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TÍTOL DEL TFC: Non-destructive testing of aerospace components

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Resumen

Este proyecto trata de ensayos no destructivos como parte de la industria aeronáutica y aeroespacial. Hoy en día, se invierten importantes sumas de dinero en mantenimiento de aeronaves, y las técnicas no destructivas tienen un papel muy importante ya que permiten combinar una seguridad máxima en cuanto a la operabilidad de las aeronaves, y el coste mínimo de inspecciones.

La primera parte de este documento trata de describir los métodos no destructivos utilizados en la industria, y explicar los factores que determinan la elección de ciertos métodos para diferentes inspecciones. La segunda parte describe los experimentos de líquidos penetrantes que se llevaron a cabo en el laboratorio sobre piezas de aviación, seguido de la descripción de los resultados y su evaluación (evaluación general del proyecto en cuanto a los costes y eficiencia, etc.). El penúltimo capítulo contiene información referente al impacto medioambiental de dichas inspecciones, y finalmente se puede hallar las conclusiones.

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Overview

This project focuses on the Non-destructive testing (NDT) as part of the aeronautical and aerospace industries. Nowadays, important amounts of money are invested in aircraft maintenance, and non-invasive inspection techniques play a major role in assuring maximum safety and minimum maintenance costs.

The first part of the document is dedicated to the description of NDT methods and factors that determine the choice of technique to apply in each case. The second part describes the liquid penetrant testing (LPI) experiments carried out in the university laboratory, and contains detailed information on this NDT method. Evaluation of the results follows, together with some information on the environmental issues relative to the LPI and an assessment of the time and cost-effectiveness of the project.

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INTRODUCTION

The goal of this project is to make an introduction into the world of NDT, which plays a crucial role in the aeronautical and aerospace industries. Since this topic has not been covered in any of the subjects of the course, this document contains some introductive information about non-destructive testing in general, and then discusses its specific aspects in the aeronautics sector. NDT is of great importance in the aviation and space field, where routine maintenance and inspections are obligatory, maximum safety is necessary, and minimum costs are desirable.

Part of this document is dedicated to the description and explanation of the experiments that were made to turn NDT into a first-hand experience. Several aeronautical components were examined applying the most widely used NDT method in aeronautics, liquid penetrants. The objective was to identify possible fatigue-induced defects on the surface of aircraft parts, and evaluate the locations and materials that were most prone to failure.

CHAPTER 1. NON-DESTRUCTIVE TESTING

1.1. The role of NDT in all industries

1.1.1. What is NDT and why it needs to be done to engineering components

Engineering products must be inspected during and after manufacture, and often during their service life, to ensure that their condition is suitable for their purpose. The field of Non-destructive Testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable way. NDT can be defined as “inspections, tests, or evaluations which may be applied to a structure or component to determine its integrity, composition, electrical or thermal properties, or dimensions without causing a change in any of these characteristics.” [1]. NDT encompasses a number of methods that are performed in a manner that does not render engineering parts and structures unusable after testing. This is particularly useful in transportation fields, where regular inspections are required to assure public safety. Because it allows testing without interfering with the products’ final use, NDT provides an excellent balance between quality control and cost-effectiveness.

Non-destructive evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically speaking, NDE is used to describe measurements that are more quantitative in nature. Not only does NDE locate the defects, but also describes them, their size, shape, and orientation. NDE may be used to determine material properties of the components, such as fracture toughness, formability, and other physical characteristics.

1.1.2. Defects that need to be controlled by means of NDT

All engineering materials contain defects, which can be divided into three main groups:

- *harmful*, either immediately or because they are of a type and in a position where they could grow to dangerous proportions in service
- *harmless*, for example because of their small size or innocuous position (such as microporosity in a low-stressed region of a casting from which associated leakage would not present a problem)
- *beneficial*, for example mobile lattice defects such as dislocations whose very mobility and ability to interact and multiply confers toughness on the material.

For non-destructive testing to be effective at minimum cost, the methods used must not only detect the flaws in the material, but also determine their type and size, task which is not always easy, and distinguish between those which are harmful and those which are harmless, and those which should constitute the rejection criteria. Election of timing and the type of inspection are also crucial.

There are four basic rules that form the examiners' approach to Non-destructive testing of engineering components:

- flaws are present in a wide range of types and sizes in all materials
- there is an equally comprehensive range of methods and devices for finding flaws
- some flaws hazard the safety of the structure, whereas others do not
- the position, orientation and shape of the flaw are extremely important for defining the importance of the defect; for example, flaws that are situated close together may act as one larger flaw.

Flaws and imperfections can appear in engineering materials and structures at any point, starting with the extraction and melting of the ore to the welding of the structure. Fig. 1 illustrates the stages of life of engineering components and the types of defects that can be introduced into them at each stage.

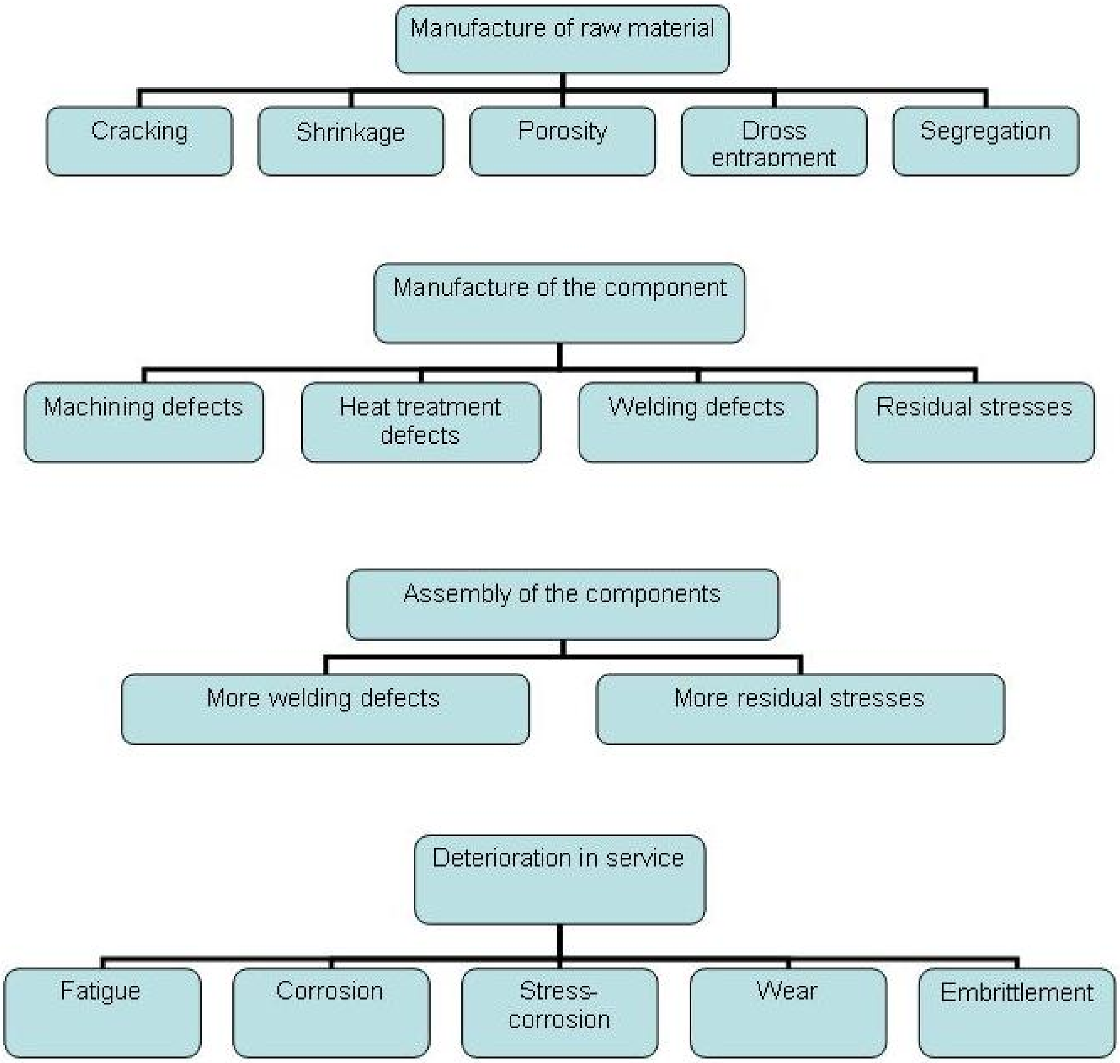

Fig. 1. Stages of life and types of defects of engineering components

Golden rules for NDT:

- Perfection is impossible; striving for it is expensive
- Lack of effective inspection costs money and can cost lives
- Excessive inspection wastes money, may not result in any improvement in reliability or performance, and will reduce the availability of the equipment

1.2. NDT and the methods that compose it

There is a number of methods, ranging from basic visual inspections to sophisticated x-ray and ultrasonic techniques, that encompass the field of non-destructive testing. Below is a list and a short description of each method, as well as a few indications as to when, for which materials and for what defects it is best suited.

1.2.1. Visual / Optical inspections

The procedures range from simply looking at the part to using a computer-controlled digital camera that recognises and records the cracks and small imperfections. It is only suitable for detecting surface flaws, and should not be relied upon as the sole method of inspection.

1.2.2. Liquid penetrants inspections

This method can be applied to any material and any type of joint. The object to be tested is covered with a dye containing solution that seeps into the surface cracks. Excess solution is then removed from the surface, but stays in the cracks. A developer – most commonly, a white powder- is then applied, usually by spraying. The dye from the cracks will seep out to stain the developer powder, and the presence of the flaw is revealed by the stain, as can be seen in the diagram in Fig.2.

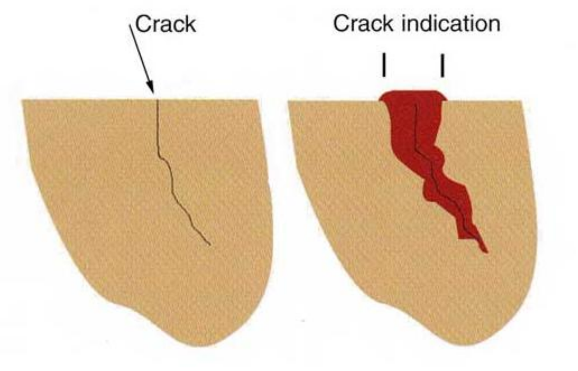

Fig. 2. Dye penetrant indication of cracks

This method is only effective for detecting surface breaking defects such as cracks, folds, laps cold shuts and porosity. It only gives information about the flaw's length, not depth.

1.2.3. Radiography

This method is similar to the one used on humans for medical purposes, such as the detection of bone fractures.

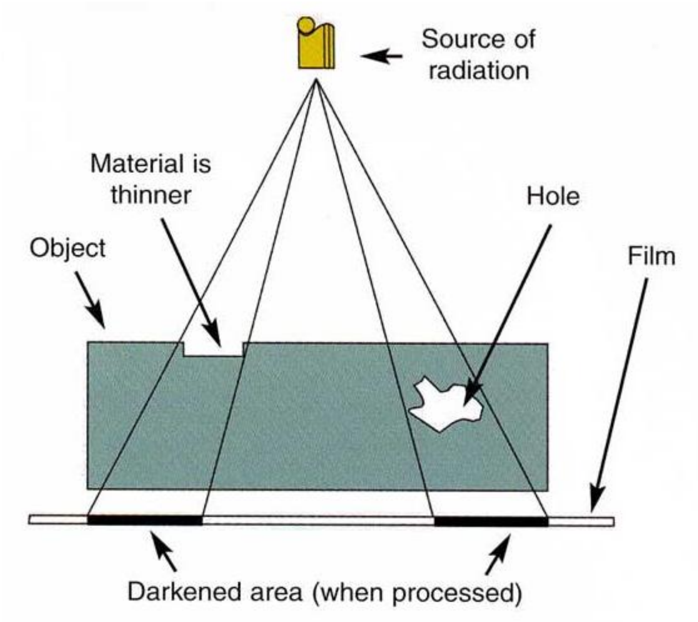

Fig. 3. Radiography testing

A film is placed behind the object that is being inspected, and a source of radiation is directed towards it, as illustrated by Fig.3. The radiation may be either Gamma or X- rays. Gamma radiation is emitted from radioactive isotopes such as Iridium 192, Caesium 137 and Cobalt 60, whereas to generate X-rays, an electrical power supply is needed. Gamma ray inspection is useful in making radiographs of areas where x-rays may not be possible either for reasons of access or material thickness.

