Non-Destructive Evaluation: Science and Technology

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Dr. Rodriguez has played important leadership roles in his profession. He was President of the Indian Institute of Metals (1966-67) and of the Indian Institute of Welding (1993-95). Currently he is a Vice President of the Materials Research Society of India and the Honorary Secretary of Indian National Academy of Engineering.

He is a recipient of many national awards [notable among them are National Metallurgist Award (2000), Shri Om Prakash Bhasin Foundation Award (1999), VASVIK Research Award (1990) and GD Birla Gold Medal (1987)] and a Fellow of the Indian National Academy of Engineering, the Indian Academy of Sciences, and the National Academy of Sciences (India).

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The excerpts of the lecture delivered by Dr. Placid Rodriguez

Prof. Mehrotra, scientists and other staff of the National Metallurgical laboratory, distinguished guests, dear students, members of the media, ladies and gentlemen. Let me first of all thank Prof. Mehrotra and the organisers of this event for inviting me as the chief guest giving me this opportunity to be with you today and also to deliver the CSIR Diamond Jubilee Lecture.

I shall make a review of the status of "Non-destructive evaluation (NDE) : Science and Technology". I am aware that this is a very mixed audience. There are the technicians and scientists of the laboratory; we have also members of the public, students and the media; so I would spend a few minutes explaining for the benefit of the uninitiated as to what non-destructive techniques are. The best way to carry the point home to all of you is to talk about the application of these techniques in medicine and physiology. I am sure all of you know about X-rays or most of you have been X-rayed sometime or the other when it was suspected that your human skeleton structure, bone structure, has undergone fracture due to an accident. Bones are opaque to x-rays, and if there is a fracture you are able to identify this in a two-dimensional picture, in a film or in a screen. There are similar other techniques. When we do computer aided scanning using X-rays, we use principles of mathematics to re-construct a three dimensional picture of the object that is being scanned; this is the technique of CATSCAN or computer aided tomography. Sonography also gives by the technique of splicing, a three-dimentional picture of an internal organ. X-rays are not very safe; in fact exposure of the humans to X-rays should be limited; if one is over-exposed, there can be danger including genetic effects. So, we have the technique of ultra-sound being used to probe, particularly to get information on the foetus, an unborn baby in the womb. It is very interesting to note that sonography, examination through ultra-sound in a three dimensional way was first developed by the United States Military Forces to detect the presence of submarines submerged in the sea; the same technology is today used to view the foetus floating in a fluid in the womb of a woman. An ultrasound produces waves that do not have any consequences on the health of the mother or the baby. Ultrasound can be used for taking image of many other organs like the kidneys; even small cysts in the kidneys can be located and also in other organs like liver. Then you have another technique, Magnetic Resonance Imaging (MRI);

actually the technique is Nuclear Magnetic Resonance; the medical people are smart, 'nuclear 'is a bad word, so they have removed the word nuclear and retained only magnetic! The technique is used to examine tissues of the brain and other parts of the body. All these techniques have their counterparts in engineering, and are used to examine industrial components, without destroying the components or their parts to get the information on defects in the components. This is the subject of my talk "Non-destructive evaluation (NDE) : Science and Technology" What I want to do is highlight some of the advances that are taking place today like multi-sensor data fusion, computer aided visualisation and artificial intelligence. There are also the issues related to reliability, risk-based assessment and how to predict life. Remnant life assessment of engineering components, is very similar to the medical people, after investigations and monitoring telling us "you may live a few more years or decades".

