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# THE NONDESTRUCTIVE MEASUREMENTS OF SURFACE CONNECTED DISCONTINUITIES

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## Introduction

To obtain the high performance in modern aircraft and missiles, it is necessary to test many of the components by high unit stresses, and to eliminate redundant structures, because failure of any one component could lead to catastrophic results. To secure positive reliability and to satisfy the high performance requirements, testing often must subject individual components to high unit stresses. It is well known that failures in highly stressed areas are often caused by the presence of cracks or other surface discontinuities which produce stress concentrations. For this reason, tests of raw materials must be continued until their quality is assured. Since destructive testing can give assurance only on a statistical basis, nondestructive testing is preferred where it can be used.

Nondestructive tests for surface flaws necessitate identical or nearly identical flaw indications for the same flaw regardless of the operator, equipment used, or the testing media. To achieve this, a uniform operating procedure, and standard equipment and testing media are required. Many investigators are attempting to do just that with nondestructive testing systems. A review of some of the work being done will aid in an understanding of the parameters related to the nondestructive test procedures, the "penetrant inspection processes."

## Types of Penetrants

The penetrant inspection process involves treating parts by immersion in a penetrant fluid containing a visible or fluorescent dye. The penetrant entering the flaw becomes trapped and remains even after the surface is cleaned by solvent removal or emulsification and water washing. The part is then dried. The trapped penetrant will exude from the flaw, in most cases, with the aid of a developer that acts as a blotter and provides a contrasting background (see figure 1).

At the present time, we have water washable penetrants and post emulsifiable penetrants of both the visible and the fluorescent variety. The water washable type penetrant is less sensitive than the post emulsifiable penetrant because penetrants containing an emulsifying or solubilizing agent are more readily removed from small flaws.

Water washable penetrants are simply called one step process materials. Cleaned and degreased parts are immersed in the penetrant for a specified time, then washed with water to remove the surface penetrant. After washing, the part is dried and examined under the proper light to insure that all surface penetrant was removed. Developer is then applied, and, after the appropriate dwell time, flaw indications will appear (see figure 2).

Penetrants of the post emulsifiable type are called two step process materials; they require the use of an emulsifier to render the excess penetrant removable by washing with water. Cleaned and degreased parts are immersed in the penetrant for a specified dwell time, then drained thoroughly and immersed in an emulsifier for the required dwell time. The parts are then washed and flaw indications will appear (see figure 3).



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## Properties of Penetrant Materials

Liquid penetrants depend upon surface tension (capillary action) to move the liquids through narrow apertures. Use of liquid penetrants is limited to exploration of accessible surfaces and channels or apertures open to the exposed surfaces of the test object. This phenomena may be more clearly understood through an investigation of the mechanism by which liquids penetrate cracks.

One of the outstanding requirements of a penetrant is its wetting ability. A penetrant that has good wetting properties will spread smoothly and cover the entire surface. Penetrants that do not have good wetting ability, on the other hand, will pull back on themselves, thereby leaving areas of the test surface uncovered. The primary factors involved are surface tension and contact angle.

Direct surface tension measurements can be made by using a Du Nuoy Ring Tensiometer. Contact angle measurements can be made by using the method of Langmuir and Schaffer.

From a study of the factors affecting surface tension and contact angles of penetrants, we see that the driving force in the penetration process is the product of solid-liquid surface tension, $\gamma \frac{S}{L}$, and Cos $\theta$, where $\theta$ is the contact angle between the air-liquid and liquid-solid interfaces. The contact angle must be 0 degrees to promote spontaneous spreading of liquids on solid surfaces. For spontaneous spreading of liquids on metal, Zisman found that the liquid surface tension must be less than 22 dynes/cm.

The investigation up to this point reveals the direction of a spontaneous process, but it yields no information as to the rate of the process or the mechanism involved. Measurement of the rate of crack penetration must be investigated under a variety of conditions of temperature, liquid viscosity, surface tension, and contact angle measurements to provide additional information for establishing a mechanism for the penetration process.

Methods for making direct studies of penetration rates in the crack itself would be difficult to develop; however, there is a close relationship between rates of spreading on flat surfaces and penetration rates in the crack. An investigation of the work of Zisman reveals that the spreading of a liquid on a high energy surface such as metal results in (1) the formation of a single mono layer of liquid ahead of the bulk liquid and (2) the subsequent spreading of the bulk liquid on the surface of its own mono layer. This being true, a liquid is unable to spread on its own mono layer when the surface tension of the liquid is higher than the critical surface tension of the mono absorbed layer. Theoretically, the best penetrant would be one for which the rates of the formation of the mono layer would be high and the bulk viscosity low.

## Crack Penetration

Another interesting aspect concerning the process or processes which will cause liquids to enter cracks is related principally to the immersional wetting system. This system is represented in figure 4. The degree to which penetration will extend in this system depends upon whether the air in the crack is trapped or has escaped.

Experience has shown that all or most of all of the air is displaced. Two conditions exist which contribute to the displacement of air. First, as penetration proceeds, the air in the crack is placed under a higher pressure than under initial conditions. This causes higher solubility in the penetrating liquid thus bringing out the eventual transfer of the air



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to the external gas phase. Second, assuming that each crack is not of uniform width and that one section of the crack will be penetrated before the other, air is then discharged at one section while penetration occurs at another.