The wavelength of the radiation should be short enough to allow some of it to pass through the metal and reach the film. If there is porosity or hollow regions in the metal, more radiation will reach the film, thus indicating the presence of the flaw in that part of the component.

Radiography is particularly useful for detecting volumetric flaws such as porosity. However, it will not detect planar flaws inclined at an angle to the beam, but only those aligned with it.

Radiography allows the detection of internal flaws and defects such as cracks, corrosion, inclusions and thickness variations.

An important advantage of this method over others is that a permanent record of the inspection is created, and the film can be examined later, under more appropriate conditions, and the results evaluated. However, it does not allow for the sizing of flaws nor their location in the direction of thickness. Other disadvantages are radiation hazard and need of specific equipment.

1.2.4. Magnetic particle testing

This method can only be applied to materials that can be magnetised. The procedure consists in creating a magnetic field around the object, and then dusting its surface with small iron particles. The surface and near-surface flaws would distort the field and cause the particles to concentrate around the flaw, as shown in the following diagram in Fig.4.

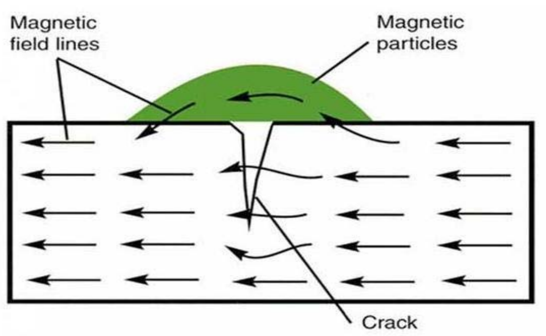

Fig.4 Magnetic particle testing

Magnetic field can be applied by permanent magnet, by an electromagnet, by induced magnetic fields from a current carrying coil, or by the passing of a heavy electrical current through the piece. To reveal the presence of flaws, the direction of the lines of force of the magnetic field must be perpendicular to the length of the defect, and generally it would be necessary to apply the technique in two perpendicular directions to cover all possible flaw orientations.

The magnetic particle inspection technique is suitable for detection of surface or very near surface flaws. It can only indicate the length of the defect, but not its height, and gives no information about embedded flaws. It is thus only used for a quick detection of surface flaws. It is generally more rapid and effective than dye penetrants inspection, but has several drawbacks: parts should be degreased and de-magnetised before and after inspection, and paint removal is required. Complex shaped components can be difficult and time consuming to examine thoroughly.

1.2.5. Ultrasonic testing

The underlying principle of this method is calculating the velocity of ultrasound waves travelling through the material in question. The speed of propagation of ultrasound waves in solid materials depends on the modulus of elasticity E and of rigidity G, and the density. There are two ways to detect flaws: the 'pulse-echo' method, and the 'time-of-flight' test.

In the pulse-echo method, ultrasound waves are sent into the material, and the echo is then recorded by the receiver. This is the method illustrated in Fig.5. If in some region it takes the waves shorter to return, it indicates a presence of flaws in the object: porosities, cracks, or deterioration of the material in such a way that either of the aforementioned constants have altered.

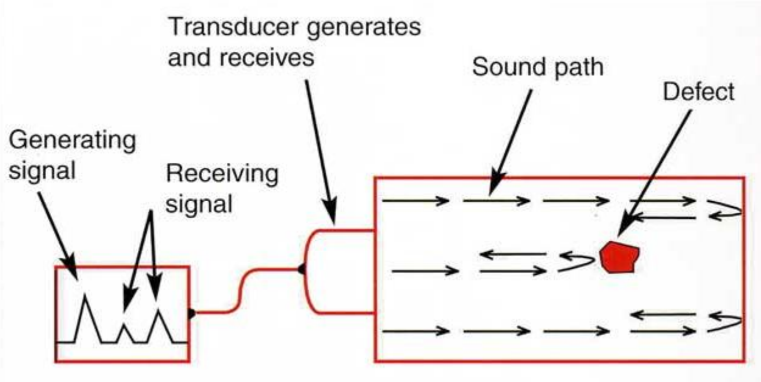

Fig. 5. Ultrasonic testing

With the time-of-flight method, other waves are recorded and analysed. When ultrasound waves are sent into the material, a new signal is generated by the refraction of the wave off the edges of the embedded crack. It is this signal that is detected, and its time of flight is calculated in order to discover the crack's location inside the material. This method is more precise than the pulse-echo technique: the sizing errors have a standard deviation of 1-3mm in this case, whereas for the other methods it is 3-5mm.

1.2.6. Electromagnetic testing

This technique can be applied to any metal, and it is used extensively in the aircraft industry where the aluminium materials used for airframe structural components are not suitable for magnetic crack detection. The general principle of eddy current testing is that an electrical coil carrying AC current is brought close to the surface of the region to be tested. This induces eddy current in the near surface parts of the component. If a flaw is present in the area, it disturbs the flow of the eddy currents. It is possible to set up and calibrate a system that would allow for a quick and effective scanning of the component, and even for an estimation of the size of a surface-breaking flaw in respect of its height. Fig. 6 presents a basic diagram illustrating the functioning of this method.

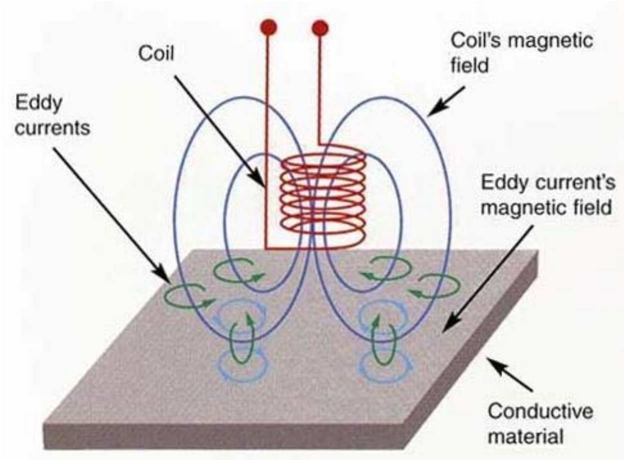

Fig. 6. Eddy current testing

This technique is suitable for detection of surface and near-surface defects in metallic components, cracks, pits, corrosion, changes in heat treatment, and conductivity.

Its primary advantages are its portability, the ability to test through coatings and through multi-layered structures, and that it's very fast to use. In fact, automated systems for the examination of aircraft wheels are not uncommon in aerospace environments.

1.2.7. Gas and air leak detection

Electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques, and a simple soap-bubble test can be used to detect cracks in pressurized containers. Nowadays, ultrasonic gas leak detectors are usually used, whose function is based on the principle that if a gas leaks through a small hole, the turbulence will generate a broad band noise in the frequency range of about 80 kHz. Such detectors are normally the size and shape of the torch, and the inspection technique is quick, adaptable and non-contact in nature.

1.2.8. Stress wave, or acoustic emission

This technique is applied to structures that are subjected to load. It consists of the application of a network of high-powered miniature microphones to the region to be inspected, and the recording of noises emitted during the test. The load is gradually increased, and when the ligaments of the material are fractured and cracks are formed, the acoustic waves emitted are recorded by the microphones. The signals are later processed and compared, thus allowing for the detection and location of the cracks. Acoustic emission cannot provide other information on the size or other characteristics of the flaws.

1.2.9. Infrared / thermal testing

Observation of the temperature reached by various parts of a component, either in service or under an imposed test condition, can be used for a variety of purposes, including searching for the integrity of bonds between honeycomb cores and surfacing panels, wall thickness variations in these components, local hot spots in electronic circuits, etc.

The means available range from making the surface with temperature sensitive crayons or paints, which either change colour or run when the given temperature is reached, to the use of liquid crystals, radiometers and infrared viewing systems.

1.2.10. New methods for characterisation of metallic microstructures

In the recent years, new techniques have been elaborated for Non-destructive evaluation of microscopic structures of metallic materials. In recent years, they have been successfully employed for characterisation of defects and microstructural features such as grain size, texture, nucleation and growth of second phases, assessment of tensile, creep and fatigue properties, deformation and damage. Non-destructive evaluation techniques are also becoming indispensable in the monitoring and control of fabrication processes for assuring quality of materials and components.

These NDE methods for microscopic structures include acoustic emission, ultrasonic attenuation and velocity, magnetic hysteresis parameters, magnetic Barkhausen emission, acoustic Barkhausen emission, laser interferometry, positron annihilation, X-ray diffraction and small angle neutron scattering [7].

1.3. Method selection

The choice of method depends on the nature of the object to be tested, and the type of imperfections that we need to detect. For example, liquid dye penetrants would not be useful in detecting embedded cracks or hollow regions – to detect these, other methods should be used, for example, acoustic emission or radiography.

In the following Table 1 inspection methods are classified by access requirements and cost of the tests, thus illustrating their most important advantages and drawbacks and contrasting them against other tests [10].

Technique	*Access requirements*	*Equipment capital cost†*	*Inspection cost‡*	*Remarks*
Optical methods	Can be used to view the interior of complex equipment. One point of access may be enough.	B/D	D	Very versatile, little skill required, repays consideration at design stage
Radiography	Must be able to reach both sides	A	B/C	Despite high cost, large areas can be inspected at one time; considerable skill required in interpretation
Ultrasonics	One or both sides (or ends)	B	B/C	Requires point-by-point search, hence expensive on large structures; skilled personnel required
Magnetic particle detection	Requires a clean and reasonably smooth surface	D	C/D	Only useful on magnetic materials such as steel; little skill required; only detects surface-breaking or near surface cracks
Penetrant flaw detection	Requires flaw to be accessible to the penetrant (that is, clean and at the surface)	D	C/D	For all materials; some skill required; only detects surface-breaking defects; rather messy
Eddy currents	Surface must (usually) be reasonably smooth and clean	B/C	C/D	For surface-breaking or near-surface flaws, variations in thickness of coatings or comparison of materials; for other than simple comparison considerable skill is usually necessary (the exception is Amlec for surface-breaking cracks in steels)
Stress wave (acoustic) emission	Can be remote	A/D	A/B	Very versatile; will figure largely in the future; requires part to be loaded
Thermal	Either direct or remote	A/D	B/D	Varies from slow, simple and cheap, to real-time, sensitive and costly
Holographic interferometry	Remote viewing possible	A/B	A/B	Specialized

†This is only a rough guide where A > £1000, B = £200–£1000, C = £20–£200, D < £20, at time of writing.
‡A guide to the cost of employing an agency to carry out the inspection of a small pressure vessel or structure (excludes transport costs). Notation is the same as in †.

Table 1. Characteristics of NDT methods

In the next table, Table 2, NDT methods are classified by the target flaw that is expected to be detected. Depending on the nature and function of each component, the importance of each defect type varies. It is thus important to choose a correct method to make the inspection most reliable and cost-effective.

Defects		Field of application		Visual inspection	Magnetic crack detection	Radiography: X-ray	Radiography: γ-ray	Ultrasonic: Defect echo	Ultrasonic: Back-wall echo or transmission	Dye penetrants	Eddy current	Magnetic coercive force	Sonic testing
Surface defects	Surface cracks Tears	Magnetic irons		★★	★★★					★★			
		Non-magnetic irons		★★						★★★			
Subsurface defects not lower than 3 mm	Blowholes Inclusions	Smooth surfaces			★	★		★	★★				
		Rough surfaces				★			★				
Internal defects	Blowholes Shrinkage cavities Gas holes Inclusions	Sections under 20 mm				★★★		★	★				
		Sections 20–150 mm	Coarse flake graphite irons			★★	★★	★					
			Fine flake graphite irons			★★★	★★	★★					
			Spheroidal graphite irons			★★★	★★	★★★					
			White irons			★★★	★★	★★★					
		Sections over 150 mm	Spheroidal graphite irons				★★	★★	★				
			Flake graphite irons				★★	★	★				
	Shrinkage porosity Open grain	Sections under 150 mm				★	★		★★				
Metallurgical defects	Inverse chill										★	★★	
	Chilled edges										★	★	
	Incorrect hardness										★★★	★★★	
	Incorrect heat treatment										★★★	★★★	
	Incorrect graphite structures		Flake graphite irons						★				★★
			Spheroidal graphite irons						★★				★★★
Dimensional defects	Core shift Wall thickness			★★					★★★				

★★★ Best ★★ Possible ★ Sometimes possible

Table 2. Method suitability by flaws

Another table presented as Table 3 complements the previous one, evaluating each method in terms of the defect the part is being inspected for.

