1. THE IMPORTANCE OF NON-DESTRUCTIVE TESTING

1.1 THE SCOPE OF NDT

1.1.1 Need and definition of NDT

An industrial product is designed to perform a certain function. The user buys it with every expectation that it will perform the assigned function well and give a trouble-free service for a reasonable period of time. The level of guarantee or certainty with which a trouble-free service can be provided by any product may be termed as its degree of reliability. The reliability of a machine or an assembly having a number of components depends upon the reliability factors of all the individual components. Most of the machines and systems in the modern day world, for example, railways, automobiles, aircraft, ships, power plants, chemical and other industrial plants, etc., are quite complex having thousands of components on which their operation and smooth running depends. To ensure the reliability of such machines it is important that each individual component is reliable and performs its function satisfactorily.

Reliability comes through improving the quality or quality level of the components or products. A good quality product can therefore be termed as one which performs its assigned function for a reasonable length of time. On the other hand products which fail to meet this criterion and their failure or breakdown occurs unpredictably and earlier than a specified time may be termed as bad or poor quality products. Both these types of products differ in reliability factors or quality levels.

The quality of products, components or parts depends upon many factors important among which are the design, material characteristics and materials manufacturing and fabrication techniques. Quality may be defined in terms of defects and imperfections present in the materials used for making the product or the presence of such defects and imperfections in the finished product itself. Many defects can also be formed in products during service. The nature of these defects differs according to the process of its design and fabrication as well as the service conditions under which it has to work. A knowledge of these defects with a view to determining them and then minimizing them in a product is essential to achieve a better or an acceptable level of quality.

An improvement in the product quality to bring it to a reasonable quality level is important in many ways. It increases, as already mentioned, the reliability of the products and the safety of the machines and equipment and brings economic returns to the manufacturer by increasing his production, reducing his scrap levels, enhancing his reputation as a producer of quality goods and hence boosting his sales. There is therefore a need to have methods by which the defects in the products can be determined without affecting their serviceability.

A wide variety of test schemes exist, some destructive and some non-destructive. Strictly speaking non-destructive testing has no clearly defined boundaries. According to ASTM E-7 non-destructive testing (NDT) is the development and application of technical methods to examine material of components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure and evaluate discontinuities, and other imperfections, to assess integrity, properties and composition; and to measure geometrical and physical characteristics. The terms non-destructive testing (NDT) and non-destructive inspection (NDI) are taken to be interchangeable, but a newer term non-destructive evaluation (NDE) is coming into use. In NDT or NDI, in flaw detection applications, the end product is taken to be a description of the flaws which have been detected in terms of their nature, size, and location. From this, either in conjunction with a standard for acceptable/rejectable flaws, or a knowledge of, for example, fracture mechanics, a decision is made by the designer, but in practice may be left to the NDT personnel, or the NDT inspector. In NDE, it is assumed that this acceptance/rejection of flaws is part of the non-destructive testing process.

Non-destructive testing (NDT) plays an important role in the quality control not only of the finished products, but also of half finished products as well as the initial raw materials. NDT can be used at all stages of the production process. It can also be used during the process of establishing a new technology by product quality or when developing a new product. Outside the manufacturing field, NDT is also widely used for routine or periodic control of various items during operation to ascertain that their quality has not deteriorated with use.

1.1.2 Methods of NDT

The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to the more complicated examinations of the interior by ultrasonics or radiography. The principal NDT methods are visual or optical inspection, dye-penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. The basic principles, typical applications, advantages and limitations of these methods are briefly described in Section 3. Given in Section 3 are also a number of other NDT methods that exist. These are used only for specialized applications and consequently are limited in use. some of these methods are neutron radiography, acoustic emission, thermal and infra-red testing, strain sensing, microwave techniques, leak testing, holography, radioisotope gauges and analytical methods.

In general the various NDT techniques can be placed into two categories: active and passive. The active techniques are those where a test medium is applied to the test specimen and a response is expected if a flaw is present. This response is then detected by some means and recorded. Magnetic particle testing, ultrasonic testing and radiography fall into this category. Passive techniques, on the other hand, are those that monitor or observe the item in question during either a typical load environment or a proof cycle and attempt to determine the presence of a defect through some reaction of the specimen. Acoustic emission, noise analysis, leak testing, visual examination, and some residual magnetic techniques are in this classification.

Non-destructive testing has become an essential part of every industrial tool box. Building industrial plants or welded structures without NDT today would be like building without measuring or cleaning or welding. Maintaining aircraft, refineries or rotating equipment without NDT would be like maintaining without lubrication or checking for tightness or for corrosion.