For extreme conditions where air is trapped in the crack, the penetration of the crack by the liquid will increase the pressure of the trapped air from $P_1$ to $P_2$ as the liquid moves from position $d_1$ to $d_2$ (see figure 4). Using the relationship of surface tension and contact angle for typical penetrants, one finds that the crack width which will fill up 50 percent is about 0.6 microns, with wider cracks filling to a lesser extent.

Experience has shown that liquids achieve good penetration of cracks which are much larger than 0.6 micron. We may conclude then that air is displaced from the crack as the liquid enters.

Variations in crack width can also lead to expulsion of air from the crack (see figure 5). Performing applicable equations for theoretical wetting and balance of forces will show that the liquid flows in at "A" and that air is released at "B," eventually filling the crack. In both cases (figures 4 and 5) the equations indicate that the condition of high surface tension and low contact angle favor maximum penetration.

Intensities of Flaw Indications

Investigations of the intensity of flaw or defect indications as a function of detection sensitivity has been mainly concerned with the fluorescence of penetrants. Fluorescent brightness of a liquid penetrant is a key property in determining the penetrant's overall performance as an aid in the detection of cracks or surface flaws in solid objects. Various methods are being used to measure the fluorescent brightness of penetrants.

One method currently used compares the detection intensity of two strips of filter paper, one carrying a reference penetrant or fluorescence standard, the other a penetrant which is being rated. Both penetrants are diluted in a volatile solvent; filter paper test specimens are dipped into this solution, dried, and measured for fluorescent intensity by reflection. In general, this test procedure gives variable results because dye concentration of penetrants tested are not known; thereby, the type of solvent used can enhance fluorescence in some penetrants but reduce it in others. Figure 6 shows the results of dilution of a penetrant using several solvent systems.

A second method developed through the investigation of the Albein Reid Foundation measures fluorescence sensitivity rather than fluorescence brightness. This method is called the "meniscus method," which makes use of an optical, flat glass platten and a convex lens ground to a spherical surface having a radius of curvature of 106 cm. A black light source and a camera are used to photograph the fluorescence pattern of the liquid penetrant placed between the lens and the optical flat. This is arranged by placing a drop of penetrant on the flat platten and the lens on the drop to form a meniscus shaped film of liquid, whose thickness increases from zero at the point of contact to an appreciable value some distance from the center. It is known that fluorescence intensity increases continuously with the thickness of a liquid film. Since this is true, we may expect that a non-fluorescent "black" spot will appear whose measure will provide an index to determine ultimate dimensional sensitivity of a particular penetrant. One advantage of this method is that photographic records can show a dark spot in addition to a uniform brightness beyond this dark spot. Also, dilution of the penetrant material is not necessary using the "meniscus method," thereby variables of dilution are eliminated. However further development of this



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method as well as alternative test methods for measuring fluorescence intensity are needed and are being investigated.

Standard Metal Specimen of Known Surface Characteristics

Proper evaluation of penetrants and adequate testing procedures depend greatly on the test specimen used. Standard test specimens should be easily prepared, reproducible, and possess defects of uniform depth and width.

Some of the more common test standards currently popular will be discussed below:

Quench Cracked Aluminum Block

The cracked aluminum block test specimens are suitable only for comparison purposes. They are a useful guide in determining whether penetrant "A" is better or worse than penetrant "B" for general use. Also, a check on technique can be accomplished through the use of aluminum block specimens.

Crack patterns produced on aluminum blocks are neither uniform, nor of controllable size; and, the dimensional distribution is rather broad.

Test specimens are panels three inches long by two inches wide cut from $\frac{5}{8}$ inch 2024 aluminum. Each block is heated over a gas burner to a temperature of 950°F. The temperature is determined by using Tempilaq by coating an area the size of a penny with the Tempilaq, which sensitizes the block. The block is quenched immediately in cold water after reaching the desired temperature to produce cracks in the block. A slot $\frac{1}{16}$ inch wide by $\frac{1}{16}$ inch deep cut in the two-inch direction across the center of the heat affected zone forms two similar specimens thus eliminating cross contamination during the penetrant comparison. Figure 7 is a photograph of an aluminum test specimen treated with a penetrant.

Magnesium Sheet Strip Test Specimens

The magnesium sheet test specimen is produced by bending an AZ-31 magnesium alloy sheet. Cracks are formed at the tension side of the bent sheet in the parallel direction to the bending stress. Flaw indications produced in this test specimen also are not uniform and are not controllable.

Brittle Metallic Plating Specimen

Another specimen may be produced from a strip of polished ductile iron. A brittle layer of iron is deposited onto the surface electrolytically and cracks are induced by thermal stress or bending. The cracks extend across the width of the plate and are parallel to each other. Such cracks are extremely narrow as well as quite small; therefore, they are not easily shown by the penetrant method.

The critical characteristics of test specimens of this kind are dependent upon two factors— the thickness of plating and the curvature of bending. Plates more than 0.2 mm thick are required to obtain line flaw indications. Test pieces with plate thicknesses of 0.25, 0.5, and 1.0 mm were prepared and placed on the bending device shown in figure 8. The bending curvature was varied by changing the displacement of the load head. Test results indicate that the larger the bending curvature and the thinner the plate, the more



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minute the cracks will become. However, micro-cracks close to the detection limits of fluorescent penetrant testing are very difficult to produce by this method.