Flaw Type / Inspection Method	Visual	Liquid Penetrant	Magnetic Particle (A)	Ultrasonic		Eddy Current (B)	X-Ray
				Straight Beam	Angle Beam		
Surface Breaking, Linear	1	3	3	1	2	3	1
Surface Breaking Volumetric Defect	3	3	3	3	3	3	3
Near-Surface Linear & Normal to Surface	0	0	2	1	2	3	1
Near-Surface, Linear & Parallel to Surface	0	0	0	3	3	0	0
Near-Surface, Volumetric	0	0	2	3	3	3	3
Subsurface, Linear & Normal to Surface	0	0	0	1	2	0	1
Subsurface, Linear & Parallel to Surface	0	0	0	3	3	0	1
Subsurface, Volumetric	0	0	0	3	3	0	3
Thickness Measurement of Thin Materials	0	0	0	3	3	3	3
Thickness Measurement of Thick Materials	0	0	0	3	3	0	3
Non-Conductive Coating Thickness Measurements	0	0	0	2	2	3	1

(A) Ferromagnetic materials only (B) Conductive materials only

(0) Will not detect (1) Not well suited (2) Fairly well suited (3) Ideal Application

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Table 3. NDT methods classified by target flaws

1.4. The role of NDT in aerospace and aeronautical industries

In the aerospace industry, the use of NDT is crucial. It equally important to inspect the components, as it is to leave them unharmed after the testing is completed. Aerospace components need to be examined numerous times throughout their lifetime – before they are assembled into the aircraft/shuttle, and then periodically during their use. Without NDT, the cost of maintaining and flying in airplanes would increase dramatically, and the safety of flying decrease. Aerospace parts are designed to be as light as possible, at the same time withstanding high levels of stress and strain, and a small imperfection could make the difference between a correct functioning of the part and its failure.

Aircraft maintenance is a very important business: the inspections are both frequent and expensive, thus making it a dynamic field, where new, cost-effective and reliable techniques are always welcome. All aircraft are subject to scheduled inspections and maintenance requirements, which may be schedules every 200 flight hours or so. According to FAA (Federal Aviation Authorities) statistics, jet aircraft average 432 hours per year and turboprop aircraft averaged 406 hours per year, which means that every aircraft must pass scheduled maintenance at least twice a year. Along with these scheduled inspections comes other maintenance (unscheduled maintenance); in fact, a common rule of thumb ratio of inspection time to resulting maintenance is 1: 1,5. That is, if an hour is spent on inspecting the aircraft, an additional hour and a half will be spent on making corrections to the discrepancies that were found, and the final bill will rise to at least 2.5 times the original budget. This, together with unscheduled repairs, might cost the aircraft owner as much as $75000 to $150000 per year [2].

An important factor that places aerospace materials in the high risk category is that such materials are subjected to cyclic stress and are therefore prone to fatigue cracking. Take-off, landing, loading and unloading, pressurizing the cabin, all contribute to the stress cycle. Fatigue involves initiation and growth of a crack under applied stress amplitude which may be well within the static capacity of the material, but with each load cycle the crack grows a microscopic amount. It often remains tightly closed, and thus difficult to find by visual inspection during the majority of the life. If cracking remains undiscovered, there is a risk that it may spread across a significant portion of the load-bearing cross section. It can occur in metals, plastics, composites and ceramics, and is the most common mode of failure in structural and mechanical engineering components, such as are aerospace components.

Cracking can also occur due to other things like a lightning strike. Aircraft have some protection against lightning strikes but occasionally they occur and can results in cracks forming at the strike location.

Another problem that aircraft have is that they are under the constant attack of corrosion. While on earth, the plane is filled with warm moist air, but when it takes off the outside temperature falls considerably, the moisture held by the air inside the cabin condenses on the inside of the aircraft skin. The water will collect at low areas and serve as the electrolyte needed for corrosion to occur.

Of course, aerospace materials are designed to withstand a certain amount of damage from cracking and corrosion without cause for concern, and NDT inspectors are trained to find the damage before it becomes a major problem. The rigorous process used to design aircraft either allows for a certain amount of damage to occur before a part fails, or in many cases, a part can fail completely and performance of the aircraft will not be affected. The job of the NDT inspector is to find the damage while it is within acceptable limits.

Over 80 percent of the inspections done to aircraft components are visual inspections. Obvious cracks, corrosion, and distortion don’t require advanced testing, and affected parts are replaced immediately. Every now and then, inspectors check for flaws on the aircraft exterior, and during heavy maintenance work, much of the interior of the aircraft is stripped out so inspectors can look for damage on the inside surface of the fuselage. However, not all areas of the aircraft can be accessed for visual inspection and not all damage can be detected by visual means. Flaws deep in the metal, fatigue cracks, or very light surface corrosion, often require more advanced techniques to identify and measure. The most commonly used in aeronautics are eddy current, magnetic particle and liquid penetrant methods. [8]

NDT methods allow for the inspection of areas of the plane that would otherwise be uninspectable without disassembling structure to gain access to the internal areas. NDT methods also allow inspectors to detect damage that is too small to be detected by visual means. Eddy current and ultrasonic inspection methods are used extensively to locate tiny cracks that would otherwise be undetectable. These techniques are also used to measure the thickness of the aircraft skin from the outside and detect metal thinning from corrosion on the inside surface of the skin. X-ray techniques are used to find defects buried deep within the structure and to locate areas were water has penetrated into certain structure.

CHAPTER 2. DYE PENETRANTS

2.1 Why Liquid Penetrant Inspections (LPI)

The intention of this project being the non-destructive testing of aerospace components, the choice of method was an easy and straightforward decision, settling rapidly on the LPI. First of all, it is one of the three NDT methods most commonly used in testing aviation parts. The other two methods are eddy current and magnetic particle inspections. In our case, eddy current could not be used because it involves a rather complex procedure, and the inspection personnel requires advanced training in order to be able to carry out the experiments safely and correctly. Magnetic particle testing was not an option because most of the parts inspected were not ferromagnetic (all parts except two were made from Aluminium).

The advantage of LPI above most other NDT methods is its low cost and the possibility of rapid inspections of large surface areas of complex parts. As can be seen and deducted from Figs. 7, 8 and 9 (tables), this method is the cheapest when inspection costs are considered; it does not require complex apparatus nor a well-equipped laboratory, and it is relatively safe (as compared to, for example, radiography). In addition, the initial purpose is to detect only surface defects.

2.2 Description of LPI

2.2.1 In-depth explanation of LPI methods and techniques

LPI include a number of different products and techniques that can be used depending on the target defect, materials to be tested, and other conditions. In general, LPI can be used to inspect almost any material provided that its surface is not extremely rough or porous. Materials that are commonly inspected using LPI include the following:

- Metals (aluminium, copper, steel, titanium, etc.)
- Glass
- Many ceramic materials
- Rubber
- Plastics

2.2.1.1. *Target defects*

LPI is used to detect flaws that are open to the surface, and this is the method’s major limitation. Flaws that can be detected using LPI are as follows:

- Fatigue cracks
- Quench cracks
- Grinding cracks
- Overload and impact fractures
- Porosity
- Laps
- Seams
- Pin holes in welds
- Lack of fusion or braising along the edge of the bond line

In general, penetrant inspections are more effective at finding:

- **small round defects than small linear defects**, because, firstly, the volume of the cavity is generally greater, which means more penetrant liquid is trapped in it. And secondly, it takes liquid less time to seep into a round cavity than into a narrow line cavity.
- **deeper flaws than shallow flaws**, because a larger quantity of penetrant will be present in it, and also because the deeper the flaw, the more resistant it is to over washing.
- **flaws with a narrow opening at the surface than wide open flaws**, because they are less prone to over washing
- **flaws on smooth surfaces than on rough surfaces**, because rough surface trap more penetrant in the small imperfections, and are harder to clean, thus making the inspection method less accurate.
- **flaws with rough fracture surfaces than smooth fracture surfaces**, since the penetrant spreads faster over a rough surface than over a smooth one. However, a particular penetrant may spread slower than others on a smooth surface but faster than the rest on a rougher surface.
- **flaws under tensile or no loading than flaws under compression loading:** as compressive loads are placed on the parts, the crack length steadily decreases as the load increases, and at a certain load the crack is no longer detectable.

2.2.1.2. *Description of the method*

Penetrant testing is a process in which the liquid penetrant is drawn into small openings by capillary action when it is applied to a surface. After a specified time, excess penetrant is removed from the surface and developer is applied to the surface. The developer absorbs residual penetrant drawn from the flaw leaving a bright-coloured penetrant (bleeding) through the developers white background giving a clear visual indication of cracks, porosity, and other flaws.

There are six basic steps to perform a penetrant test.

1. Pre-cleaning of the surface
2. Application of the penetrants liquid
3. Removal of excess penetrant
4. Application of developer
5. Inspection
6. Post-inspection cleaning (removing of developer)

2.2.1.3. *Classification of LPI techniques*

There are various types of penetrants and developers, and the choice of which to use depends on various factors, such as sensitivity required, materials cost, number of parts, size of area requiring inspection, and portability. Detailed information about this classification can be found in Annex A.

CHAPTER 3. EXPERIMENTAL

3.1 The theory behind the experiments

During the experiments, metal aircraft parts were to be inspected in order to reveal any defects present on their surface. Special attention was given to the possibility of encountering cracks produced by stress fatigue, which is a major cause of component failure for metal components in general (90% fail from fatigue), and for aircraft parts in particular.

Fatigue is a progressive, localised and permanent structural damage that occurs under fluctuating stress. When being subjected to cycling stressing, a component can fail at a stress level considerably lower than its tensile or yield strength for a static load. For example, for many steels fatigue limits range between 35% and 60% of the tensile strength. Fatigue occurring in regions of concentration of stress has been known to cause major problems in the aircraft industry; it was brought to attention of aircraft engineers in 1954 when three de Havilland Comet passenger jets broke up in mid-air and crashed; the cause of the accidents was found to be the deterioration of aircraft coating by fatigue, with the cracks initiating in the sharp corner window of the ADF antenna. Since then, all windows have been designed round-cornered to reduce the effect of the concentration of stresses, which intensifies in regions of material's irregularities and discontinuities.

The term 'fatigue' implies that this type of failure occurs after a lengthy period of repeated stress. It is classified into two groups, low-cycle fatigue, when failure occurs at less than 10^4 to 10^5 cycles, and high-cycle, when fatigue life is greater [3].

A standard S-N curve (stress vs number of cycles), as exeplified in Fig. 7, is used to illustrate fatigue behaviour of a material. The higher the magnitude of stress, the lower number of cycles a component can sustain before failure. Some materials present a fatigue, or endurance limit, which means that fatigue failure will never occur if the stress is kept below this limit. The S-N curve of such materials becomes horizontal when the stress magnitude reaches their fatigue limit. The rest of the materials, for example most non-ferrous alloys, do not have a fatigue limit; in them failure will occur eventually regardless of the magnitude of stress applied.