NDE AND DEFECTS

In the case of engineering components you want to avoid a defect. Ultimately if the defect grows to a large size, it can lead to fracture. So

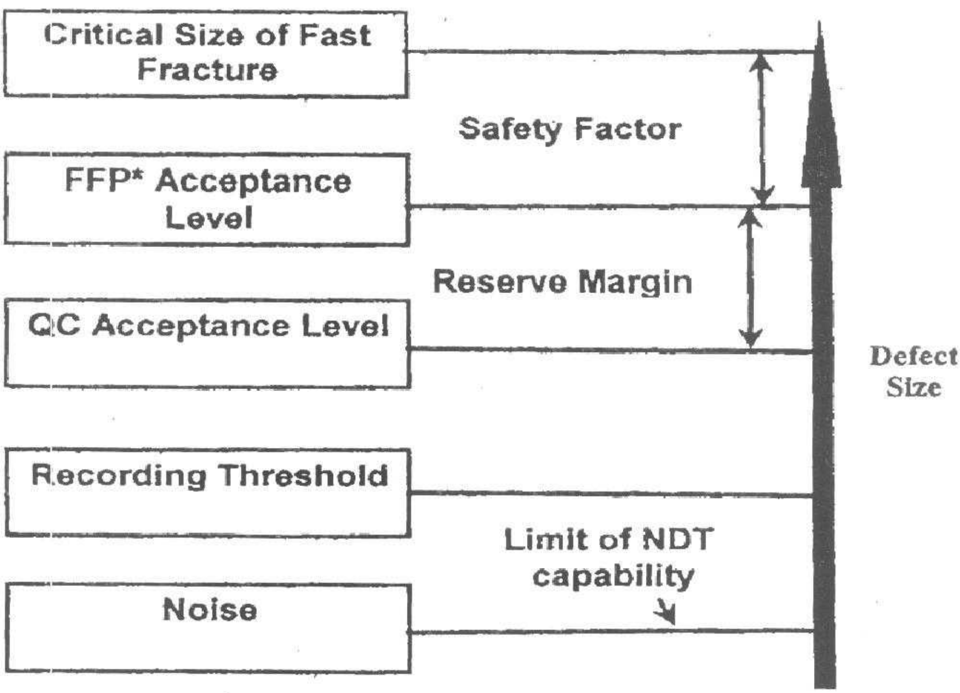

Fig. 1 : Defect size ranges covering quality (QC), FFP and NDT capability

there is a range of sizes[1] from the size that can be detected, to the critical size of defect that would cause fast fracture (Fig. 1) : For quality control purpose one may settle for a defect size which is larger than the detectable defect size. Even if there is a defect which is not acceptable according to the quality control programme, sometimes you make an evaluation of its tolerability on the basis of the "fitness for purpose".