1.1.3 Relationship to destructive testing

To verify the integrity of a fabricated component, it is always possible to cut or section through the components and examine the exposed surfaces. Components can be pulled or stressed and pressurized until failure to determine their properties of strength and toughness. Welds can be bent to determine the presence of cracks. Materials can be chemically treated to determine their composition. These are some forms of destructive testing. Unfortunately this approach of destructive testing renders the component useless for its intended use as against non-destructive testing which can be performed on the components and machines without, in any way, affecting their service performance. A comparison of destructive and non-destructive testing methods is given in Table 1.1

1.2 THE APPLICATIONS OF NDT

1.2.1 Applications in design

The beneficial effects of non-destructive evaluation can be felt in engineering design. For example, in mechanical design, a factor-of-safety, typically defined as the ratio of design stress over the expected stress, is introduced in order to allow for a variety of uncertainties. The nature and often catastrophic results of these uncertainties have been well described in the literature dealing with fracture and material failure. One of the principal uncertainties is the performance of the components used in the construction of a mechanical system. Manufacturing irregularities, such as voids, inclusions, unfavourable patterns, and hardness affect the performance of the final part. It is no longer satisfactory for the engineer to simply specify that the material shall be free of defects. There must be more assurance that this is the case. The use of non-destructive evaluation in the quality control of manufactured parts can provide this assurance and thus increase the certainty that an item will perform as intended. With this, then, a lower factor-of-safety may be possible with a resulting overall saving in weight and cost of an item. This can best be done in the presence of firm knowledge that there are no flaws, as shown, for example, by 100% radiography. In practice, this is done by the writers of codes. For example, the widely used ASME code permits the full thickness of a weld to be used in calculations if the weld is radiographed 100%. In the absence of such radiographs, the designer is limited to using 80% of that thickness in his calculations.

Non-destructive evaluation can play a significant role in obtaining an efficient, long-lived design of components and operating mechanics. The combined advances of NDE and fracture mechanics in recent years have radically affected the approach to mechanical design.

Several axioms describing this new approach to design are given. Axiom 1 states "All materials contain flaws." This is in contrast to the earlier philosophy where it was felt to be sufficient for the design engineer to simply state in his specifications that the materials contain flaws. It is now the responsibility of the design engineer to first know the fracture mechanics characteristics of the material that is being used and, second, to assure that NDE has been used to prevent the occurrence of potentially hazardous defects.

TABLE 1.1 : COMPARISON OF DESTRUCTIVE AND NON-DESTRUCTIVE TESTS.

DESTRUCTIVE TESTS	NON-DESTRUCTIVE TESTS
1. Tests usually simulate one or more service conditions. Consequently, they tend to measure serviceability directly and reliably.	1. Tests usually involve indirect measurements of properties of no direct significance in service. The correlation between these measurements and serviceability must be proved by other means.
2. Tests are usually quantitative measurements of load for failure, significant distortion or damage, or life to failure under given loading and environmental conditions. Consequently they may yield numerical data useful for design purposes or for establishing standards or specifications.	2. Tests are usually qualitative and rarely quantitative. They do not usually measure load for failure or life to failure, even indirectly. They may, however, reveal damage or expose the mechanisms of failure.
3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) is usually direct. Hence most observers may agree upon the results of the test and their significance with respect to the serviceability of the material or part.	3. Skilled judgement and test or service experience are usually required to interpret test indications. Where the essential correlation has not been proven, or where experience is limited, observers may disagree in evaluating the significance of test indications.
4. Tests are not made on the objects actually used in service. Consequently the correlation or similarity between the objects tested and those used in service must be proven by other means.	4. Tests are made directly upon the objects to be used in service. Consequently there is no doubt that the tests were made on representative test objects.
5. Tests can be made on only a fraction of the production lot to be used in service. They may have little value when the properties vary unpredictably from unit to unit.	5. Tests can be made on every unit to be used in service, if economically justified. Consequently they may be used even when great differences from unit to unit occur in production lots.
6. Tests often cannot be made on complete production parts. The tests are often limited to test bars cut from production parts or from special material specimens processed to simulate the properties of the parts to be used in service.	6. Tests may be made on the entire production part or in all critical regions of it. Consequently the evaluation applies to the part as a whole. Many critical sections of the part may be examined simultaneously or sequentially as convenient and expedient.

TABLE 1.1. (cont.)