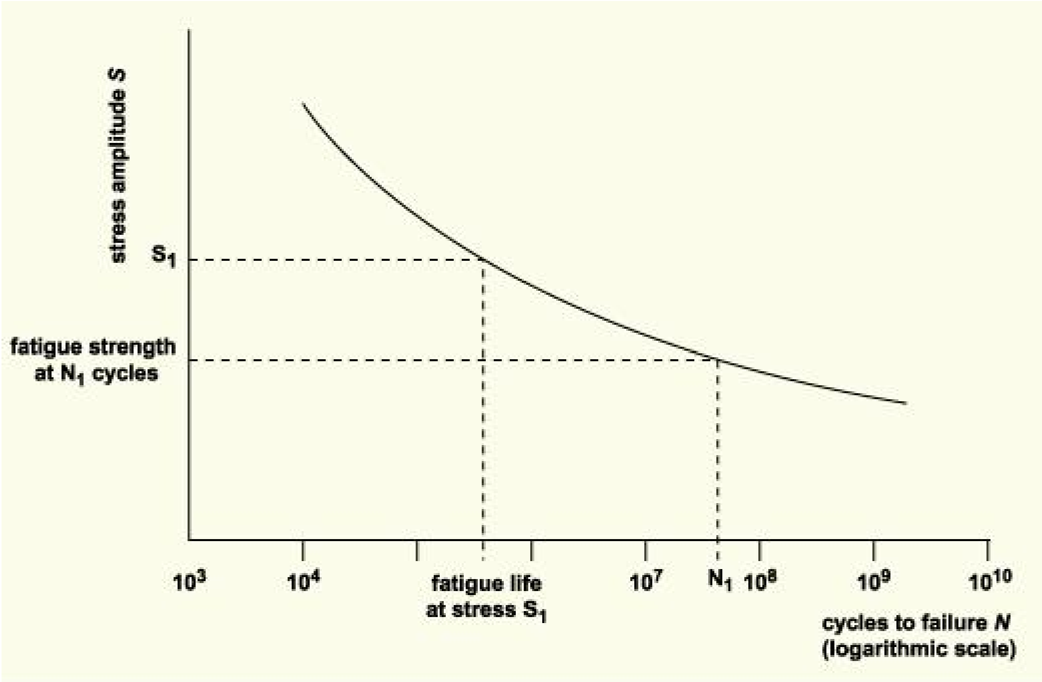

Fig. 7. S-N curve for a material that does not display a fatigue limit

3.2 Purposes and objectives of the experiments

The experimental part of this project was designed to reveal fatigue cracks on the surface of aerospace components that were undetectable by naked eye. The method chosen was LPI, because, as explained in section 2.1, it is one of the cheapest and easiest method of NDT that can be performed in a university laboratory, and that need the least specific equipment.

Aircraft parts inspected during the examinations have been lent to us by courtesy of FPAC (Fundació Parc Aeronàutic de Catalunya), and consisted of a wing tip, a sheet metal engine cover, a metal ring designed to attach this cover onto the aircraft structure, a mooring, and a small metal T-shaped bar. All these parts had been in use on flying aircraft, and all were expected to have fatigue cracks on their surface because of the cyclic stress all aircraft parts undergo. Some components had low-cycle stress (wingtip), whereas in other cases it was very high (engine vibrations for the mooring). Also, they were expected to have cracks in different locations depending on their usage, but, in general, always in the points of concentration of stress: holes, edges, any other discontinuities, connections with other parts (welding, screws).

Apart from that, two different types of aluminium alloy sheet were inspected: 7075-T6 and 2024-T3, the former being a high-strength alloy used to strengthen aircraft structure or as skin panels, and the latter, an extremely fatigue-resistant one used for aircraft skins, cowls, and aircraft structures. Aluminium metal sheet was brand new and was to be inspected before and after the application of stress-strain tests. No defects were expected to be found in the first round of experiments, although there existed a possibility of fabrication defects. New stress fatigue cracks were expected to be found afterwards.

3.3 Products and methods applied

Ely visible dye penetrants were used in all the experiments. The penetrant liquid used was Ely Checkmor 222 spray, which is a non-water washable colour contrast penetrant widely used in many industries for the detection of defects which are open to the surface of solid objects. Although red dye penetrants can be used effectively using either hydrophilic or lipophilic removers, the solvent ‘wipe-off’ technique is the most common and convenient. This is the technique that was applied during the experiments.

Checkmor 222 is a solution of dyestuffs in a blend of surfactants and high boiling point distillates, and comes as a dark red mobile liquid which does not mix with water and is used in conjunction with developers and solvent cleaner / removers as part of the dye penetrant inspection technique. The developer used was Ely LP2 spray, and as a solvent, an Ely solvent cleaner (S32) especially designed for the LPI process. However, when I ran out of solvent, new solvent was bought, this time not specifically designed for penetrant testing inspections, and in form of liquid rather than spray. The application resulted tedious and ineffective, because, due to the parts’ complex shapes, it was easier to clean them by spraying than by cloth. Also, the new solvent cleaner proved to have a stronger, disturbing smell, indicating a higher concentration of solvent than in the original Ely spray.

3.4 Quality control

When carrying out the experiments, various factors had to be controlled in order to assure a correct testing and reliable results. There were three different products and quite a few steps in the procedure, thus making quality control a very important factor in the experiments.

Quality procedures:

- Part/Penetrant Temperature
- Penetrant
- Dwell
- Emulsifier
- Wash
- Drying
- Developer
- Lighting
- System Performance Check

3.4.1. Temperature

The temperature of the penetrant liquid and the part being inspected can have an effect on the results. As the temperature increases, surface tension of the liquid will decrease, thus facilitating the wetting of the surface and the capillary forces. Lowering the temperature will cause the opposite effects. Another factor on which temperature change can have effect is the concentration of the dye. At high temperatures, concentration will increase due to the more rapid evaporation. This is useful only if the concentration quenching point is not reached, and the liquid's flow characteristics are not changed. This happens when the temperature is too high and the speed of evaporation is elevated.

The optimum temperature to carry out the examination is reported to be in the range of 27 to 49^{o}C, but most penetrants allow testing in the range of 4 to 52^{o}C. In the case of the ELY Checkmor 222 dye penetrant, the optimal temperature for its application was not specified, and the experiments were carried out at the temperatures ranging between 18-25ºC.

3.4.2. Penetrant quality control

The quality of the penetrant liquid used is a key factor in the quality of the inspection. Ageing and contamination are two factors that cause deterioration of the penetrants, which results in loss of colour or fluorescence response. Adequate storing conditions can prolong the life of penetrants: most importantly, the liquids should be protected from exposure to extreme temperatures. Freezing can cause separation, and high temperatures dull the colour of the dye.

Contamination of the penetrant liquid can occur during storage and use. Spray penetrants, such as the one used during the experiments, are of course less susceptible to contamination than open tank systems. During use, the penetrant can be contaminated with water or other agents present on the part being inspected. Water is the most common contaminant. Water-washable penetrants have a definite tolerance limit for water, and above this limit they do not function properly. Cloudiness and viscosity both increase with increasing water content. In self-emulsifiable penetrants, water contamination can produce a gel break or emulsion inversion when the water concentration becomes high enough. Water does not readily mix with the oily solution of lipophilic post-emulsifiable systems.

Most other common contaminates, such as cleaning solvents, oils, acids, caustics and chromates must be present in significant quantities to affect the performance of the penetrant. Organic contaminants can dilute the dye and absorb the ultraviolet radiation before it reaches the dye, and also change the viscosity. Acids, caustics, and chromates cause the loss of fluorescence in water-soluble penetrants.

When open systems are used for penetrant storage and application, regular checks must be performed to ensure that the material performance has not degraded, comparing the colour, smell and consistency of the penetrant with a previously stores sample, that was taken at the moment that the container was first opened. This issue is not a problem with spray penetrants, since they cannot be contaminated during storage.

3.4.3. Application and cleaning of the penetrant

The application of the penetrant is the step of the process that requires the least amount of control. The method of application does not matter as long as the surface is clean and dry, and receives a generous coating of penetrant. The decision on which method to use is usually based on various economic or convenience factors (more dye penetrant is wasted when spraying than when using. In our case, penetrant was applied by spraying.

The wash temperature, pressure and time are three parameters that are typically controlled in penetrant inspection process when water-washable penetrants are used. In our case, however, the penetrant was cleaned off using a cotton cloth, and only visual checks were performed to determine whether the part has been adequately cleaned.

When a solvent removable penetrant is used, such as in our case, care must be taken to remove the penetrant from the part surface while removing as little as possible from the flaw. James Hill [13] offers a cleaning procedure to maximize the inspection sensitivity for a visible dye penetrant. The first step in this cleaning procedure is to dry wipe the surface of the part in one direction using a white lint free cotton rag. Next, the surface should be wiped with one pass in one direction with a cleaner-moistened rag. Only one dry pass followed by one damp pass is all that is recommended, since it has been noticed that sensitivity is reduced with every additional wipe. During the experiments, these indications were followed whenever possible; however, due to the complex shapes of the parts inspected, the absorption quality of the cloth or a large quantity of excess penetrant, sometimes it was necessary to wipe the same area more than once, and in different directions. In fact, these instructions seem fit only for inspecting small concrete areas where cracks are expected, or where they have been found during previous examinations, and not for the overall inspection of an object with complex geometry.

3.4.4. Quality control of drying process

In our case, the parts inspected were dried at room temperature before the application of the dry powder developer. Generally, drying temperatures should not exceed 71ºC in order to avoid deterioration of the dye. Dye colours can fade at high temperatures, or dye can get dry inside the flaw, and will thus be unable to flow back onto the surface to indicate the crack.

3.4.5. Quality control of developer

The function of the developer is crucial in the LPI process. The developer has to pull the penetrant from the flaw and spread it over the surface of the part to a width that is detectable by the eye. A thin layer of developer can spread more of the available penetrant horizontally since there is less distance for vertical spread. A thin layer of developer would produce an indication faster and improve sensitivity within limits. A reduction in the developer layer thickness will actually reduce sensitivity because it will not absorb enough penetrant. In addition, if the developer layer is not thick enough, it will not provide good contrast, which is another important function of the developer.

Ideally, dry powder developer should be checked daily to ensure the powder is fluffy and not moist or stuck together. In our case, spray cans of developer were used, and it was assumed that as long as the can was used before its expiration date, and was shaken thoroughly before application, the quality of the powder will be acceptable.

Concerning development time, parts should be allowed to develop for a minimum of 10 minutes and no more than 2 hours. According to the statistics brought up in a FAA study, the effective contact time to produce optimal indication are similar for most developers. It takes 1 to 10 minutes to reveal large fatigue cracks, and 1 to 3 minutes to reveal porosity and small corrosion cracks. In our case, the parts inspected were usually left for 15-20 minutes after the application of the developer, being 10 minutes the minimum specified by the developer manufacturer.

3.4.6. Lighting

It is extremely important to choose an adequate lighting when visually inspecting a surface for penetrant indication. Inspections can be conducted using natural or artificial lighting. During my experiments, artificial lighting was used, given that they were conducted in an underground lab. The light intensity is required to be 100 foot-candles at the surface being inspected, and white flood or halogen lamps are usually used. In our university lab the lighting is provided by means of white halogen lamps.

During my experiments, light intensity measurements were not taken, given that most LPI do not require an exhaustive supervision of light intensity.

3.5 Experimental procedure

The experimental procedure was the same for all inspected components, as were the products used. Fig.8 below portrays the ELY dye penetrant products that were applied:

Fig. 8. ELY LPI products

Throughout the experiments, protective gear had to be worn in order to protect oneself from the hazards of the chemical products. This gear included safety goggles, a respiratory filter, gloves and a lab coat. Fig. 9 illustrates the first three articles of this safety kit.

Fig. 9. Personal protective equipment

The procedures of the experiments were as follows:

1. Cleaning the part with the S72 Ely solvent. The solvent can be sprayed onto the part directly, or applied with a cotton cloth. The cloth to be used should be a highly absorbent cotton cloth, preferably white, so that no textile dye is left after the application of the solvent. The part is then left to dry for several minutes.

   Later on in the experiments, when the ELY solvent cleaner spray had finished, another solvent cleaner (portrayed in Fig.10) was bought. It proved to work just as well for cleaning the parts, but turned out to have a more pungent, dizzying smell than the ELY cleaner. It was probably a rather higher concentrated solvent; when it was used, a respiratory filter had to be worn, and special attention had to be paid to provide a correct ventilation of the lab.

Fig. 10. “Norai” solvent cleaner

2. Application of the Checkmor 222 penetrant by spraying, as portrayed in Fig. 11. The spray should be situated at a distance of about 15-20cm in order to allow for a uniform and spread out covering of the part’s surface.