### Pressure Type Fixture as a Standard

A more controlled test involves the use of a pair of highly polished blocks which are pressed together on top of each polishing surface; the gap between the surfaces is to represent the defect. The advantages of this procedure are that the size of the defect is controllable simply by regulating the pressure applied; also the fixture is readily disassembled after use. The major disadvantage is that when two ground metal surfaces are pressed together, the mating surfaces deform as the pressure increases and the gap representing the defect loses some of its characteristics. Figure 9 shows a pressure type fixture used in penetrant testing.

### Chromium Electroplates

Work being done on the production of chromium electroplates of known crack geometry is promising. It is known that under controlled conditions of current density temperature and bath composition, chromium plate on nickel base will produce reproducible crack systems.

Plates are produced using 24-gage uniform "blue steel," 3 by 4 inches in size. First, an electrodeposit of nickel is laid down; then a layer of chromium is electrodeposited on top of the nickel. The conditions for electroplating are varied to develop crack systems. Also in this work, a system has been developed for recording the crack pattern. A photographic paper impregnated with dimethylglyoxime is pressed against the specimen surface and electric current is passed through the paper so that the nickel ions migrate through the cracks and deposit in the paper as a red precipitate of nickel dimethylglyoxime.

Test runs of these plates indicate that if the plating bath temperature is not closely controlled, a wide range of crack counts will be observed. When temperature is controlled within close limits, the crack counts (number of cracks per linear inch) are independent of plate thickness in the thickness range from 80 to 400 micro inches. At 113° ± 2°F, the crack count is in the range of 440 to 525 cracks per linear inch over a range of plate thicknesses of 80 to 400 micro inches. These results indicate that the crack count of a chromium electroplate is directly dependent on plating bath temperature. To investigate further the effect of temperature, crack counts may be obtained also by direct microscopic observation, with another series of plates (see figure 10).

Other variables being investigated such as plate thickness and plate age, will influence the crack count of a chromium plate. Tests indicate that there is an increase in crack count as the plate thickness increases from 855 to 117 micro inches. For thickness above 150 micro inches, the crack count does not change appreciably.

## CONCLUSIONS

Although the penetrant process of inspection has been in use for many years and has become a standard procedure in testing structural parts for surface defects, we are only now discovering, through investigations of its chemical and physical properties, how a penetrant works. Yet, much work is left to be done. Correlation studies of the physical properties of penetrants with the results of tests using standard test specimens with known crack geometry, and establishment of proper relationships between detection sensitivity and testing procedure are only two of the many problems left to be solved.



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Some assistance in this direction may have been contributed by results of the theoretical study and experimental investigations discussed in this report which lead to the following conclusions:

1. It is possible to control accurately the sensitivity of penetrant systems to almost any desired level of inspection, and

2. Direct comparisons between penetrants for full advantage of detection sensitivities may be accomplished by using standard test specimens of known surface characteristics and by confining dimensional distribution of defects within a narrower range than that found in other test standards.

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4. Third International Conference on Nondestructive Testing, "The Standardization of Magnetic Particle and Penetrant Testing." Keynote Paper No 24.

5. U. S. Department of Commerce, "Penetrant Inspection." Quality Control Digest, No. 2, November 1959.



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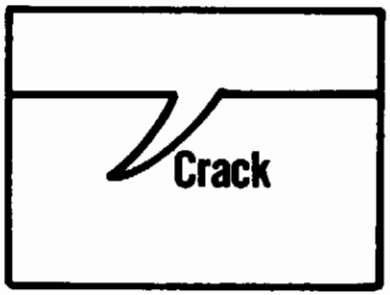
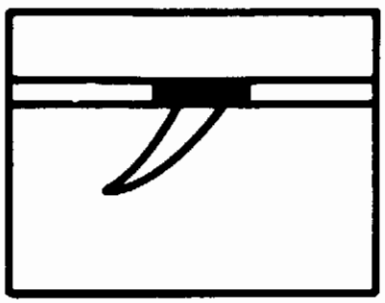
# MECHANISM of PENETRANT FLAW DETECTION




Cleaned Surface

Penetrant Covered

Excess Penetrant Removed



Developer Applied

Figure 1.



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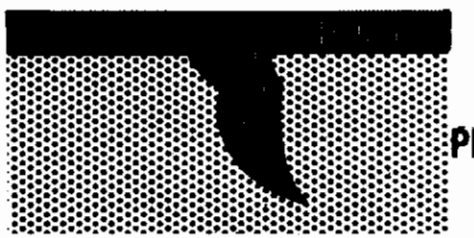
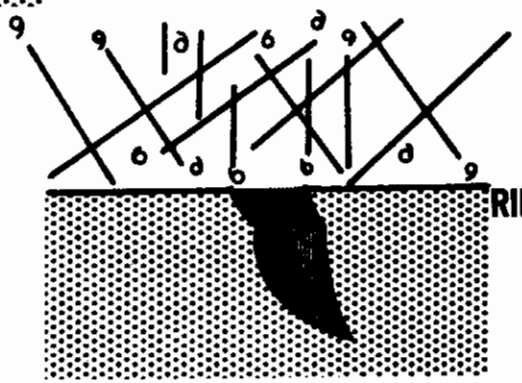
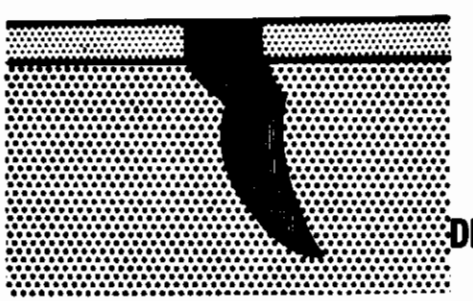
## ONE -STEP PROCESS WATER WASHABLE PENETRANT



PENETRATION - Penetrant On Surface Seeps Into Crack



RINSE - Water Spray Removes Penetrant From Surface But Not From Cracks And Pores



DEVELOPMENT - Developer Acts Like A Blotter To Draw Penetrant Out Of Crack

Figure 2.