DESTRUCTIVE TESTS	NON-DESTRUCTIVE TESTS
7.A single destructive test may measure only one or a few of the properties that may be critical under service conditions.	7. Many non-destructive tests, each sensitive to different properties or regions of the material or part, may be applied simultaneously or in sequence. In this way it is feasible to measure as many different properties correlated with service performance as desired.
8. Destructive tests are not usually convenient to apply to parts in service. Generally, service must be interrupted and the part permanently removed from service.	8. Non-destructive tests may often be applied to in service parts or assemblies without interruption of service beyond normal maintenance or idle periods. They involve no loss of serviceable parts.
9. Cumulative change over a period of time cannot readily be measured on a single unit. If several units from the same lot or service are tested in succession over a period of time, it must be proven that the units were initially similar. If the units are used in service and removed after various periods of time, it must be proven that each was subject to similar conditions of service, before valid data can be obtained.	9. Non-destructive tests permit repeated checks of a given unit over a period of time. In this way, the rate of service damage, if detectable, and its correlation with service failure may be established clearly.
10. With parts of very high material or fabrication costs, the costs of replacing the parts destroyed may be prohibitive. It may not be feasible to make an adequate number and variety of destructive tests.	10. Acceptable parts of very high material or fabrication costs are not lost in non-destructive testing. Repeated testing during production or service is feasible when economically and practically justified.
11. Many destructive tests require extensive machining or other preparation of the test specimens. Often, massive precision-testing machines are required. In consequence the cost of destructive testing may be very high, and the number of samples that can be prepared and tested may make severe demands upon the time of highly skilled workers.	11. Little or no specimen preparation is required for many forms of non-destructive tests. Several forms of non-destructive testing equipment are portable. Many are capable of rapid testing or sorting and in some cases may be made fully automatic. The cost of non-destructive tests is less, in most cases, both per object tested and for overall testing, than the cost of adequate destructive tests.
12. The time and man-hour requirements of many destructive tests are very high. Excessive production costs may be incurred if adequate and extensive destructive tests are used as the primary method of production quality control.	12. Most non-destructive test methods are rapid and require far fewer man-hours or actual hours than do typical destructive tests. Consequently testing all the production units cost normally less than, or comparable, to the costs of inspecting destructively only a minor percentage of the units in production lots.

The beneficial role that NDE is able to play in the initial design process may be presented through evaluation of fatigue characteristics of components. In general the parts operating at lower stress levels would be expected to have a longer fatigue life than the ones operating at higher stress levels. However, largely due to material and manufacturing variations actual practice has shown that in the vicinity of fatigue failure line there is a considerable uncertainty. In order to produce a more conservative design, the operating stress should be removed from this uncertain area. This is accomplished with the factor of safety. Changes in the operating conditions after the component is placed in service will result in a new factor of safety. For example, either an increase in the load stress or an extended life operation would result in a decrease in the factor of safety and a corresponding increase in the likelihood of failure.

The study of fracture mechanics has given the design engineer an added dimension in the creation of designs as an integrator of material properties, design stress, and flaw detectability. In fracture mechanics, a distinction is made between the initiation of a crack and its subsequent propagation. In calculating the critical stress levels, fracture mechanics assumes the presence of a crack when most likely one does not exit. Thus, the analysis begins with a conservative assumption. With the presence of a crack assumed, the propagation in metals begins from the onset of plastic flow in a very localized region at the crack tip. Once started, it is further assumed that the crack will travel until arrested by some condition in the material. Failure prevention, then, demands that the crack be detected before reaching the critical, final failure stage.

In NDT the detectability of a flaw generally increases with its size. It is also true, however, that the probability of failure generally increases with flaw size. Recognizing the catastrophic potential for a fatigue related failure, it is prudent for the designer to consider future inspections in the original concept. Where considerable effort is required to gain access to inspect a critical part, the inspection will be more costly. Moreover, inspections that are required to be conducted in places that are difficult to reach are more likely to be performed in an ineffective manner. It is therefore imperative that the original designer plans for convenient inspection for critically stressed locations.

The items in the design process which are critical to the inspectability of a part or system are briefly mentioned here. Firstly the materials selected should have favourable fracture toughness properties. Certainly the ability of a material to arrest a crack rather than allowing it to propagate suddenly to full failure is conducive to successful NDE. The importance of a material having well established NDE properties is also stated. For example, ultrasonics may have a response in some cast materials that is different from similar wrought materials because of the increased scatter at the grain boundaries of the former. Fabrication processes that may inflict flaws or other anomalies into the part should be avoided. Of particular importance in this area are tensile stresses, introduced during fabrication, which can facilitate the initiation and propagation of a crack. The configuration of the part should be such that unnecessary section changes that might inhibit inspection are minimized. Further, critical areas should be easily accessible, either for visual inspection, NDT, or both. Finally, it is recommended that the design engineer consults frequently with the NDT engineer so that an overall satisfactory design emerges.

1.2.2 Applications in manufacturing quality

Defects in materials are either present because of the faulty manufacturing processes or due to fatigue, corrosion or similar damage during service. However, it is important to have the materials of the right quality before these are accepted for being put into service. The application of NDT during manufacture is therefore very important.