Fig. 11. Applying dye penetrant to the mooring

The layer of dye should be just enough to colour the whole region red; too little dye would not allow for proper penetration, and too much would simply drip onto the floor, tinting it a reddish colour that is hard to remove. The dye is left to dwell for approximately 10 minutes, as indicated in the manufacturer’s instructions. The following Fig.12 illustrates dwelling for the motor hood.

Fig. 12. Motor hood dwelling

Although this is the most straightforward step, there are several quality control points that should be kept in mind. Firstly, the penetrant liquid should be in good conditions. In my case, the penetrant came in form of spray and was only recently bought, thus assuring that it had not been contaminated in storage. Both the part and the penetrant should have an acceptable temperature; in my case, both were kept at room temperature. The optimum temperature to carry out the examination is reported to be in the range of 27 to 49^{o}C, but most penetrants allow testing in the range of 4 to 52^{o}C. In the case of the ELY Checkmor 222 dye penetrant, the optimal temperature for its application was not specified, and the experiments were carried out at the temperatures ranging between 18-25ºC.

The control of dwell time is also important; in my case, the parts were left for approximately 20 minutes, which is the time proposed by the manufacturer.

3. Removal of excess penetrant with a cotton cloth. The first wipe should be done with a dry cloth, and successive wipes with a cloth slightly moistened with the solvent. No red colour should be left on the surface, but no excessive attempts should be made to remove all the dye from possible flaw sites.

   This step is very important; if done incorrectly, too much dye would be retrieved from the cracks, and no indication of them would appear during developing. On the other hand, if too much dye is left, too much red colour would appear after the application of a developer, thus making it hard to distinguish between real cracks and regions that had been poorly washed.

4. Application of the non-aqueous solvent developer LD3 by spraying. A thin film of white powder should be left on the surface, which should be

then left for 10 - 15 minutes.

This step is fairly straightforward; quality control of the developer must be made, in this case it was a recently bought closed spray can, that presented no reasons for concern about its quality of possible contamination while in storage.

5. Examination of the part. In some regions, the white powder (developer) would have turned red. Depending on the nature and shape of the flaw, the red bleedout will have different characteristics.

   This is the most important part of the whole experiment. At this point, the most important factor is correct lighting in the room where the examination is taking place. In my case, it was carried in a well lit university laboratory with white light lamps, which is considered to be appropriate for such inspections.

6. Cleaning off the developer and the bleedout penetrant, first by cloth, then by spraying the solvent directly onto the surface to eliminate the penetrant from part with complex shapes, such as small holes or cylinders.

   This is the least critical part of the test, since no results depend on its quality. However, it is important to fully clean the part, especially in case that it needs to be examined again at some point. Fig. 13 pictures a part of the motor hood that was hard to clean off, because of the overlapping of two metal sheets that were also screwed together. In this region, dye kept seeping out repeatedly, even after the surface had been sprayed with the solvent cleaner several times.

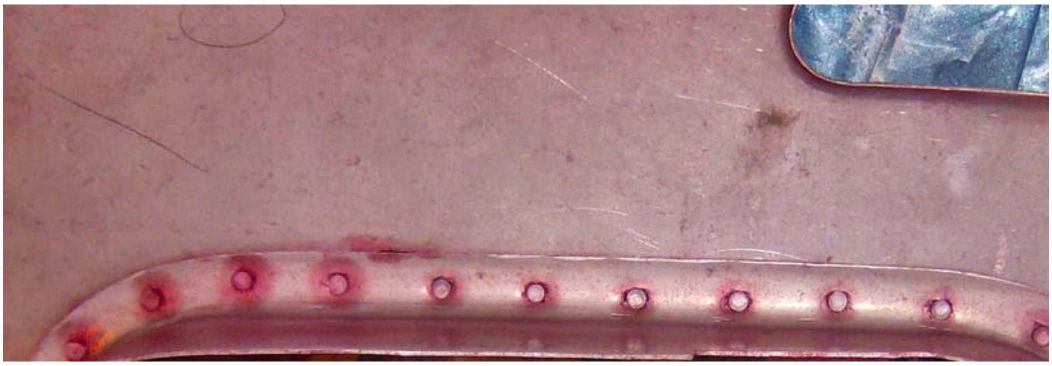

Fig. 13. A problematic part of the motor hood

The following Table 5 summarises all the factors that can affect the quality of inspection, resulting in fewer defects being found (or, on the contrary, contaminating the surface with false indicators).

Materials	Penetrants	Surface Wetting Viscosity Specific gravity Color and fluorescence brightness Dimensional threshold of fluorescence Ultraviolet stability Thermal stability
	Emulsifiers	Removability Emulsifier contact time and wash time
	Developers	Permeability, porosity, and dispersivity Surface energy Liquid carrier Whiteness
Inspection Method/Technique	Preparation of the part	Part cleanliness Metal smear from machining or cleaning Use of etchant Plugging of defects with cleaning media Chemical cleaning process Dryness of part and defects Previous penetrant inspection
	Selection of penetrant method/technique	Penetrant type Sensitivity level Application method Dwell time
	Penetrant removal procedure	Emulsifier concentration Emulsifier contact time Rinse method and time
	Developer	Use of a developer Type of developer used Application method
Process/Quality Control	Control of materials	Freshness of materials/tank life Penetrant contamination Emulsifier bath concentration Emulsifier contamination Developer contamination Storage temperature
	Control of the procedure	Temperature of the materials Wash temperature and pressure Drying temperature Thickness of developer layer Inspection lighting
Inspection Variables	Human factors of inspectors	Visual acuity Color vision Eyewear Training and knowledge of defects Inspectors attitude and motivation Inspection environment
	Nature of part and defect	Surface condition of part Complexity of part Defect type Defect dimensions Loading condition of part (closure)

Table 5. Factors that can affect quality of the inspection

Regarding the effects on various aspects mentioned in this table on my experiments, it can be said that some had much more noticeable effects, whereas others did not. Some factors could be controlled, and some not. In the “Materials” group, none of the aspects could be controlled or even compared to ideal results, because there was only one set of the LPI products, and no previous knowledge of such testing.

In the “Inspection method/technique” group, there was no possibility of choosing and/or comparing various techniques, because there was only a limited set of products. However, an extensive quality control was kept of the testing procedures; the parts were thoroughly cleaned, and were always left to dwell for the amount of time advised by the manufacturer. Previous penetrant inspections did prove to be bothersome, because in some cases it was hard to completely clean off the dye, because some areas were not easily accessible.

Concerning Process and Quality Control, no problems were encountered; this aspect is extensively covered in the preceding paragraphs.

The trickiest aspects proved to be those classified as “Inspection variables”, namely the human factors and nature of part and defects. Training and knowledge of defects proved to be lacking; several experiments had to be carried out before the technique was mastered to a reasonable extent. Even so, it has been made clear that specific training is needed in order to carry out reliable examinations.

As for the parts, most proved to have complex shapes, thus complicating their examination. Defect type and dimensions were most likely an issue too; small defects could easily have been missed.

3.6 Description of the parts inspected and results of each test

3.6.1. Aircraft parts.

3.6.1.1. *Wing tip*

Wing tips (as the one portrayed in Fig.14, which is the specimen used in the experiments), are located on the outermost part of the aircraft wings. Their configuration depends on the design specifications and that is why they come in different shapes and sizes. Their frequent design criterion is to minimize the wing tip vortices. The fatigue forces wing tips are subjected to are low cycle fatigue, caused by the wing loading during flight.

Fig. 14. Wing tip.

In this case, the supplier did not specify the material of this part, but according to the metal's brightness and density, it has been deduced that it was most certainly Aluminium.

Imperfections were detected around and on the edges of the holes where the bolts would be screwed, as can be seen in Fig.15, as well as one small defect on the surface. The crack on the surface of the wing tip might indicate a single accident, most likely a collision with another object, either in flight, taxiing or parked, or later handling of the part, e.g. by an operator during maintenance.

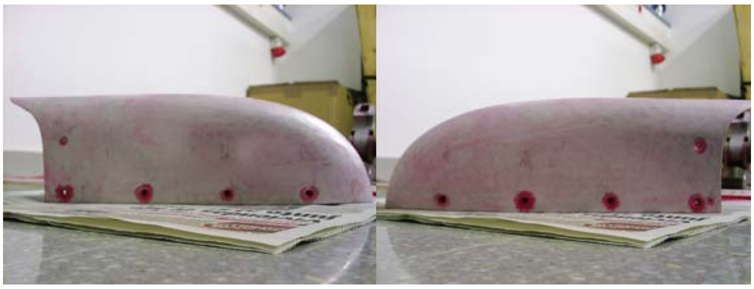

Fig. 15. Wing tip after applying the developer.

Imperfections in the bolt holes were expected as they are points of stress concentration, as theory predicts for circular holes in laminas [11]. Also, load transfer through the bolts takes place in these regions. Such areas are more prone to the appearance of defects. They have to withstand cyclic loading caused by their contact with the bolts, when the aircraft was in functioning, both due to the vibration of aircraft parts because of the vibration of the engine, or due to the low frequency deformation cycles associated with the loading of the wings during flight.

3.6.1.2. *Motor hood*

The motor hood, portrayed in the Fig.16 below, is designed to cover the engine in a small aircraft. In this case, the supplier did not specify the material of this part, but according to the metal's brightness and density, it has been deduced that it was most certainly Aluminium.

The motor hood presented areas of a geometry similar to that of the wing tip (circular holes in metal sheet). In such regions imperfections were expected to be found, as predicted by theory and the experience with the wing tip testing. The tests certified this hypothesis, as illustrated by Fig.16. Bolt holes and their surrounding areas presented a significant number of imperfections in form of small cracks. The surface of this part was also full of stains after the developer was applied, thus revealing that porosity is present on most of the surface, that was most likely caused by corrosion. It is also possible that these stains were the result of an incorrectly conducted inspection.

Fig.16. Motor hood after the application of developer.

There were still parts welded or screwed together, which meant that the penetrant liquid could not be properly cleaned off, and kept seeping back through during the revelation process. This part was the most difficult one to examine due to its complex geometry.

3.6.1.3. *Motor hood anchor ring*

The main function of the motor hood engine ring is to anchor the motor hood to the aircraft structure. It is a metal ring with 20 square-shaped metal bulges where bolt – holes are allocated; this part can be seen below in Figs.17 and 18. This exact material composition of this part is also unknown, but its higher density, compared to that of the other components, indicates that it is made most probably of steel.

Fig.17. Motor hood anchor ring

This part presented defects very similar to those found in the wingtip and the motor hood. Small cracks were found on the edges of the holes due to the concentration of stresses, as can be seen in Fig.18. Since this part is attached to the aircraft structure in the proximity of the engine, these imperfections were most likely produced by fatigue generated by cyclic stresses produced by the vibration of the engine, which would have caused the bolts to exert cyclic loads onto the edges ring. Because the vibration of the engine was taking place at a rather high frequency, it most probably produced high frequency cyclic loads, thus allowing us to speak of high cycle fatigue in this case.

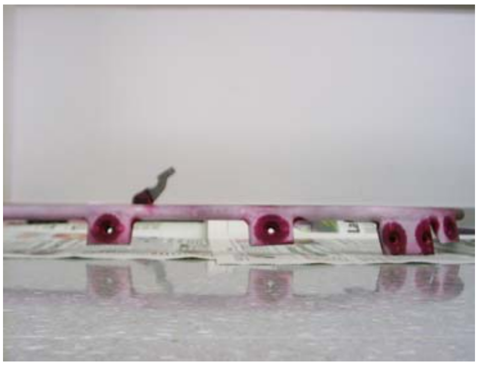

Fig.18. The ring during inspections.

3.6.1.4. *Mooring*

The mooring (pictured below in Fig.19 and in Fig.20) is a steel part used for anchoring the General Electric J79 engine to aircraft structure in Phantom planes. It is constantly subjected to high-value and high-frequency, as well as low-frequency cyclic loads determined by the vibration of the engine, and was expected to have some fatigue defects.