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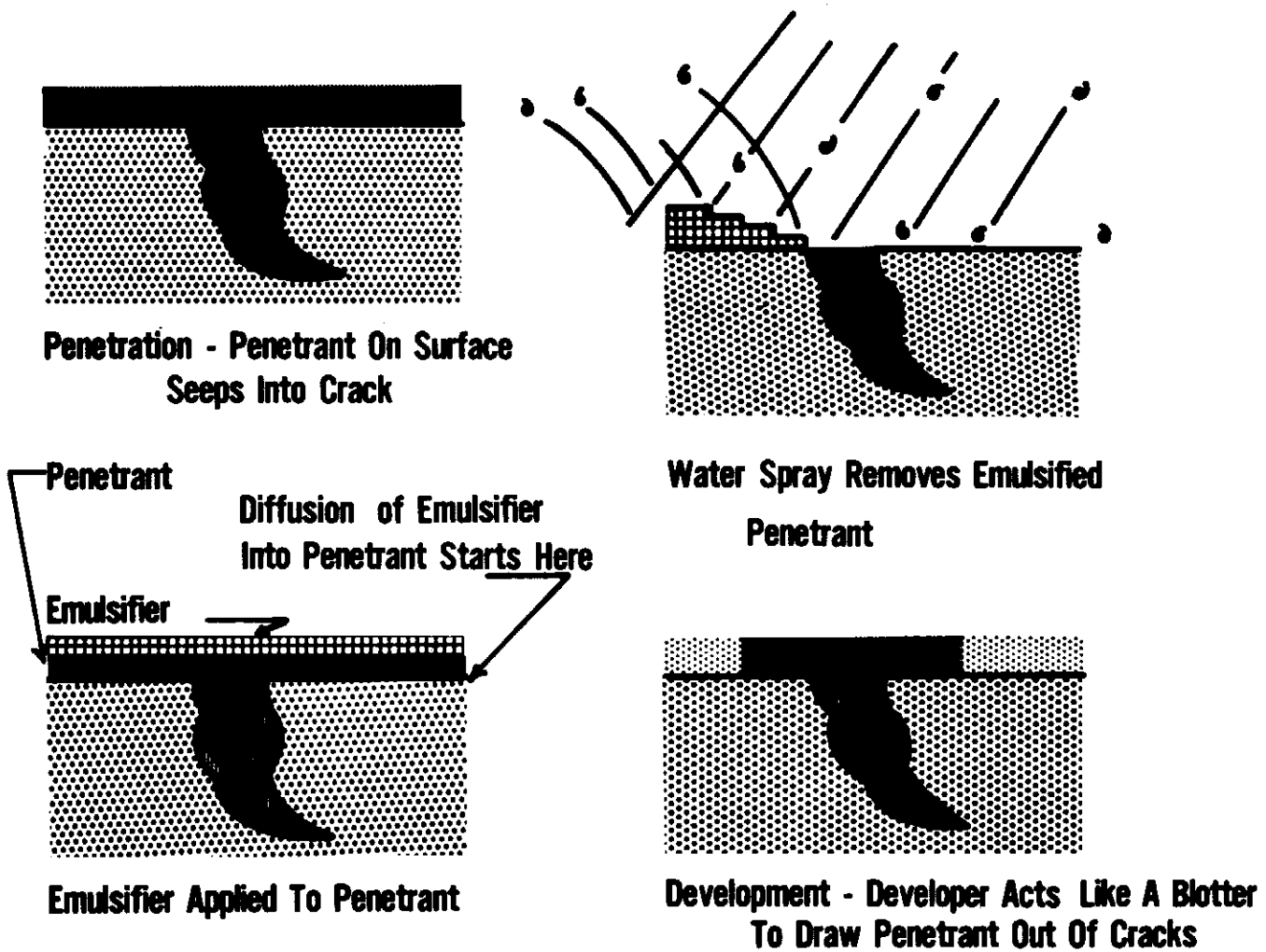
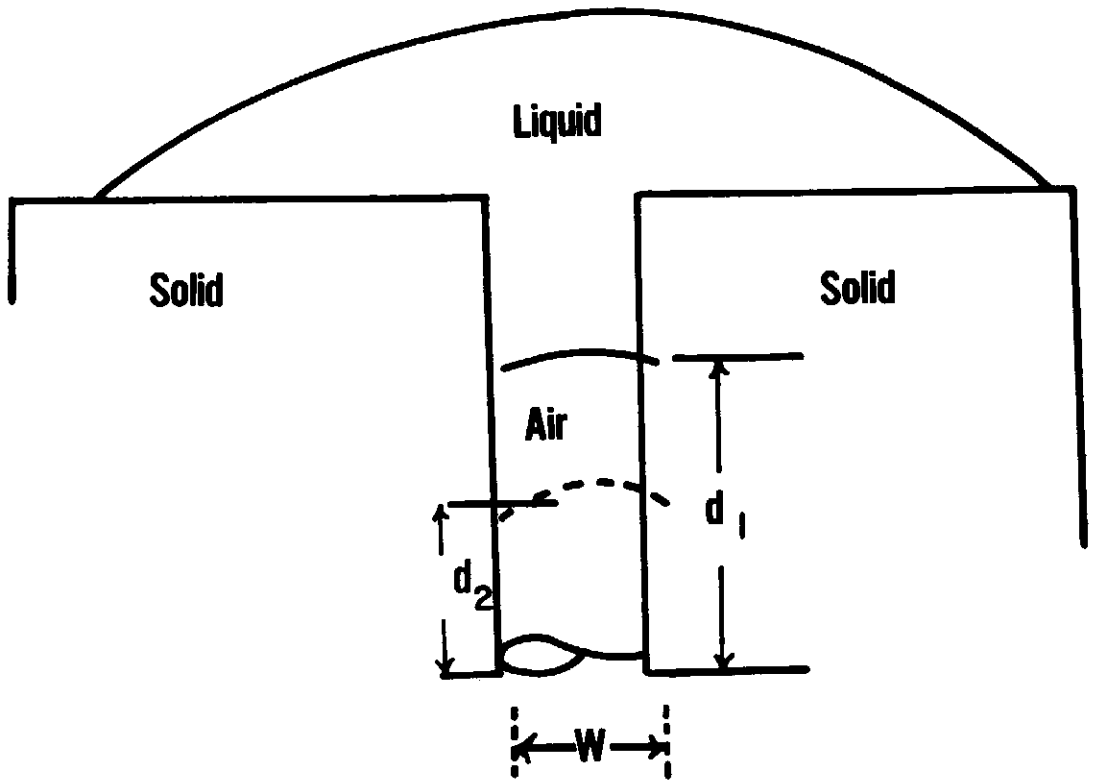