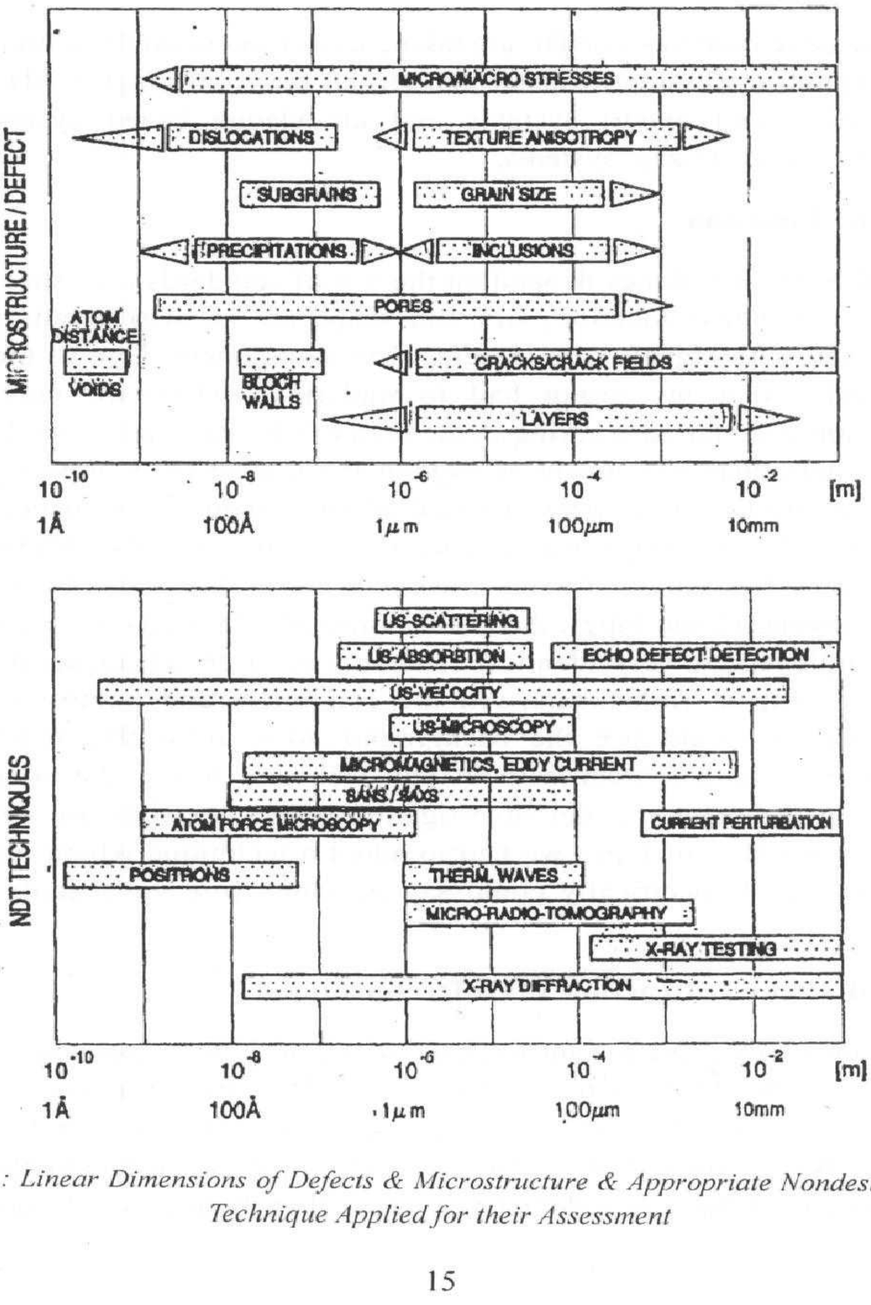

Fig. 2 : Linear Dimensions of Defects & Microstructure & Appropriate Nondestructive Technique Applied for their Assessment

Fig. 2 shows the linear dimensions of defects and microstructural features and the appropriate NDE techniques that can be applied for their assessment. This is determined by the wavelength of the probing radiation, and the most interesting point is that sound has the largest range possible, even more than X-rays, and with these two probes you have a large number of techniques possible.

DEVELOPMENTS IN NDE

The developments in NDE are taking us to risk-based life estimation, to intelligent processing of materials, virtual reality through CAD/CAM visualisation and expert systems and knowledge based systems to emerging Neuro-Fuzzy systems.

Acoustic Emission

All NDE techniques depend on the use of standards (i.e. specimens with defects whose location, size and shape are known) or alternately comparison with signals from a defect-free component. One of the very early tasks, that my group had to undertake when we moved to Kalpakkam and started working in the area of non-destructive evaluation was this particular assignment of looking at a reactor in an atomic power station, where two tube sheets also called end shields were suspected to be cracked[2-4]. The heavy water reactor has a horizontal configuration with around 306 tubes, in many rows and the problem was to locate a leak in anyone of the tubes. Acoustic Emission (AE) was the technique to be employed. A very identical reactor was in an advanced stage of commissioning at Kalpakkam. All the equipment and pumps were in place and we could use the background noise from this reactor as characteristic of a system without any leak and locate the source of leakage in the reactor under investigation. Later on when we detected leaks in a number of tubes we had to adopt a technique where pressure was varied and specifically could say in which row the leaking tubes were.