Fig.19. Mooring

The part could not be completely disassembled for the experiments, thus complicating the access to some of its parts and rendering the examination less effective in the places where most flaws were expected. Defects were expected where two parts of this component are joined together through a bolt, making this area a stress concentration point, in the same way as there is a concentration of stress in oval holes in laminas.

Fig. 20. Inspecting the mooring

As has been mentioned, no defects were found, therefore proving this component more resistant to fatigue than expected. The first hypothesis is that steel alloys are known to exhibit an endurance, or fatigue, limit, below which repeated stress does not induce failure – theoretically, for an infinite number of cycles of load. Such parts, if cycled at stresses below their endurance limit, will fail from some other mode before failing from fatigue. [5]. The contrary happens with other non-ferrous alloys, which will fail from fatigue at very small stresses, as has possibly happened with other aircraft parts that were examined.

The second hypothesis is that dye penetrant testing was not suitable for the inspection of this part, or that it was not carried out correctly. In any case, ultrasound testing would seem like a suitable suggestion for a further evaluation of the mooring, as it would allow us to detect surface defects that are present in inaccessible regions (inside the juncture), as well as the subsurface flaws.

3.6.1.5. *Cessna plane metal bar*

This piece is a small, 15cm-long T-shaped metal bar belonging to a part of a structure of a Cessna airplane. As can be appreciated in Fig.21, a fatigue crack was found in this part. The location of this crack indicates that this bar undergoes tensile forces when in functioning, most possibly by being bolted onto the structure through the visible orifices, and being held in place by standing out metal plates.

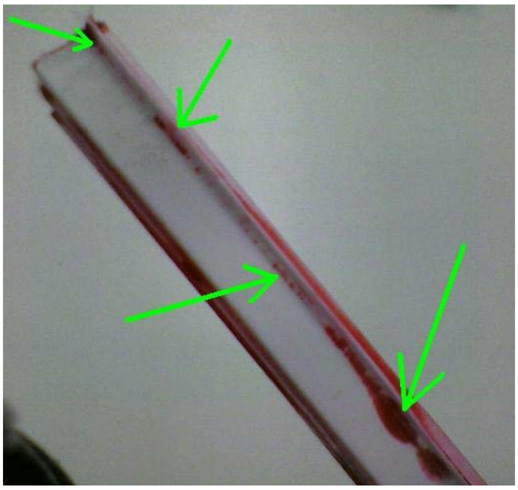

Fig.21. Cessna metal bar defects

This part presented considerable difficulties in its handling during the experiments because of its small size, and, as with most parts examined, this one had to be divided into two or more areas, and each of them had to be inspected separately, in order to allow for the part's handling and resting it on the table during dwell and developing time periods.

3.6.2. Aluminium alloy laminas

In this part of the experiment, 150 aluminium alloy laminas (portrayed in Fig.22.) were to be inspected before and after the application of dynamic cycling loading tests. The purpose of these tests was to produce fatigue and instigate crack initiation and growth. There were 100 AA 2024-T3 laminas measuring 10cm wide and 15cm long, and 50 AA 7075-T6 laminas, measuring 10cm wide and 15cm long. Both Aluminium alloys are used in the aeronautical industry as skin panels on the wings of aircraft.

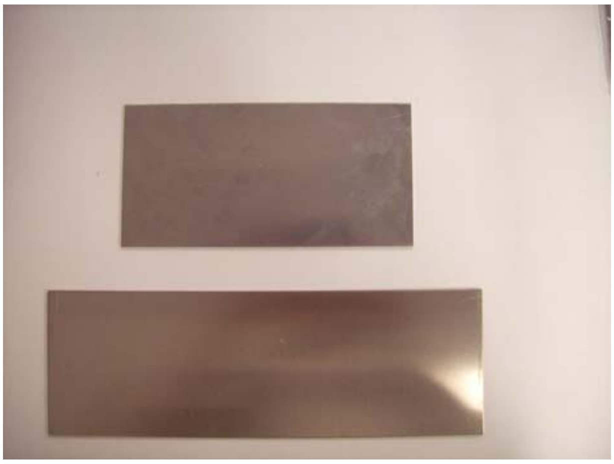

Fig. 22. AA2024-T3 and AA7075-T6 laminas

In the following Table 6 the composition of each of the two alloys is detailed:

AA2024		**AA7075**	
Element	**Composition (wt%)**	**Element**	**Composition (wt%)**
Copper	4.4	Zinc	5.6
Magnesium	1.5	Magnesium	2.5
Manganese	0.6	Copper	1.6
		Chromium	0.23

Table 6. Composition of the AA2024 and AA7075 Aluminium alloys [6]

Following the hyphen after this 4-digit code is the temper designation, that describes the mechanical and/or heat treatment to which the alloy has been subjected. In particular, T3 means that the alloy was solution heat treated, cold worked, and then naturally aged. T6 indicates that the alloy was solution heat treated and then artificially aged.

AA2024-T3 has lower UTS (Ultimate Tensile Strength) and yield strength than AA7075-T6, but has higher fracture toughness, thus demonstrating a better behaviour against crack growth. It is used on the on the lower surface of aircraft wings, because, the lower surface is more prone to fatigue failure as it withstands tensile stress during the operation of the aircraft (cruise).

AA7075-T6 has greater UTS and yield strength, but is more brittle (presents a ductility of 11%el in 50mm, compared to the other alloy’s 50%el), and is used on the upper surface, which is less prone to fatigue because it withstands compressive, rather than tensile stress.

No flaws were expected to be found in the first round of inspections, because the laminas were brand-new and right from the factory. The inspections were successfully carried out, examining the 150 laminas and finding no original defects in them. The purpose of the test was to verify the status of the laminas and to certify that they have been produced and delivered without defects. This testing could be qualified as “system performance check” as quality control requires.

The second round of tests was thought to be performed after the laminas had been dynamically tested with a cyclic load profile in the tensile stress region. After the dynamic tests, it was expected that inspections would reveal the presence of defects that did not exist previously (as verified by the first round of dye penetrant inspections). These defects would have grown due to a fatigue process in the specimens.

3.7 Evaluation of the experiments

3.7.1. Technical problems that arose during the experiments

Regarding dye penetrant testing, it can be noted that this method presented more problems than expected at the begging of the experiments.

Firstly, most inspected objects had parts with complex geometry (motor hood and the welded cylinder) and small holes through which they had been attached onto the airframe structure. In such areas penetrant liquid could be applied, but not cleaned off with the cloth, due to the small size of the area. It had to be cleaned off by spraying the solvent onto the surface of the part, thus removing it completely and not allowing for a reliable examination of the area in question.

- The dye was hard to clean off due to the shape and small size of the objects inspected.

  Proposed solution: use water-washable penetrants, then a part could be simply rinsed with water without having to access its entire region with a cloth.

- The dye was hard to clean off because the cotton cloths used were not absorbent enough.

  Proposed solution: use water-washable penetrants, the the part could be simply left to dry off at room temperature after rinsing.

- The dye was hard to clean from the cracks, and kept seeping out repeatedly after numerous cleaning with the solvent

  Proposed solution: disassemble the parts, release the bolts and the screws.

Another problem that arose during the LPI is that the defects found were fewer than expected. In some cases, this is coherent with the theoretical prediction of the results, because some of the tested components or their parts do not suffer from fatigue. In these cases no cracks were expected to be found. However, in other cases, for example, the mooring, cracks were expected due to the nature of the loads during the component's operational life, but were not found. There can be several reasons for this:

- Poor inspection technique, i.e. the cracks exist but have not been detected because the method used is inadequate or is performed incorrectly. This could be valid for very small cracks, or cracks situated in those critical places where access could not be gained.

  Proposed solution: use water-washable penetrants, so that the part could be rinsed with water rather than having to clean off the dye with a cloth.

- Inadequate technique, i.e. the cracks exist but cannot be detected by LPI. This could be valid for thee cracks located beneath the surface.

  Proposed solution: carry out other NDT experiments that would allow for the detection of subsurface defects, for example ultrasonic testing.

- Non-existence of defects despite the theoretical prediction of the contrary. This could happen because the component had not undergone enough stress as to suffer fatigue.

It can thus be concluded that the LPI method cannot be conclusive about the part's health status and functionality without combining LPI results with other NDT methods to detect smaller defects and sub surface irregularities. LPI seems to be more useful for the inspection of larger surfaces and less complex shapes. Also, water soluble penetrants might be more practical, and rend the experiments less expensive and tedious.

3.7.2. Evaluation of cost- and time- effectiveness of the experiments and the project

LPI is supposed to be a relatively fast, easy and cheap method of non-destructive testing. During my lab experiments, however, it turned out to be somewhat laborious and time-consuming, with the detailed time per activity detailed in the following Table 7:

Activity	Time
LPI inspection of 1 side of each part:	
• Cleaning	3-10 min
• Application of the penetrant	1-2 min
• Dwelling	20 min
• Cleaning	3-10min
• Application of the developer	1-2 min
• Leaving developer to react	20 min
• Inspection time	3-5min
• Cleaning	3-10min
Total time one side	54-79min
Total time one piece (two sides)	108-158min

Table 7. Time consumed by each activity

According to this table, it took from 108 to 158 minutes to completely examine each piece. This amount of time seems a little excessive, given the relatively small size of the parts, and the total number of such parts that an average aircraft might have.

A minimum of two experiments was carried out for each part, except for the laminas. This was due to the fact that the method was not fully mastered until quite a few experiments had been carried out – this is especially valid for the first parts examined, the wingtip and the mooring. The examination was repeated to assure the accuracy of the results, and sometimes to repeat the inspection in a neater manner in order to achieve better pictures for the documentation of the experiment. In some objects, separate areas were inspected more than twice, for the aforementioned reasons. Taking the reference examination time to be 2 hours per component, the total experiment time would be:

5 objects x 4 inspections each x 2 hours for inspection = 40 hours.

The laminas' inspections, being the last in order (i.e. counting on the most experience and skill), and the most straightforward in terms of object shape, were only carried out once for each piece; the laminas were inspected 20 at a time as illustrated in Fig.23, and the time consumed by these inspection was therefore 16 hours.


Fig.23. Examining the laminas.

Total time for all dye penetrant inspections carried out for this project is 56 hours. Comparing to the inspections done to the aircraft by professionals, which cost 65€ per hour of work, this would have summed a total of 2340€.

It is difficult to make reasonable comparisons of these experiment to the real-life non-destructive testing carried out on the aircraft. However, a rough estimation can be made in what refers to the laminas' examination. A total area of $5.0m^2$ was examined during the inspections. Wing surface of an A320 aircraft (which is where such laminas might be used) totals 122.6 m^2; by simple direct proportion rule (which, stricktly speaking, should not be applicable in this case, and is only used to create a general, if not very accurate, comparison), the time needed to inspect A320 wings would be 392 hours, and the inspection would cost 25480€.

This comparison is rather unaccurate, since in LPI time taken is not directly proportional to surface area. In fact, the greater the surface to examine, the more cost-effective the method. However, knowing that annual maintenance cost of a meduim-sized jet averages some 100000€ [2], and that the maintenance cost for A320 is probably higher, it is evident that, using our method (and our numeric approximation), it would cost ¼ of the annual budget to inspect one side of the wings, using only one NDT method, and only once a year. This conclusion is indicative of the poor time-effectiveness of the my experiments. They were carried out too slowly, demonstrating a lack of skill and possibly an incorrect application of the LPI method. The very fact that such inspection are indeed used on flying aircraft, and are considered cheap and fast, indicates again that during the experiments, this method was not fully mastered.

However, a lot of time would have been saved if water-soluble penetrants been used. It would have also been more cost-effective: water is cheaper than solvent cleaner, and a much lower number of washcloths would have been spent. It would also have been more environment-friendly and less damaging in terms of personal safety, given that the solvent cleaner was the most toxic of the products required for the inspections.

Materials that were used for the experimental part of the project are detailed in the following Table 8:

ITEM	PRICE
1 can of dye penetrant spray (ELY) 1 can of Developer spray (ELY) 1 can of solvent cleaner spray (ELY)	100€
1 can of a common solvent cleaner	3€
Cotton cloths (25 pieces)	15€ (0.6€ each)
Spray can for the second solvent cleaner	2€
Lab coat	free
Two pairs of rubber gloves Goggles Respiratory filter	30€
Digital camera	free
Total cost	**150€**

Table 8. Price of the products used in the experiments

The total cost of the laboratory equipment and products bought for the experiments rises to 150€.