Figure 3.

# IMMERSIONAL WETTING IN CRACK PENETRATION




$d_1$ = Air Column At Pressure $P_1$

$d_2$ = Air Column With Increased Pressure $P_2$

Figure 4.

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# EXPULSION of AIR FROM A CRACK THROUGH CRACK WIDTH VARIATION

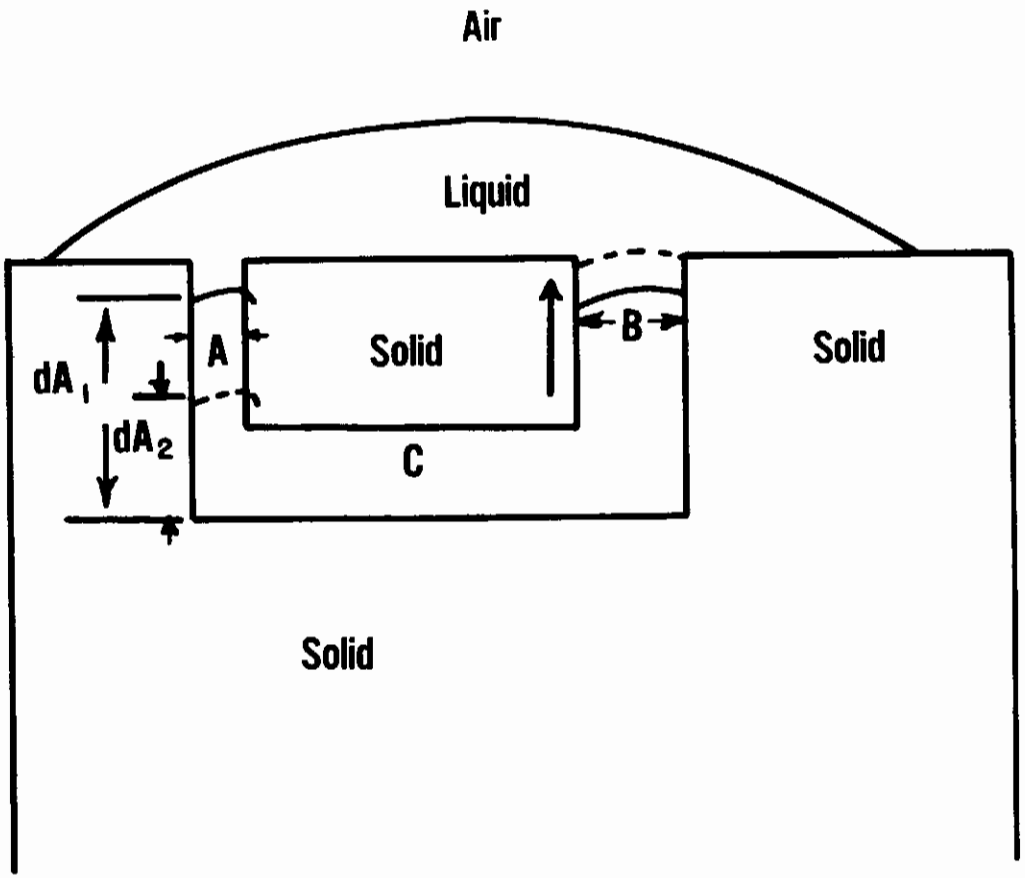


Figure 5.



