END) Y_2: JUST AHEAD OF BACK SURFACE ON STANDARD
MODE OF SCAN: HELICAL – TURNTABLE WITH VERTICAL INDEX
RECORDER DEFINITION: NOT LESS THAN 32 LINES PER INCH

SCAN II – PERFORM ONLY IF INDICATIONS APPEAR IN SCAN I

ALL INSTRUMENT SETTINGS SHALL BE THE SAME AS FOR SCAN I EXCEPT FOR THE WATER PATH AND GATE SETTINGS

WATER PATH: FOCUS ON HOLE WHICH IS .125 IN. - 1

GATE SETTING:
Y_1: JUST FOLLOWING FRONT SURFACE
Y_2: .30 FOR P/N 407957 & 407958

ACCEPTANCE CRITERIA:

CLASS I RA0107-027

PENETRANT INSPECT PER RA0115-116, TYPE III

REFERENCE STD. DIMENSION

FOR	P/N 405716	P/N 405706
D	9.625	7.410
t	0.312	0.205
L	0.434	0.310

Figure 24. Typical NDT Sketches for Controlling X-ray and Ultrasonic Inspection Procedures

drawings or sketches selected at random to illustrate the detail callouts for radiography or ultrasonic inspection of a particular part or assembly. The NDT sketches are illustrated portions of the engineering drawing with applicable notes. They are prepared and controlled by the Quality Assurance Laboratory and issued to the production inspection areas within Rocketdyne and to approved NDT inspection laboratories performing work for Rocketdyne, or one of our subcontractors. These NDT sketches are extremely important for controlling the test techniques or procedures.

The final phase of NDT is initiated to evaluate those parts or components which fail during dynamic or hot-fire testing. In some cases, the testing is done at the test facilities at Santa Susana or Edwards Air Force Base, California. In most cases, the components are removed from the engine and sent to the Materials and Process Laboratories for evaluation and failure analysis. The results of the failure analysis generally indicate a discrepant process which is quickly controlled. The determination of parts having the discrepant process or discontinuity is usually determined by one of the NDT methods. If the discrepancy is determined detrimental to the function of the part, then a general production line stoppage occurs with a resultant expedite situation prevailing throughout the organization until the problem is solved and all discrepant parts accounted for. This is accomplished by complete traceability of forgings, castings, weld assemblies, etc., and a good test report retrieval system.

In conclusion I might say that nondestructive testing along with many other tests and inspections ensures product quality assurance and system reliability.

DISTRIBUTION OF LABOR

It is natural in most large organizations to divide the labor burden and have different units working on specific tasks organized for optimum productivity. At Rocketdyne, NDT is divided basically into three groups: (1) Engineering Development Laboratory, (2) Quality Assurance Laboratory, and (3) Production Inspection.

The Engineering Development Laboratory (EDL) is responsible for design, review, specification preparation and revision, failure analysis, material evaluation, test method research and development, and introduction of new test methods into production inspection.

The Quality Assurance Laboratory (QAL) is responsible for NDT drawings, inspector training, production inspection support, in-house and supplier surveillance, field test support, and introduction of new test methods into production inspection.

The Production Inspection Departments (PID) main function is to support manufacturing and evaluate components, materials and processes in accordance with engineering drawing requirements and specification, or QAL drawings. Well-trained inspectors working in facilities equipped with modern instruments ensure both rapid flow of hardware and reliable test evaluation. The PID are also responsible for much of the planning or sequencing of test methods during fabrication.

ACKNOWLEDGMENT

The success of nondestructive testing at Rocketdyne is related to the fine equipment obtained from numerous suppliers and a working team of dedicated personnel. It was my pleasure to present this information in behalf of the many people directly related to NDT at Rocketdyne.

I want to extend my gratitude to the ASM Program Committee of the Materials for Space Exploration Session and especially the chairman, Mr. Leo Gatzek, for asking me to prepare this paper on nondestructive testing.

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