Time consumed by various activities related to this project is summarized in the following table. To evaluate the monetary cost of this time, it can be assumed that dye penetrant inspections and related lab work go at a rate of 65€ per hours as it is for professional LPI personnel, and all the other activities can be rated at 6€ per hour – the amount a BEng student would get for an internship in an engineering company. The costs are summarized in Table 9.

ACTIVITY	RATE	TOTAL TIME	TOTAL COST
Dye penetrant experiments	65€/hour	56 hours	3640€
Other laboratory work	65€/hour	18 hours	1170€
Bibliography reading	6€/hour	100 hours	600€
Writing up	6€/hour	200 hours	1200€
Other chores	6€/hour	20 hours	120€
Total cost			**6730€**

Table 9. Theoretical costs of work hours per activity

CHAPTER 4. ENVIRONMENTAL AND HEALTH ISSUES ASSOCIATED WITH LPI

As with dye penetrants in particular, and with numerous other activities in general, the aerospace industry uses a large number of hazardous materials and generates a significant amount of hazardous wastes. Nowadays, a correct procedure of disposal of such dangerous wastes is a growing concern.

In the LPI sector, apart from the indications of each manufacturer on how their materials are to be handled and disposed of, there are numerous governmental and private centres and organization dedicated to industry control and waste management, that advise and control the handling and recycling of dye penetrants and the associated solvents and developers. Among the most common advices are the following:

- Replace cutting oils with water soluble coolants.
- Convert to water-based cutting fluids.
- Separate dye penetrants from water.
- Consider ultrafiltration for water/organic mixtures.
- Phase out flammable solvents and convert to water-based cleaners.

When it comes to the specific rules of disposal of a certain substance, it is the local legislation that regulates it. In Catalunya there are three separate regulations for hazardous waste handling: the Catalan regulation, the Spanish one and the European. The European Committee elaborates a list of all possible industrial and domestic residues, very similar to the one elaborated by local governments (Spanish and Catalan, in this case), and the correct way of their disposal and/or recycling. Each product can be fitted into one (or sometimes more) of the categories published by the European Council, and it is the local governments' duty to establish an adequate procedure for the identification and correct disposal of such products.

In this residue catalogue, each product if defined by a 6-digit code: the first two numbers (from 01 to 15) define the industry sector the waste comes from, the next two digits specify the activity, and the last two sort the products according to their chemical composition. For example, for the solvent cleaner the classification would be as follows:

Residue group 11: wastes from chemical surface treatment and coating of metals and other materials; non-ferrous hydrometallurgy
Sub-group 11 01: wastes from chemical surface treatment and coating of metals and other materials (for example galvanic processes, zinc coating processes, pickling processes, etching, phosphating, alkaline degreasing, anodising)
Residue type code 11 01 13: degreasing wastes containing dangerous substances

It is then the local government's responsibility to establish proper ways of recollection and treatment of each group of industrial residues. In Catalunya it is the Agència de Residus de Catalunya (ARC) that establishes such procedures [4].

First of all, the company producing hazardous waste must register with the ARC and indicate what type of residue it is. The registration bears a certain tax, which is similar in concept to the local community tax on waste recollection most of people are subjected to, and the company is then assigned an identification code. It is then the company's responsibility to separate the residues by their type, using the European residue catalogue as a guideline, and find one, or several transport companies that collect these types of waste, and that would take it to the waste management facilities. Some facilities also provide the transport service; both transport and residue treatment plants' details can be found using the ARC database. For each European residue code there is a 'treatment code' (a letter and a 2-digit number), and a list of facilities that provide the necessary treatment, for example:

Residue type code 11 01 13: degreasing wastes containing dangerous substances
V43 (treatment code) Regeneration of acids or bases -> (waste management facility) "Ecológica Ibérica Y Mediterranea, S.A." Barcelona, (Barcelonès)
T31 Physico-chemical and biological treatment -> "Ecocat, S.L." Martorell (Baix Llobregat); "Ecológica Ibérica Y Mediterranea, S.A." Barcelona (Barcelonès) "Tratamientos Y Recuperaciones Industriales, S.A." (TRISA) Constantí (Tarragonès). A complete list of the products' codes and proposed treatment is presented in ANNEX B.

Of the products used, solvent cleaner is the one that presents most risks for the personnel using it as well as for the environment. Risk phrases associated with it are: R11, R38, R50/53, R65 and R67. And safety phrases relative to them are: S09, S16, S23, S33, S43, S57, S60 and S62. A complete list of risk and safety phrases used for chemicals classification is attached in ANNEX E.

CHAPTER 5. CONCLUSIONS

This project was designed to discover and evaluate defects that has been produced on the surface of metallic aerospace components due to fatigue. Five used aircraft parts were inspected: a mooring, a hood of an engine, a ring that connects this hood with the aircraft structure, a wing tip, a metal bar from a Cessna plane, and 150 brand new aluminium alloy laminas that would be used as skin on modern aircraft.

Quite a few defects were found on all the pieces, except for the mooring and the laminas. In the case of the mooring, ultrasound tests could be carried out to look for subsurface cracks. In the case of the laminas, such results were expected; the laminas, coming straight from the factory, were not to have any defects caused by fatigue (they underwent no fatigue).

The defects that were found presented themselves mostly as small cracks on the edges of the holes in sheet metal, thus demonstrating once again the results of the stress concentration. Such places, as edges in general and other surface discontinuities, are known to be the least resistant to stress and fatigue.

Other defects that were found include surface scratches and roughness, caused most probably by collisions with other objects and ageing, porosity, caused most probably by corrosion, and a crack in the metal bar, caused by tensile stress fatigue.

All the defects were revealed by red spots on the surface of the object when the developer was applied. In most cases, the components had complex shapes and/or small sizes, thus complicating their inspection and requiring several test attempts in order to finally achieve a satisfactory evaluation of its surface.

On the whole, the results have been satisfactory: a new method of non-destructive testing has been mastered, and has allowed to reveal a number of surface cracks in the aerospace components that were not visible to the naked eye.

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Webpages

NDT Resource Center
www.ndt-ed.org

NASA Engineering Resources. Penetrant Testing of Aerospace Materials.
www.nasa.gov

ANNEX A. Different Ways of Classification Of LPI Techniques

A.1. Sensitivity

Dye penetrants are classified into 5 groups depending on their sensitivity, as illustrated in the following Table 4:

Sensitivity Level	Description
1/2	Low sensitivity penetrant. Exhibits excellent washability. (for castings and rough surfaces)
1	Low sensitivity penetrant. Higher brightness than 1/2 sensitivity
2	Normal sensitivity penetrant. For general purpose applications
3	High sensitivity penetrant. Provides an excellent combination of sensitivity/washability
4	Ultra-high sensitivity penetrant. For extremely critical applications

Table A. Classification of dye penetrants by Sensitivity level.

If sensitivity is the factor to consider, fluorescent penetrants are generally more capable of producing a detectable indication from a small defect. Also, the human eye is more sensitive to a light indication on a dark background and the eye is naturally drawn to a fluorescent indication. Visible dye penetrants, on the other hand, do not require a darkened area for the use of an ultraviolet light, and are thus more easy to use in the field.

A.2. Removability

Another selection criterion is removability, i.e. whether water washable, post-emulsifiable or solvent removable penetrants should be used.

Liquid penetrant systems are classified into four methods based on the penetrant removal process:

- Method A: Water-Washable
- Method B: Post-Emulsifiable, Lipophilic
- Method C: Solvent Removable
- Method D: Post-Emulsifiable, Hydrophilic

Water washable penetrants are removed by manual or automated water spray, manual wipe or air agitated immersion wash. Although water washable processing has its advantages, certain specifications will restrict its use because over-washing can occur in shallow discontinuities, which makes rinsing time critical to the process.

Such penetrants work best on rough surface parts, threaded or grooved parts and those with holes and orifices, which may be difficult to remove with the post emulsification method. It is especially suitable for automation, larger parts, leak testing, and use on parts which are incompatible with oil based systems.

Advantages to Water Washable Penetrant

- Lower cost (no emulsifier needed)
- Fewer processing steps
- Process time reduced
- Variables associated with PE dwell time eliminated

Disadvantages to Water Washable Penetrant

- Over washing can occur in shallow defects
- Water rinsing time is critical
- Water contamination is susceptible.

Post-emulsifiable penetrants require a separate emulsifier to break the penetrant down and make it water washable. Such penetrants are designed to reduce the possibility of over-washing, which is one of the factors known to reduce sensitivity. The parts to inspect should normally be smooth surfaced and perform critical functions which require higher sensitivity to smaller defects. However, these systems add another step, and thus cost, to the inspection process. As indicated by the classification table, there are two types of post-emulsifiable systems:

Lipophilic emulsifiers (Method B), introduced in the late 1950's, work with both a chemical and mechanical action. After the emulsifier has coated the surface of the object, mechanical action starts to remove some of the excess penetrant as the mixture drains from the part. During the emulsification time, the emulsifier diffuses into the remaining penetrant and the resulting mixture is easily removed with a water spray.

Hydrophilic emulsifiers (Method D) also remove the excess penetrant with mechanical and chemical action but the action is different because no diffusion takes place. Hydrophilic emulsifiers are basically detergents that contain solvents and surfactants. The hydrophilic emulsifier breaks-up the penetrant into small quantities and prevents these pieces from recombining or reattaching to the surface of the part. The mechanical action of the rinse water removes the displaced penetrant from the part and causes fresh remover to contact and lift newly exposed penetrant from the surface.

The hydrophilic method is more sensitive than the lipophilic method and has made the latter method virtually obsolete. The major advantage of hydrophilic emulsifiers is that they are less sensitive to variation in the contact and removal time. While emulsification time should be controlled as closely as possible, a variation of one minute or more in the contact time will have little effect on flaw detectability when a hydrophilic emulsifier is used. However, a variation of as little as 15 to 30 seconds can have a significant effect when a lipophilic system is used.

Advantages of the Post- Emulsifiable Penetrant Process

- Higher sensitivity to smaller defects
- Shows wide, shallow defects
- More controlled removal of surface penetrants

Disadvantages of the Post- Emulsifiable Penetrant Process

- Extra processing step
- Emulsification time control is critical
- Penetrant removal is difficult in threaded parts, holes and slots
- Not good on rough surfaces

Solvent removable penetrants are used primarily for inspecting small localized areas. This method requires hand wiping the surface with a cloth moistened with the solvent remover, and is, therefore, too laborious for most production situations. Of the three production penetrant inspection methods, method A, Water-Washable, is the most economical to apply. The excess penetrant may be removed from the object surface with a simple water rinse. These materials have the property of forming relatively viscous gels upon contact with water, which results in the formation of gel-like plugs in surface openings. While they are completely soluble in water, given enough contact time, the plugs offer a brief period of protection against rapid wash removal. Thus, water-washable penetrant systems provide ease of use and a high level of sensitivity.

A.3. Nature of defect

The nature of the defect can have a large affect on sensitivity of a liquid penetrant inspection. Sensitivity is defined as the smallest defect that can be detected with a high degree of reliability. Typically, the crack length at the sample surface is used to define the size of the defect. A survey of any probability-of-detection curve for penetrant inspection will quickly lead one to the conclusion that crack length has a definite affect on sensitivity. However, the crack length alone does not determine whether a flaw will be seen or go undetected. The volume of the defect is likely to be the more important feature. The flaw must be of sufficient volume so that enough penetrant will bleed back out to a size that is detectable by the eye or that will satisfy the dimensional thresholds of fluorescence.

ANNEX B. Recycling Information On The Products Used In The Experiments.

The correct disposal of toxic and non-toxic chemical products and other waste associated with chemical and industrial processes is regulated by the Agència Catalana de Residus (ACR) and the European Waste Catalogue. Table B below presents a classification of all the products used in the experiments according to the European scheme of waste classification. It also describes the group that has been thought the most adequate for each residue, and its treatment as suggested by the ACR.