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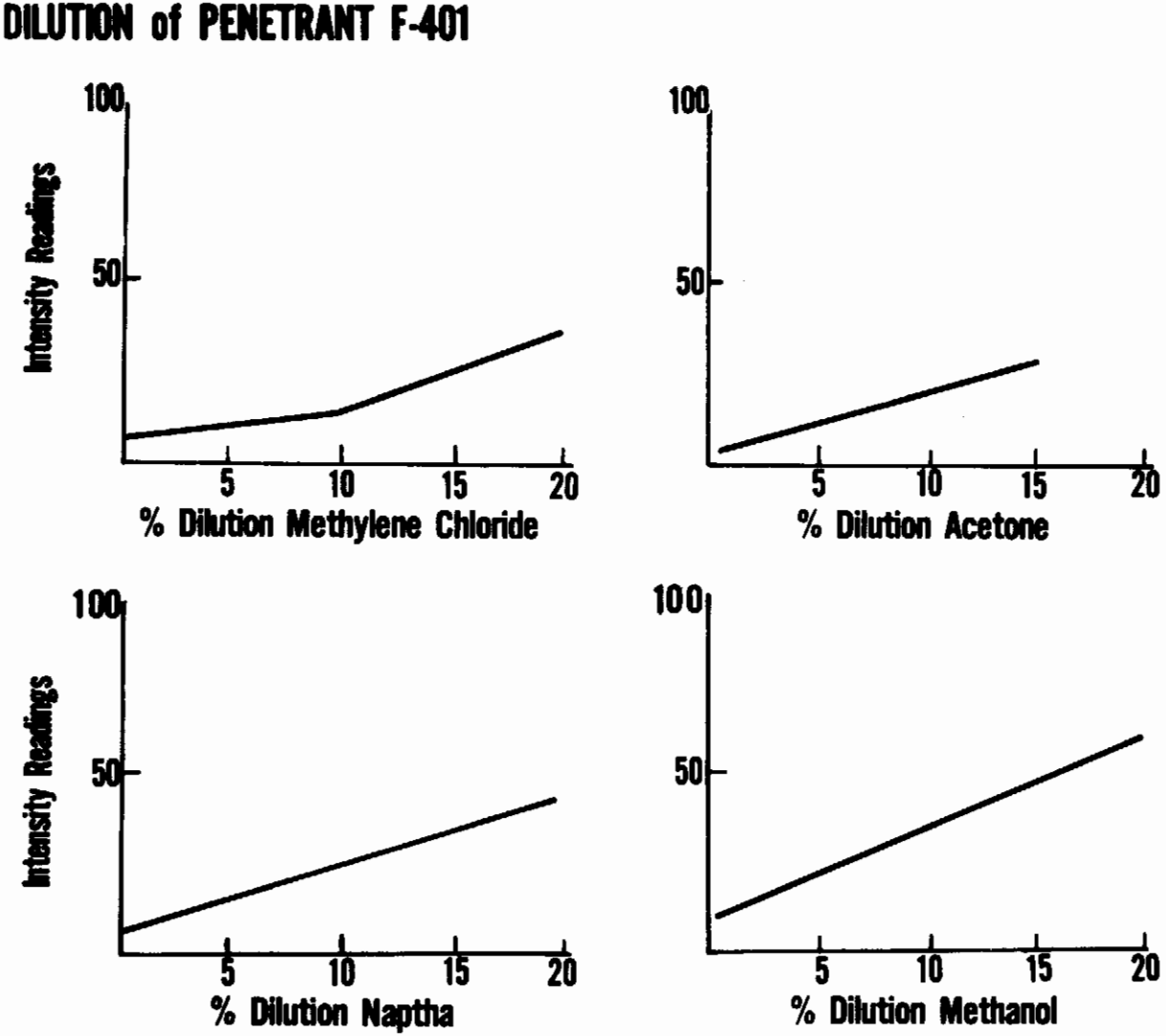


Figure 6.

