SHEng
SMART HEALTHCARE ENGINEERING
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# NDT TESTING IN HEALTHCARE INFRASTRUCTURES

## Part 1

**Class content material**

This document is part of a training materials collection developed within the Erasmus+ project “Smart healthcare engineering”, SHEng, project No. 2023-1-RO01-KA220-HED-000159985.

The collection is intended for engineering students and professionals working in the healthcare sector. It covers technical subjects relevant to hospital infrastructure, equipment, materials and support services, helping readers understand how engineering contributes to safe patient care and the reliable operation of healthcare facilities.

These materials support classroom teaching and independent study. They should be used alongside the project handbook and the presentations, courses and other learning resources available on the project website. Each document addresses a specific subject, while the collection provides a broader understanding of the responsibilities and practical challenges of healthcare engineering.

The content is educational. Its application in practice requires consideration of the conditions of each healthcare facility, the applicable standards and the instructions provided by equipment manufacturers.

Project website: www.smarthealtheng.com

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# LIQUID PENETRANT

Nowadays, the healthcare sector benefits from modern NDT testing and analysis methods that help prevent system failures. Liquid penetrant testing is used to detect surface-breaking cracks and other discontinuities in non-porous components, including welds in stainless steel pipelines, tanks and hospital equipment, helping identify defects before they cause leaks or equipment failure.

**Introduction**

Liquid penetrant testing (PT) is a fast, cost-effective and highly sensitive non-destructive testing method suitable for inspecting a wide range of materials, components and assemblies. The primary purpose of PT is to identify surface-breaking discontinuities, regardless of whether they originate from raw material manufacturing, fabrication processes or operational wear and environmental degradation. Due to its portability, PT is particularly well-suited for field inspections and remote locations.

For effective application, PT requires three fundamental conditions:

- Surface-connected discontinuities: the flaws must break the surface, as sub-surface or fully encapsulated defects cannot be detected
- Meticulous surface preparation: thorough pre-cleaning is required to ensure contaminants do not block penetrant ingress
- Visual acuity: the inspector must possess adequate visual capacity to accurately interpret indications.

Everyday examples like coffee highlighting fine cracks in a ceramic mug or oil leaking from a cracked engine blocked demonstrate how penetrant testing works: a fluid seeps into a surface defect and exits to form a visible line. In non-destructive testing, penetrant testing (PT) uses contrasting liquids and absorbent developers to draw the fluid out and reveal surface-open defects.

While PT requires less mechanical complexity than other NDT techniques, success relies heavily on strict procedural compliance, correct dwell timing, absolute cleanliness, and a thorough understanding of potential defect types.

The main execution steps include:

- Pre-inspection and surface preparation – inspect the surface visually and clean it thoroughly (removing rust, dirt and coatings) so defects are completely unblocked and accessible.
- Penetrant application – apply penetrant and allow sufficient dwell time for the liquid to migrate into any surface opening.
- Intermediate cleaning – carefully wipe or rinse away excess surface penetrant without flushing it out of the discontinuities
- Development – apply developer to draw the entrapped penetrant back to the surface and create a high-contrast visual indication
- Interpretation and post-cleaning – evaluate and document the indications, then clean the component a final time to remove developer and a chemical residue.

Penetrant testing (PT) is widely implemented across diverse industries – such as aerospace, power generation, automotive, fabrication and composite manufacturing- due to its extreme adaptability and economic efficiency. It effectively identifies inherent, fabrication and service-induced surface flaws across almost any solid material, including select porous items using tailored systems.

The primary strengths of PT lie in its remarkable versatility, cost-effectiveness and operational adaptability across various component sizes and geometries. Single-operator portable kits allow for convenient field deployment while the process can also be automated for high-volume production lines or simple geometries. Furthermore, when performed by qualified personnel, PT delivers exceptional flaw sensitivity with minimal false-positive indications. However, the technique has notable operational limitations. It is strictly restricted to surface-breaking discontinuities, making subsurface flaws or extremely tight cracks undetectable. Test reliability is heavily influenced by surface condition, as excessive roughness, contamination or porosity can easily obscure genuine defects or trap chemicals. Operational temperatures also present constraints, standard consumables require specimen surface temperatures between 4°C and 49°C, necessitating specialized formulations for extreme thermal windows ranging from -12°C up to 175°C. Finally, the chemical

nature of penetrant materials requires proper ventilation and compliant waste management to address health, safety and environmental risks, which can add to overall processing costs.