European residue code	**Description**	**Proposed treatment**
	Dye penetrant	
14 06 03	Waste organic solvents, refrigerants and propellants	T21, V21
07 01 04	Wastes from organic chemical processes; other organic solvents, washing liquids and mother liquors	T21, T24, V21, V61
04 02 16	Dyestuffs and pigments containing dangerous substances	T13, T21, T24, T33, V21
04 02 17	Other dyestuffs and pigments	T12, T24, T31, T33
	Developer	
06 08 99	Wastes from inorganic chemical processes; wastes from the MFSU of silicon and silicon derivatives	no special treatment
	Solvent cleaner	
14 06 03	Waste organic solvents, refrigerants and foam/aerosol propellant	V21, T21
08 01 17	Wastes from paint or varnish removal containing organic solvents or other dangerous substances	T21, T22, V21, V61,
11 01 13	degreasing wastes containing dangerous substances	T31, V43
07 01 04	wastes from organic chemical processes; other organic solvents, washing liquids and mother liquors	T21, T24, V21, V61

Packaging and wiping cloths		
15 01 01	Paper and cardboard packaging	T12
15 01 02	Plastic packaging	T12
15 01 10	packaging containing residues of or contaminated by dangerous substances	V51, T21, T36, T13
15 01 11	metallic packaging containing a dangerous solid porous matrix (for example asbestos), including empty pressure containers	T32
15 02 02	absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by dangerous substances	V13, V41, T24, T21, T22, T13, T31, T36
15 02 03	absorbents, filter materials, wiping cloths and protective clothing other than those mentioned in 15 02 02	V13, T24, T21, T12

Table B. Classification of wastes generated by LPI experiments

Below is an explanatory list with the treatments mentioned in Table 6:

T12 Deposition of non-special residues.
T13 Deposition of special residues.
T21 Incineration of non-halogenated residues.
T22 Incineration of halogentaed residues.
T24 Treatment by evaporation.
T31 Physico-chemical and biological treatment.
T32 Specific treatment
T36 not specified
V13 Recycling of textile products
V21 Regeneration of solvents
V41 Recycling and retrieval of metals or metal composts
V51 Retrieval, reutilization and regeneration of packages
V61 Use as a fuel

ANNEX C. Characteristics Of The LPI Products Used In The Experiments.

C.1. Dye penetrant

Description of the product:

An aerosol containing a solution of red dyes in a blend of hydrocarbons, surfactants, and couplants with liquified petroleum gas propellant.

Disposal considerations:

Likely Residues or Waste Products: Used product with dissolved contaminants. Dilute emulsified washings.
Safe Handling: Pressurised containers must be punctured in suitable retaining equipment, liquids may then be disposed of by incineration in approved licensed facility. Disposal must be in accordance with local and national legislation.

Ecological Information:

Environmental Mobility: Product will emulsify with water.
Environmental Degradability: Based upon suppliers data for the constituent substances the product is expected to be "readily" biodegradable according to OECD guidelines. It is expected to be removed in a waste water treatment facility.
Ecotoxicity: One of the consitituents has a harmful effect on aquatic organisms. Product must not be released directly to the environment.

Stability and Reactivity:

Stability: Product is stable.
Conditions to Avoid: Exposure to excessive temperatures.
Materials to Avoid: Strong Oxidising Agents, such as chromates and nitric acid. May stain, dissolve or swell rubbers and organic coatings.
Hazardous Decomposition Products: At fire temperatures may give off toxic fumes.

C.2. Developer

Product Description:

PD3 is a mixture of inert white powders which contains talc and amorphous silica.

Disposal Considerations:

Disposal must be in accordance with local and national legislation, this will normally be through an authorised contractor to a licensed site.
Unused Product: Dispose of in accordance with local and natonal regulations.
Used Product: Dispose of in accordance with local and national regulations.
Packaging: Dispose of in accordance with local and national regulations.

Ecological Information:

Environmental Assessment: Inert. No ecotoxicological effects of the powder mixture, nor of its components, have been reported.
Mobility: Free flowing powder.
Persistence and Degradability: Persistent but inert.

Stability And Reactivity

Stability: This product is stable.
Hazardous polymerisation: Will not occur.
Conditions to Avoid: Exposure to moisture/high humidity.
Materials to Avoid: None known.
Hazardous Decomposition Products: None known.

Regulatory Information

Hazard Label Data
Not classified as hazardous (for supply in the U.K.)
Label symbol: None

Risk phrases:

None

Safety phrases:

S22, S24/25 (see ANNEX C)

C.3. Solvent Remover

Physical And Chemical Properties
(Product before filling into aerosols)
Appearance: Clear, volatile, mobile liquid.
Odour: Faint hydrocarbon odour.

Disposal Considerations
Unused Product: In accordance with local requirements.
Used Product: In accordance with local requirements.
Packaging: Empty containers should be taken for recycling, recovery or disposal through a licensed contractor, in accordance with local regulations.

Ecological Information:

Environmental Assessment: This substance is highly volatile and will rapidly evaporate to the air.
Mobility: Clear, volatile mobile liquid.
Behaviour in water: Immiscible, floats. The small quantity dissolved is expected to be removed in a waste water treatment plant.
Persistence / Degradability: Material can degrade rapidly in air, immiscible with water. However, the closed system test method specified for the European Classification results in a classification "Very toxic to aquatic organisms, may cause long term adverse effects in the aquatic environment".

Product is classified Harmful, Highly Flammable, Dangerous for the Environment.

Label symbols
Xn, Flame, N

<u>Risk Phrases</u>
R11, R38, R50/53, R65, R67 (see ANNEX C)

<u>Safety Phrases:</u>
S09, S16, S23, S33, S43A, S57, S60, S62 (see ANNEX C)

ANNEX D. European Catalogue of Hazardous Waste.

Below is the European catalogue of hazardous waste: all substance that presents one or more of these characteristics is considered harmful for the environment [12]:

- Flash point ≤ 55 ºc
- One or more substances classified (2) as very toxic at a total concentration ≥ 0,1%
- One or more substances classified as toxic at a total concentration ≥3 %
- One or more substances classified as harmful at a total concentration ≥ 25 %,
- One or more corrosive substances classified as R35 at a total concentration ≥ 1 %
- One or more corrosive substances classified as R34 at a total concentration ≥ 5 %
- One or more irritant substances classified as R41 at a total concentration ≥ 10 %
- One or more irritant substances classified as R36, R37, R38 at a total concentration ≥ 20 %,
- One substance known to be carcinogenic of category 1 or 2 at a concentration ≥ 0,1 %,
- One substance known to be carcinogenic of category 3 at a concentration ≥ 1 %
- One substance toxic for reproduction of category 1 or 2 classified as R60, R61 at a concentration ≥ 0,5 %,
- One substance toxic for reproduction of category 3 classified as R62, R63 at a concentration ≥ 5 %,
- One mutagenic substance of category 1 or 2 classified as R46 at a concentration ≥ 0,1 %,
- One mutagenic substance of category 3 classified as R40 at a concentration ≥ 1 %.

ANNEX E. Complete List of Risk and Safety Phrases for Chemicals.

R1 Explosive when dry.
R2 Risk of explosion by shock, friction, fire or other source of ignition.
R3 Extreme risk of explosion by shock, friction, fire or other sources of ignition.
R4 Forms very sensitive explosive metallic compounds.
R5 Heating may cause an explosion.
R6 Explosive with or without contact with air.
R7 May cause fire.
R8 Contact with combustible material may cause fire.
R9 Explosive when mixed with combustible material.
R10 Flammable.
R11 Highly flammable.
R12 Extremely flammable.
R13 Extremely flammable liquefied gas
R14 Reacts violently with water.
R15 Contact with water liberates extremely flammable gases.
R16 Explosive when mixed with oxidizing substances.
R17 Spontaneously flammable in air.
R18 In use, may form inflammable/explosive vapour-air mixture.
R19 May form explosive peroxides.
R20 Harmful by inhalation.
R21 Harmful in contact with skin.
R22 Harmful if swallowed.
R23 Toxic by inhalation.
R24 Toxic in contact with skin.
R25 Toxic if swallowed.
R26 Very toxic by inhalation.
R27 Very toxic in contact with skin.
R28 Very toxic if swallowed.
R29 Contact with water liberates toxic gas.
R30 Can become highly flammable in use.
R31 Contact with acids liberates toxic gas.
R32 Contact with acid liberates very toxic gas.
R33 Danger of cumulative effects.
R34 Causes burns.
R35 Causes severe burns.
R36 Irritating to eyes.
R37 Irritating to respiratory system.
R38 Irritating to skin.
R39 Danger of very serious irreversible effects.
R40 Limited evidence of a carcinogenic effect.
R41 Risk of serious damage to the eyes.
R42 May cause sensitization by inhalation.

R43 May cause sensitization by skin contact.
R44 Risk of explosion if heated under confinement.
R45 May cause cancer.
R46 May cause heritable genetic damage.
R47 May cause birth defects
R48 Danger of serious damage to health by prolonged exposure.
R49 May cause cancer by inhalation.
R50 Very toxic to aquatic organisms.
R51 Toxic to aquatic organisms.
R52 Harmful to aquatic organisms.
R53 May cause long-term adverse effects in the aquatic environment.
R54 Toxic to flora.
R55 Toxic to fauna.
R56 Toxic to soil organisms.
R57 Toxic to bees.
R58 May cause long-term adverse effects in the environment.
R59 Dangerous to the ozone layer.
R60 May impair fertility.
R61 May cause harm to the unborn child.
R62 Risk of impaired fertility.
R63 Possible risk of harm to the unborn child.
R64 May cause harm to breastfed babies.
R65 Harmful: may cause lung damage if swallowed.
R66 Repeated exposure may cause skin dryness or cracking.
R67 Vapours may cause drowsiness and dizziness.
R68 Possible risk of irreversible effects.

SAFETY PHRASES

S1 Keep locked up.
S2 Keep out of the reach of children.
S3 Keep in a cool place.
S4 Keep away from living quarters.
S5 Keep contents under ... (there follows the name of a liquid).
S6 Keep under ... (there follows the name of an inert gas).
S7 Keep container tightly closed.
S8 Keep container dry.
S9 Keep container in a well-ventilated place.
S12 Do not keep the container sealed.
S13 Keep away from food, drink and animal foodstuffs.
S14 Keep away from ... (a list of incompatible materials will follow).
S15 Keep away from heat.
S16 Keep away from sources of ignition.
S17 Keep away from combustible material.
S18 Handle and open container with care.
S20 When using, do not eat or drink.
S21 When using do not smoke.
S22 Do not breathe dust.
S23 Do not breathe vapour.

S24 Avoid contact with skin.
S25 Avoid contact with eyes.
S26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
S27 Take off immediately all contaminated clothing.
S28 After contact with skin, wash immediately with plenty of soap-suds.
S29 Do not empty into drains.
S30 Never add water to this product.
S33 Take precautionary measures against static discharges.
S35 This material and its container must be disposed of in a safe way.
S36 Wear suitable protective clothing.
S37 Wear suitable gloves.
S38 In case of insufficient ventilation, wear suitable respiratory equipment.
S39 Wear eye / face protection.
S40 To clean the floor and all objects contaminated by this material, use .... (there follows suitable cleaning material).
S41 In case of fire and / or explosion do not breathe fumes.
S42 During fumigation / spraying wear suitable respiratory equipment.
S43 In case of fire use ... (there follows the type of fire-fighting equipment to be used.)
S45 In case of accident or if you feel unwell, seek medical advice immediately (show the label whenever possible.)
S46 If swallowed, seek medical advice immediately and show this container or label.
S47 Keep at temperature not exceeding...
S48 To be kept wet with (there follows a material name).
S49 Keep only in the original container.
S50 Do not mix with ...
S51 Use only in well ventilated areas.
S52 Not recommended for interior use on large surface areas.
S53 Avoid exposure - obtain special instructions before use.
S56 Dispose of this material and its container at hazardous or special waste collection point.
S57 Use appropriate container to avoid environmental contamination.
S59 Refer to manufacturer / supplier for information on recovery / recycling.
S60 This material and its container must be disposed of as hazardous waste.
S61 Avoid release to the environment. Refer to special instructions / safety data sheets.
S62 If swallowed, do not induce vomitting; seek medical advice immediately and show this container or label.