Time of flight Diffraction (TOFD) Technique

Another example I want to share with you is the emergence of the time of flight diffraction technique (TOFD)[4]. In ultrasonic testing, reflected or transmitted waves are very strong signals that help to locate a crack. When you use the pulse echo technique you measure the time of flight and if there is a defect you know that there is an alteration in

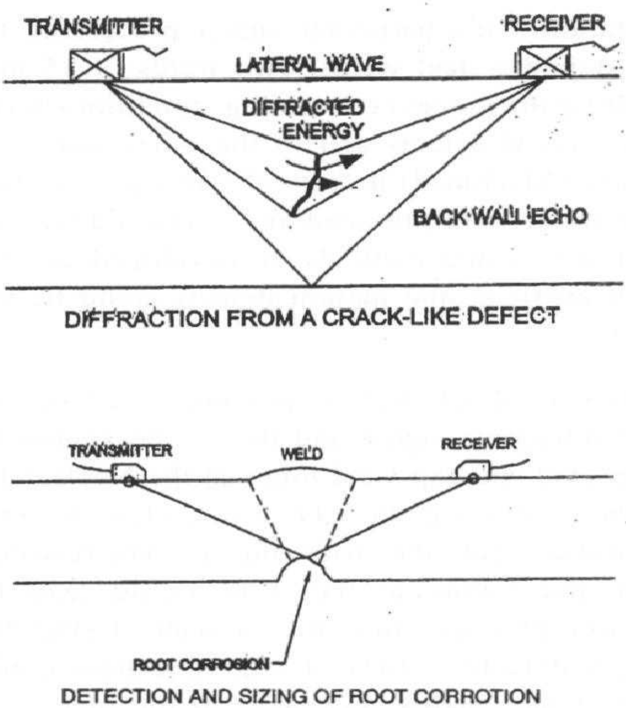

Fig. 3 : Principal of TOFD Technique

the time of flight. In the case of time of flight diffraction (TOFD), more specifically you are looking at the phenomenon of diffraction from the edges of the crack. You are looking at the difference in the time of flight between the diffracted beam and the lateral wave which is transmitted directly (Fig. 3). The advantage of this approach is that you are able to quantify the size of the defect; even a minute corrosion at the root of a weld can be detected and quantified. This technique was originally developed in the middle of Seventies at the National NDT Centre at Harwell and today it is a very well established powerful technique for quantitative work across the world.

Signal Processing in Ultrasonic Testing

Signal processing is very important in the ultrasonic testing of stainless steel welds; due to the presence of noise, the signals from small defects can be masked. Kalyansundaram and colleagues[6] at IGCAR have evolved a number of methods to overcome this problem. One is what is known as a de-modulated auto-correlation function (DMAC). It is essentially a mathematical process of pattern recognition that is done through computation. This particular signal processing technique was applied to 304 stainless steel welds. Two welds (~ 15 mm thick),were made; in one during the process of welding, conditions were so provided that there were natural defects and in the other weld, artificial EDM (Electric Discharge Machined) defects of varying sizes from 1% to 5% thickness of the weld, were provided and single side-drilled holes were also given. Not only could methods be developed to characterise the defects but even artificial and natural defects could be well correlated with the patterns.

Another type of signal analysis possible is taking the auto power spectrum of the ultrasonic signal and this is the approach[7] we took to evaluate the fuel-clad end cap weld joints at the Nuclear Fuel Complex. This is a crucial weld since the UO_2 fuel pellets are encapsulated in zircaloy-2 thin-walled clad tubes with endcaps. The resistance weld joint is most crucial and failure at the weld would lead to leakage of radioactive fission products into the coolant. Using the autopower spectrum analysis defects ~ 10% of wall thickness could be reliably detected as part of the Quality Assurance of the fuel.

Corrosion Damage in Rocket Motor Casing

In the space programme of the Indian Space Research Organisation, just one week before the scheduled launch of a Space Vehicle, 4 or 5 years ago, there was a fear that the rocket motor casing has undergone corrosion attack and the authority had to make a decision to go ahead with the launch or to abort it and replace the rocket motor with a new one. Sometimes the metallurgists have to do forensic work of this kind. It was a challenging job because we had to give advice on the basis of which, a crucial decision was to be made. We were able to clearly tell that there was a corrosion pit, there were multiple stress corrosion cracks and also a linear defect. To do this, we had to fabricate a standard but we could tell ISRO that it is wiser not to accept the launch with defective rocket motor casing. And before the next launch was organised, all care had to be taken after understanding why the corrosion took place and also ensuring that corrosion will never be there again.