At the heart of liquid penetrant testing (PT) is the penetrant fluid's ability to achieve complete surface wetting and migrate deep into surface-breaking discontinuities – phenomena ruled by surface tension, contact angle, capillary action and dwell time.

Surface tension accounts for everyday fluid dynamics, such as soap bubble formation or water beading on a freshly waxed vehicle compared to spreading on weathered finish. At a molecular level, a molecule within the bulk liquid experiences symmetrical, omnidirectional cohesive forces, yielding a net force of zero. Conversely, molecules at the liquid-gas interface experience asymmetrical, hemispherical cohesive attraction directed inward toward the liquid bulk. Work is required to bring a molecule to the surface against this inward force, which is stored in the surface lawyer as elastic potential energy, termed surface energy. To attain thermodynamic equilibrium, the fluid naturally minimizes its surface energy by minimizing its surface area – causing an isolated droplet to assume a spherical geometry.

The tangential elastic force acting along the fluid interface to minimize surface area is defined as surface tension ($\gamma$ or $\gamma_{lg}$, representing the liquid-gas boundary). In classic thin-film wire-frame experiments, the required force F to extend a film across a slider of length $l$ yields:

$$\gamma = \frac{F}{2l} \tag{1}$$

Unlike elastic membranes such as rubber, the force required to expand a fluid film is independent of its existing area; as the film expands, bulk liquid molecules simply transition to the surface without enduring shear stresses at low strain rates. Furthermore, surface tension establishes a pressure differential across a curved interface, expressed via the Young-Laplace relationship:

- For a hollow thin-walled sphere (soap bubble): $p_i - p_o = \frac{4\gamma}{r}$ (2)
- For a solid liquid droplet: $p_i - p_o = \frac{2\gamma}{r}$ (3)

The execution of a liquid penetrant test follows a precise, sequential methodology. It begins with a detailed initial visual examination of the test piece, followed by thorough surface preparation to ensure all surface-breaking discontinuities are free of obscuring contaminants. Once the surface

and chemical temperatures are verified to be within acceptable operational limits, the penetrant is applied across the test surface. During the subsequent dwell period, the liquid wets the substrate and is drawn deep into surface openings via capillary action. Excess surface penetrant is then selectively removed to preserve the fluid entrapped within the defects. Next, a developer coating is applied to bleed the entrapped penetrant back out to the surface through blotting action, simultaneously establishing a contrasting background to maximize indication visibility. Finally, under proper ambient or ultraviolet lighting, the resulting indications are located, evaluated and interpreted.