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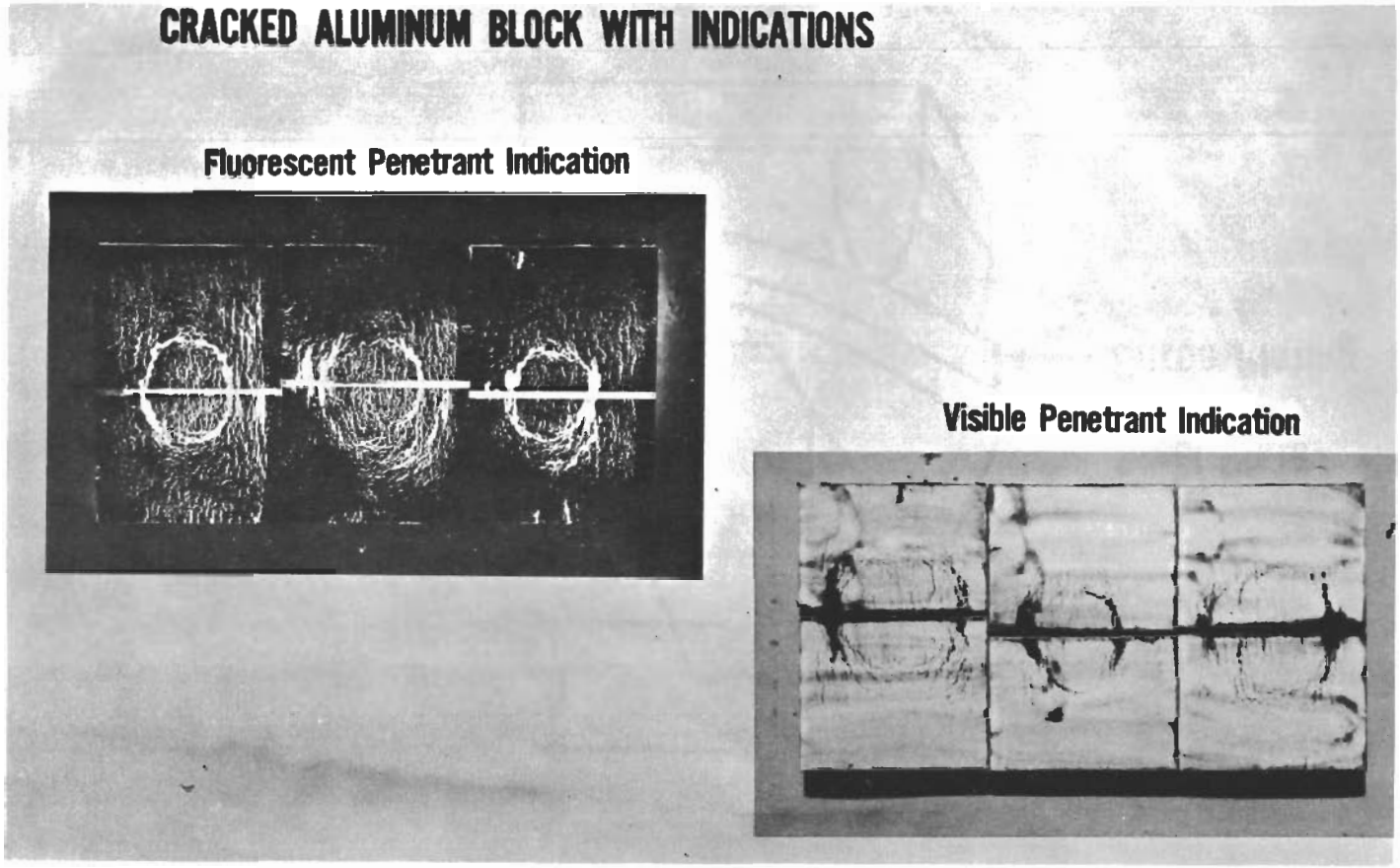


Figure 7.

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# BENDING DEVICE

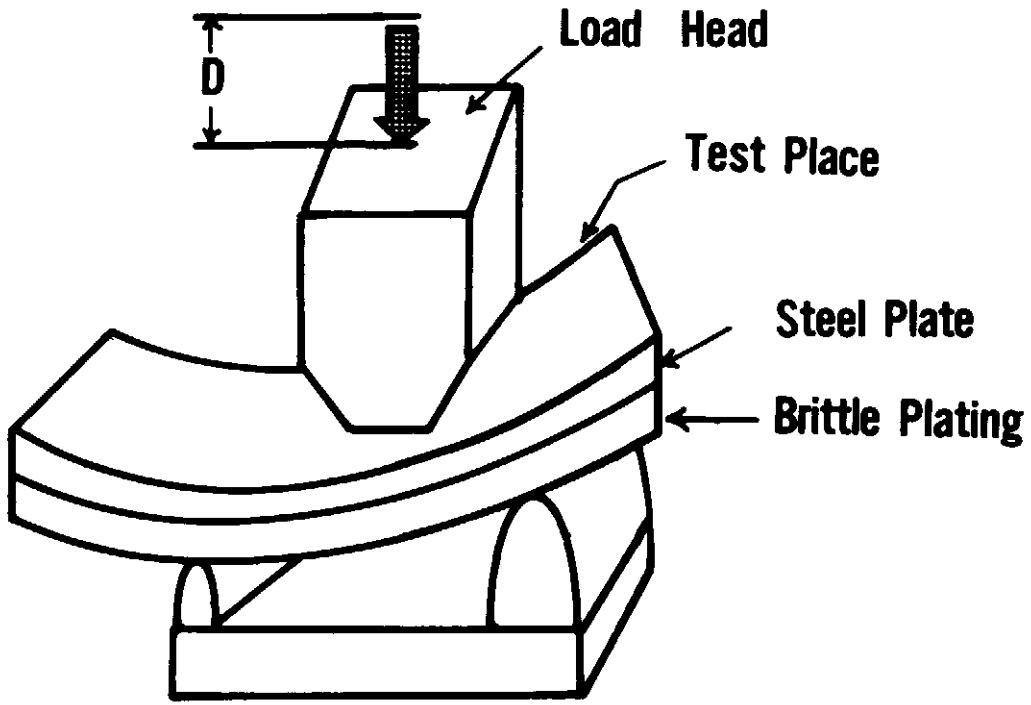


Figure 8.