Magnetic Barkhausen Noise

I want to discuss another technique, the application of Magnetic Barkhausen Noise (MBN). This is a technique pioneered by D. K.

Bhattacharya of your Laboratory in our country. This was his Ph.D thesis at Kalpakkam (thesis submitted to IISc Bangalore). We developed the technique to examine a tube to tube-sheet weld [8]. There is a tube sheet and from that tube sheet a spigot has been machined out and then welded onto a tube (Fig. 4). This particular tube to tube-sheet design is chosen for our prototype fast breeder reactor (PFBR). You have sodium on the shell side, and water inside the tubes and therefore you have a situation that if there

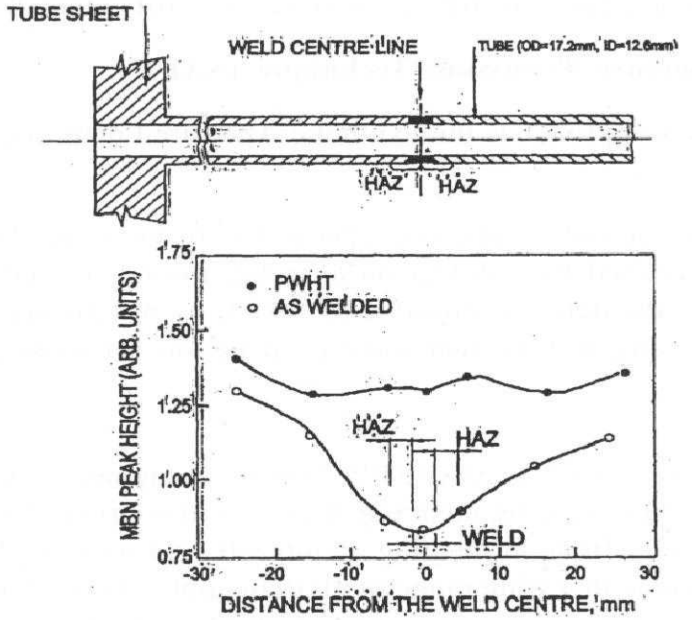

Fig 4: Variation in MBN Peak Heightfrom the Weld Centre Line for Tube to Tube - Sheet Weld Joint

is a weld failure and leakage sodium and water will react releasing hydrogen. So, the integrity of this weld is supreme and therefore we had to ensure quality assurance of the joint by micro-profiling of the weldment with rotating probe ultrasonics and micro focal radiography with 25 μm sensitivity.

Another requirement is that residual stress has to be absent and this is the where Magnetic Barkhausen Noise technique was used. The peak height of the MBN for the weld shows a pattern with a trough as shown in Fig. 4 and once the residual stress is removed and the hardness of the microstructures from the base metal to the fusion zone is made uniform, the pattern flattens out. You are sure there is no more any residual stress remaining, once the peak height reaches a flat level.

This technique has further applications. Because in the case of chrome-moly steel welds, one of the problems is the retained austenite in the intercritical region which makes the region softer and reduces the creep strength locally. We have found that the presence of a soft intercritical region shifts the MBN peak to a higher magnetic field. This is attributed to the paramagnetic austenite phase which is a strong barrier to domain wall movement. Thus we have a technique to inspect and assess whether a weld joint has the undesirable soft intercritical region.

Synthetic Aperture Focussing Technique (SAFT).

A very new approach is the Synthetic Aperture Focussing Technique (SAFT).

The basic idea of a synthetic aperture is to measure the complete sound field scattered by a defect on an orbit around it. Reconstruction of the image of the defect is possible by SAFT, by describing the surface of the defect using well known wave propagation formulae[9].