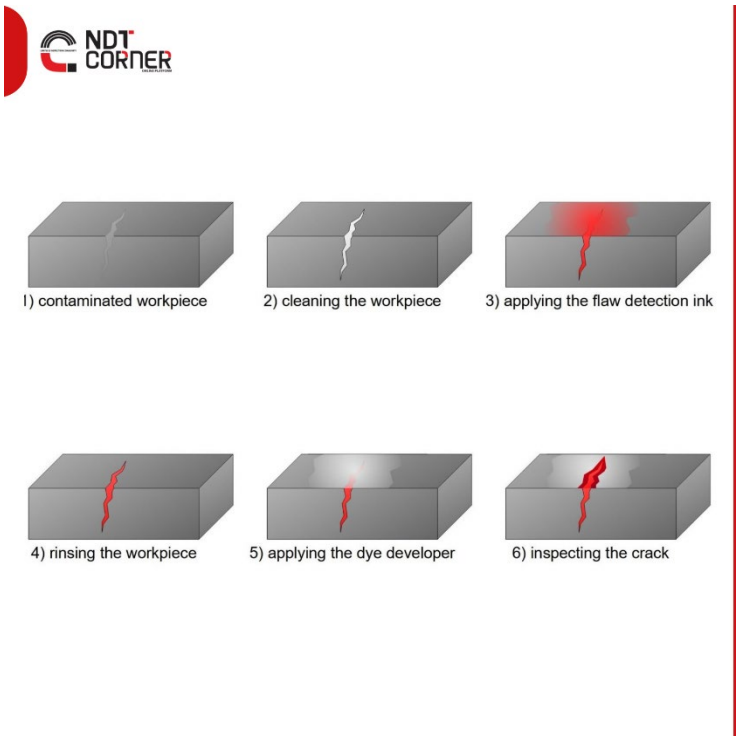


Fig. 1. Liquid penetrant method steps [1]

**PENETRANTS**

Any effective liquid penetrant serves two essential purposes: it acts as a high-visibility medium to indicate flaws and as a fluid vehicle that distributes the indicator across the surface and into surface-breaking discontinuities. In accordance with standard specifications, penetrants are categorized into two primary types based on their detection method:

Type I – fluorescent penetrants – utilize brightness contrast under ultraviolet illumination

Type II – visible (color contrast) penetrants: utilize color contrast under ambient light.

Fig. 2. Sprays kit for colored penetrant [2]

Penetrant materials are further classified by their removal method:

- Method A: water-washable
- Method B: post-emulsifiable (oil-based)
- Method C: solvent removable
- Method D: post emulsifiable (water-based)

Visible penetrants are evaluated under standard ambient lighting, typically employing a deep red dye. Red dye is preferred due to its fine particle size, high solubility in penetrating carrier oils and strong contrast against the white developer layer.

Fluorescent penetrants offer higher sensitivity but require inspection under ultraviolet light (320-400 nm wavelength) in a dark or subdued environment. The fluorescent dye absorbs UV radiation and re-emits light in the yellow-green spectrum (480-580 nm), which corresponds directly to the peak spectral sensitivity of the human eye under dark-adapted conditions.

Penetrants can be applied via immersion, brushing or spraying, chosen according to part geometry, quantity and testing location:

- Immersion – ideal for large components or batch processing of smaller parts. Specimens are placed on racks and dipped into the penetrant tank, then removed. Parts must not remain submerged during the dwell period; proper drainage during dwell is required.
- Brushing and spraying – commonly used for localized or field inspections. Soft-bristle brushes designated exclusively for penetrant use are recommended. Spraying via aerosol

cans or spray guns should be conducted at approximately 15-20 cm to minimize overspray. Proper workplace ventilation is essential for operator safety and bath purity.

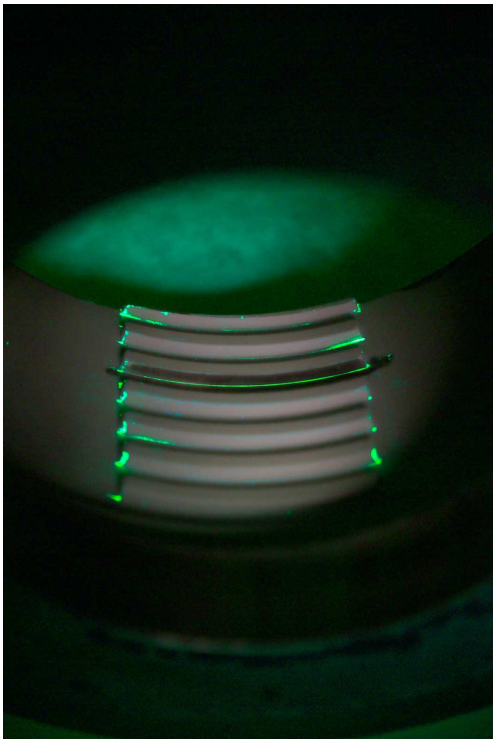

Fig. 3. Fluorescent penetrant under UV light [3]

Dwell time is defined as the total duration between penetrant application and excess penetrant removal. It represents the required timeframe for the liquid to wet the substrate surface fully and migrate deep into open discontinuities via capillary action.