The cost of manufacturing of products is enhanced ultimately by the costs of repair, rework, replacement and even a possible loss of customer as well as the costs of delay of schedules, etc. A very careful consideration has therefore to be made to the production of quality goods during manufacturing. A key item to assure the maintenance of consistent quality and productivity can be the employment of a new process involving non-destructive testing (NDT) and inspection systems to assess and feedback product quality information. In a properly designed and qualified product that has been demonstrated as producible, NDT techniques have proved to be very reliable tools to assure consistent parts, materials, processes, and workmanship, as well as product quality.

NDT methods offer not only the advantages of discovering potential or real problems early in the production programme but also a definite feedback as to how to correct the problem at the earliest possible point.

Subcontractors can make good use of NDT capabilities. As an electronic product is built up from its piece parts to modules to printed wire boards to black boxes and eventually to the system assembly, the cost of any anomalous performance that can result in additional tests, troubleshooting, removal, rework, repair, and as a worst case the scrap increases at an exponential rate. We must therefore discover and correct any quality problems at the lowest level of assembly and as early in the product production phase as possible. To this end, NDT methods can provide a very positive approach. It is not the answer to every problem but surely should be considered. NDT methods offer a helping hand for making this a reality at all times. Consistent high quality goes hand in hand with increased productivity.

The NDT methods that are suitable for application during manufacturing are those which can detect the desired levels of defects at speeds compatible with the particular production rates. In certain pipe, tube and plate manufacturing, for example, two to three joints or lengths must be inspected every minute to keep up with production. In some other cases where a number of tests have to be performed on the same product, the inspection time may be much longer. The producer is faced with the situation that he must inspect his products at relatively high speeds and at the same time meet the quality levels verified through deliberate and comprehensive customer inspections. This, though expensive, is no more an impossible task. Considerable research and development, engineering and manpower have been expended world-wide to develop NDT systems to meet the needs and specifications of particular customer, plants and production methods. Research and development were dedicated to devising automatic systems that could operate at speeds compatible with production rates and could detect and mark deviations from acceptable product quality with a high degree of accuracy. This work has resulted in NDT systems that are fast, accurate and give reproducible results. Automated inspection is now available for almost all the NDT methods but for regularly shaped products, such as pipes and plates, etc., ultrasonic and eddy current methods are generally employed. These have, relative to other NDT methods, much greater speeds of inspection. But such modern systems, of course, are quite expensive and therefore quite a number of manufacturers prefer to get NDT done by third parties to the satisfaction of the customer.

Many producers have adhered to the practice of using NDT solely to satisfy customer and industry requirements for finished products acceptance. These tests may be conducted at the producer's plant, at downriver marshalling yards or warehouse, or at the customer's facility. This practice provides a high degree of quality assurance, but there is little or no opportunity to apply timely corrective measures for quality-control purposes. Consequently, NDT is used only for finished product inspection, whereas a significant portion of its cost-saving can be realized only from using in-process NDT in addition to the final inspection. Some of these savings are evident. If the product that is flawed or out of tolerance because of dimensions or mechanical properties is identified early in production, it can be diverted or scrapped, thus avoiding further processing and related costs. This information alerts production planning to the fact that a certain number of make-up pieces must be processed and that there are a number of downgraded pieces available for other markets. Through early detection and repair of imperfections, the quality level of the products going into final inspection is improved. This results in a significant reduction in final inspection rejections, increased yield, and fewer miscalls by the NDT system. In-process NDT can also avoid damage to equipment which may make use of the manufactured components. The direct cost savings are evident, and additional saving through reduced handling, shipping, manpower, and claims can be surmised.

NDT techniques have advanced to the point that when properly applied, they can read mechanical and physical product parameters predictably and repeatedly. A programme that combines in-process and final NDT in a comprehensive manner might be called a non-destructive quality-control (NDQC) programme. The NDQC programme would use the appropriate NDT methods at various stages of the product manufacturing process to monitor such parameters as steel grade, dimensions, physical properties, and the nature, distribution, and occurrence rate of imperfections for feedback and feed-forward purposes. The numerous devices that are being developed for this purpose include photodiode arrays, matrix array TV cameras, lasers, infra-red devices, electromagnetic-acoustic transducers (EMATs), computer-aided tomography (CAT). The products being manufactured, say a pipe for example, could be monitored at speeds of up to 1.5 metres per second. Therefore it can be said that conscientious application of NDQC will reduce scrap losses and increase total yield by applying corrective measures before large amounts of out-of-tolerance components are produced. In short NDT can help to "make it right the first time" which is the fundamental concept of quality assurance.

1.2.3 Applications for in-service inspection

For most industrial plants the objective of its ownership is profitable and safe operation throughout its life. The required life of the plant will relate to the period of time for which its product is going to be in market demand and also the time that