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# PENETRANT TESTING JIG

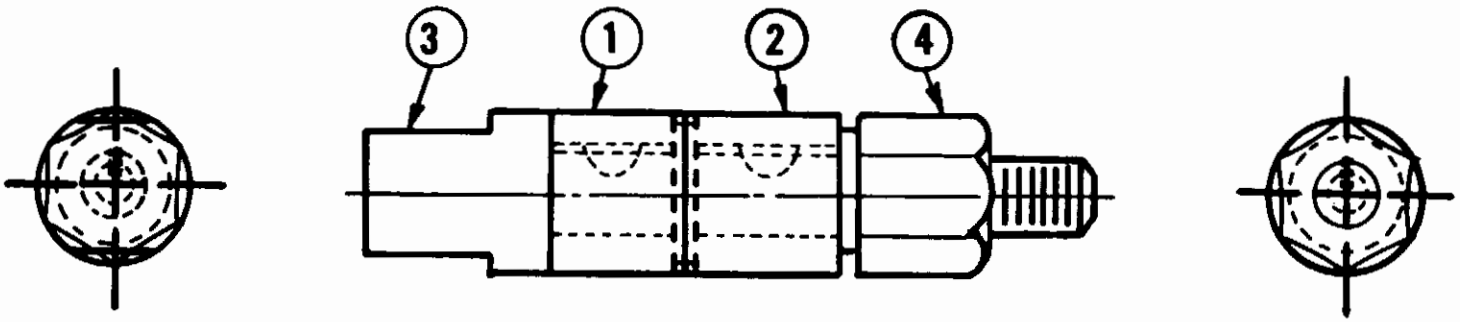


Figure 9.

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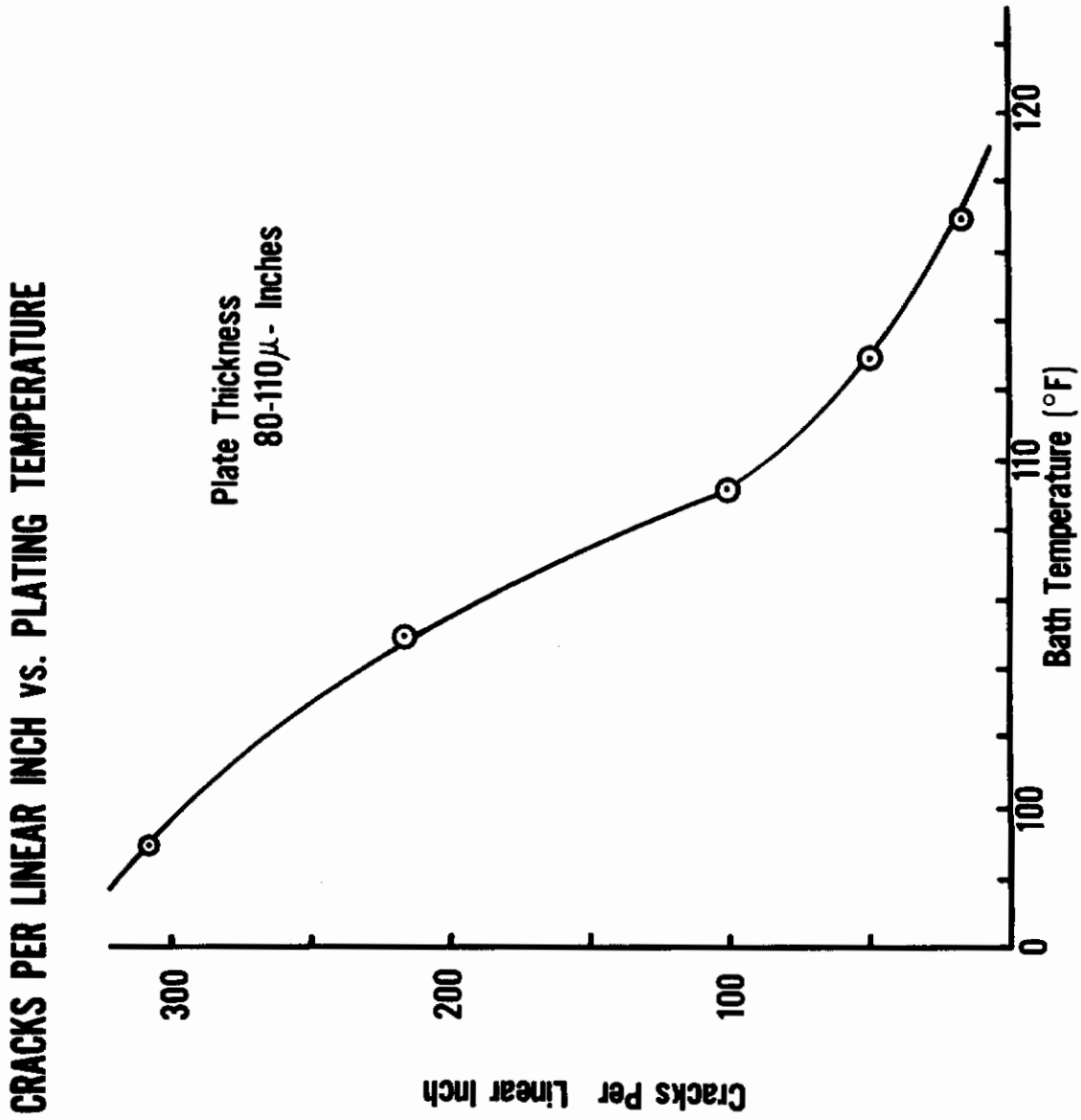


Figure 10.



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