Dwell time is governed by several interrelated factors:

- Higher temperatures accelerates penetration kinetics, resulting in shorter dwell times, whereas lower ambient temperatures increase viscosity and require extended dwell periods. Standard penetrant formulations typically operate within the temperature range of 10°C to 49°C. Testing outside standard thermal limits requires procedural qualification or pre-warming of components and consumables.
- Inadequate surface preparation, residual contamination or mechanical surface distortion necessitates longer dwell durations.

- High strength, high temperature alloys (ex. Ti Gr II, stainless steel, etc) generally require extended dwell times compared to standard carbon steels or ferrous materials.
- The size, orientation and morphology of flaws strongly dictate required exposure times. While standard guidelines specify a minimum dwell time of 10 minutes at ambient temperature for common alloys, extremely tight flaws – such as intergranular stress corrosion cracking or tight fatigue cracks under residual compressive stress – may demand dwell times exceeding 24 hours.

Extended dwell periods or elevated processing temperatures can cause penetrant evaporation and drying on the component surface. If drying occurs, penetrant reapplication is mandatory prior to intermediate washing.

**DEVELOPERS**

Following excess penetrant removal, a thin developer coating is applied to the component surface. The developer serves two primary functions: acting as a blotting agent to extract entrapped penetrant from flaw cavities, and spreading the exuded penetrant to enhance indication visibility. The developer powder draws fluid out through a combination of **absorption (penetration of liquid into powder particles)** and **adsorption (adhesion of liquid to particle surfaces)**. Furthermore, the developer establishes a high-contrast background to maximize defect detectability:

- Type I – fluorescent systems – the developer appears dark blue-black under ultraviolet radiation, contrasting with the bright yellow-green fluorescence of the penetrant
- Type II – visible systems – a brilliant white powder layer provides a contrasting backdrop against vivid red dyes.

Developers are categorized according to their carrier mechanism and application state:

- Dry powder developers – low-density, highly buoyant powders applied within specialized cabinets via air-agitated powder clouds or electrostatic spraying
- Water-soluble developers – powder particles completely dissolved in a water medium
- Water-suspendable developers – insoluble particles suspended in water. Continuous tank agitation is mandatory to prevent particle settling. Wetting agents and corrosion inhibitors are added to ensure uniform coverage and protect specimen surfaces.

- Solvent-suspendable (nonaqueous) developers – suspend developer particles in a volatile organic solvent. The solvent dissolves residual penetrant to enhance blotting action and evaporates rapidly without requiring forced-air drying. These are typically applied via aerosol cans or spray equipment during field inspections.

Developer application is strictly governed by coating uniformity and film thickness. Uniformity ensures consistent indication sizing across the entire part, while excessive developer thickness must be avoided, as thick powder layers can cover or completely mask minor indications.

Fig. 4. Developer applied on the inspected piece's surface [4]

## EVALUATION AND INSPECTION

Accurate evaluation and interpretation of liquid penetrant testing (PT) indications demand significant technical expertise and practical experience. Personnel must possess a thorough understanding of the PT sequence, material defect morphology and non relevant or false indications. Essential prerequisites for inspection personnel include adequate lighting conditions and certified visual acuity (specifically near-vision acuity and color contrast discrimination). Observing indication development as a function of time provides critical insight into flaw geometry:

- Shallow discontinuities tend to produce indications almost immediately during development
- Deep discontinuities continue to bleed out over an extended period, yielding larger indications.

- The final size and intensity of the indication directly correspond to the volume of penetrant entrapped within the flaw cavity.

Test results may be documented through various photographic, digital or mechanical techniques. Standard digital or high-contrast photography provides permanent archival records, while video recording offers cost-effective, real-time documentation of both the inspection process and indication bleed-out dynamics. For physical records, indications can be captured using transparent adhesive tape lifts or preserved temporarily with strippable transparent plastic sprays.