Data Fusion

Data fusion, which is essentially looking at signals from a number of sensors and then merging them together, was also originally developed for military applications in locating an aircraft or a missile. This is now finding importance in a wide range of civilian applications. There are two approaches here. One, you can employ multiple sensors using the same technique for example, a number of ultrasonic transmitters can be used or you can use one ultrasonic sensor and one eddy current instrument. You may use sensors of different techniques and of variable accuracy. You can have additional complimentary information from another sensor. You can infer more features. Finally and ultimately a decision has to be made, how to fuse the data from a large number of sensors to make, a decision as to what is the correct answer? Here you go to advanced statistical techniques. One is based on a straight statistical approach, the Bayesian statistical theory and the other is the Dempstar-Shafer theory of evidence[10]. I can explain the two approaches to you by making a reference to a well known TV Programme. I am sure all of you have watched the programme 'Kaun Banega Crorepati.' In 'Kaun Banega Crorepati' , if you do not know the answer to a question at any stage, you are given two options. One is you can refer the question to the audience, a large number of multiple sensors and then you go by the statistical approach that majority of the audience should be giving the correct answer. But quite often there are people who do not follow the majority and they have an expert whom they bring along. You have faith in one of the techniques, and believe it is the accurate.

Expert systems

I want to give an example of an expert system developed at Kalpakkam[11] for the ultrasonic examination of austenitic stainless steel welds. You must have a knowledge base of inspection in the form of rules; the total number of rules that has gone into the expert system is about 3,000. The interaction between the user and the expert system is through entry of any of these rules. There is a lot of information on the weld, such as geometry, voltage of the arc, the current, the weld conditions, weld dimensions and materials involved and rate of cooling. Then there is a metallurgy module, an ultrasonic testing module etc., what kind of codes you have, what kind of probes are available with you i.e. depending on different situations. The best results are obtained when you optimise the probes, frequencies and other parameters. Then signal analysis module and then the applicable code, for example codes for Boilers, Nuclear Reactor etc.

So all these have to be put in and then at the interface, the scheduler, essentially looks at the information given by the user, asks for supplementary questions so that the information is updated and even corrected and finally an answer is given. Similar expert systems have been developed at Kalpakkam for eddy current and X-ray testing.

Computer-aided Visualisation

Every person who is involved in non-destructive evaluation would agree that if you get, one non-destructive evaluation image, it is more useful than getting a signal. A signal has to be interpreted and also as individuals we feel comfortable if you have an image, two-dimensional or three-dimensional, shown to you visually. This is where computer-aided visualisation is making fantastic advances. Essentially an image is an input to the human neuro-system of the inspector. In the first instance, when the inspector is using the equipment, it even allows him to model the interaction of probing waves with the component extensively and he is able to do more than that he can even see or visualise how the interaction varies with experimental parameters. If you are doing real time X-radiography, for example, you can clearly see how better the picture is if you increase the voltage and make the X-rays more penetrating. In eddy current testing the skin effect can be modelled. In ultrasonic testing, there are reflections and transmissions, you can see both happening if you visualise appropriately. You can select the probe, optimise the scan path and direction and in situations where multiple sensors are used, you can also chose the optimum locations of sensors.

We will soon have in this century, telerobotics supported by augmented virtual reality in NDE. You don't have to go to Rajasthan to examine the power plant there. You can sit in Kalpakkam, all the information obtained by equipments at the plant in Rajasthan will be communicated to you digitally for you to visualise and analyse. This is already happening in what is known as telemedicine. Today if you have an X-ray picture or a MRI picture which a doctor in a particular hospital is not able to interpret, or if he desires to get a second opinion, the image can be sent digitally to a well-known specialist to get his opinion. So, the era of telemedicine has already arrived and the era of non-destructive evaluation through similar advanced technology will also come.

Today, people talk in the corporate world about new business models. So, if you can plan ahead that the NDT centre that is going to come up at NML is so well equipped that from the beginning of the centre, non-destructive evaluation results can be communicated digitally from and to the laboratory at Jamshedpur, you are going a step ahead of the other centres in the country.