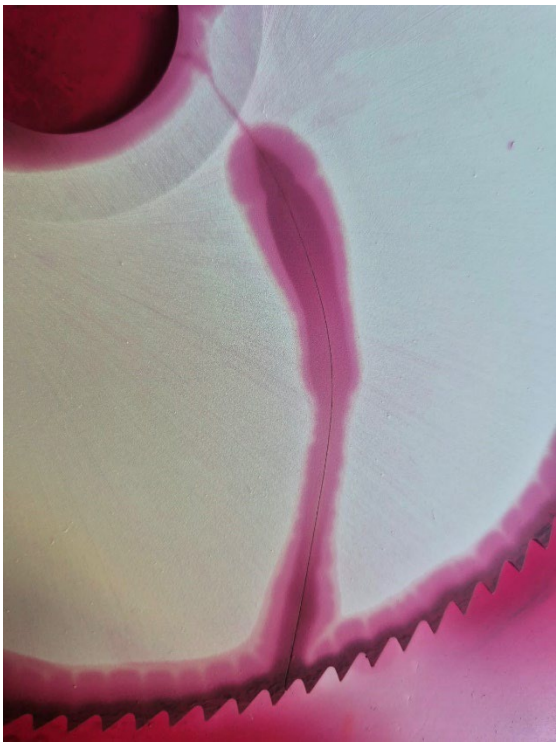

Fig. 5. Discontinuity shown by liquid penetrant testing

Liquid penetrant testing (PT) offers a rapid, straightforward, cost-effective and highly sensitive non-destructive evaluation (NDE) method applicable to an extensive array of materials and structural systems. Its portability makes it exceptionally well-suited for field operations and remote locations where structural integrity is critical to operational safety, yet alternative NDE methods remain impractical. Comprehensive technical literature, industry standards and manufacturer specifications are readily available to guide practitioner training and process implementation. Delivering reliable inspection results relies on inspector competence and visual acuity, strict compliance with established testing procedures, meticulous surface cleaning and the presence of

surface-breaking flaws. When these foundational criteria are met, penetrant testing offers an outstanding combination of high defect sensitivity and practical simplicity.

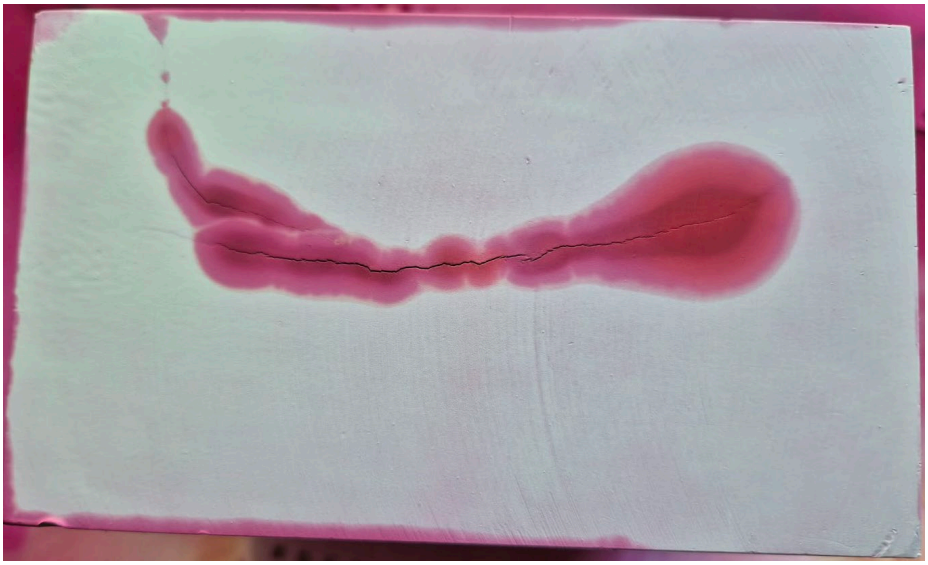

Fig. 6. Discontinuity shown by liquid penetrant testing

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**Acknowledgments**

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