Remnant Life Assessment

Lastly, I want to touch a philosophical aspect, that is to talk about the relationship between design, quality assurance, life cycle, operating history, reliability and maintainability. In fact I'll add one more i.e. design and actual processing and forming. Today for example CAD /CAM is in so that it is a new paradigm between actual design and manufacturing. Computer aided design and computer aided manufacturing are in. Ultimately the aim of any endeavour in engineering is that the total life-cycle cost must be reduced and in the context of non-destructive evaluation, we have to be concerned not only about the material conditions when the material is going into service but how the degradation takes place while in service and the consequent failure models and the risk involved in failure due to the degradation. In conventional manufacturing, based on this approach you will either accept or reject a component but today we would rather introduce a feedback and do intelligent control of the process to get the right quality so that there is no rejection at all. This is the concept of Intelligent Processing of Materials where again NDT sensors are being used.

Let me share with you another paradigm shift that is taking place. In the 60's and 70's when fracture mechanics emerged, as a new concept that enables us to assess the life of a component with an already existing crack, the question that was often asked was: "What is the sensitivity of the detection by an NDE technique or what is the minimum flaw that can be detected by the use of this technique during fabrication"? And then the decision was since this was the minimum defect detected with the NDE technique do your fracture mechanics calculation for prediction of life assuming that defect size for an existing crack. Today, we are not talking about sensitivity limit but what is the probability of detection as the defect or flaw size increases and that probability is one, above a certain flaw size. For any lower flaw size the probability of detection is less than one. For any other flaw size there is a finite probability, less than one and the probability of not detecting a flaw lower than a certain size is zero

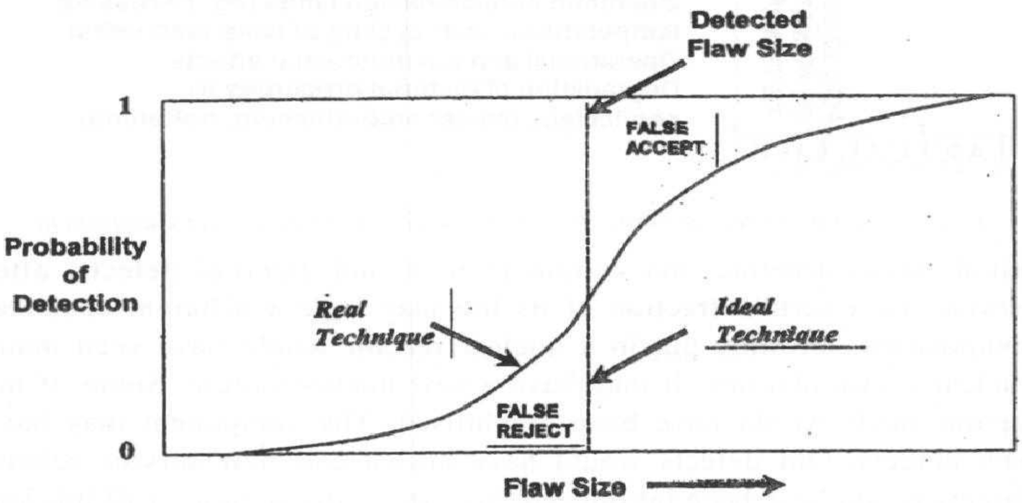

Fig 5: Probability of detection (POD) curve as a function of flow size for both ideal and real technique

(Fig. 5). What this means is, in the old concept you had, flaw size, which is detected or not detected. But today, you have a range of flaw sizes with probability of detection varying from 0 to 1 and you have situations where you will falsely accept a component and you have situations where you will falsely reject a component. When you say that a material has a fracture toughness of 100 MPa all that it means is that with 3 specimens the fracture toughness has got a range of values with an average value of 100 MPa and you have to actually assign a probability less than one for the fracture toughness to have a higher value. A material that is put into service with a certain chemical composition which has a certain

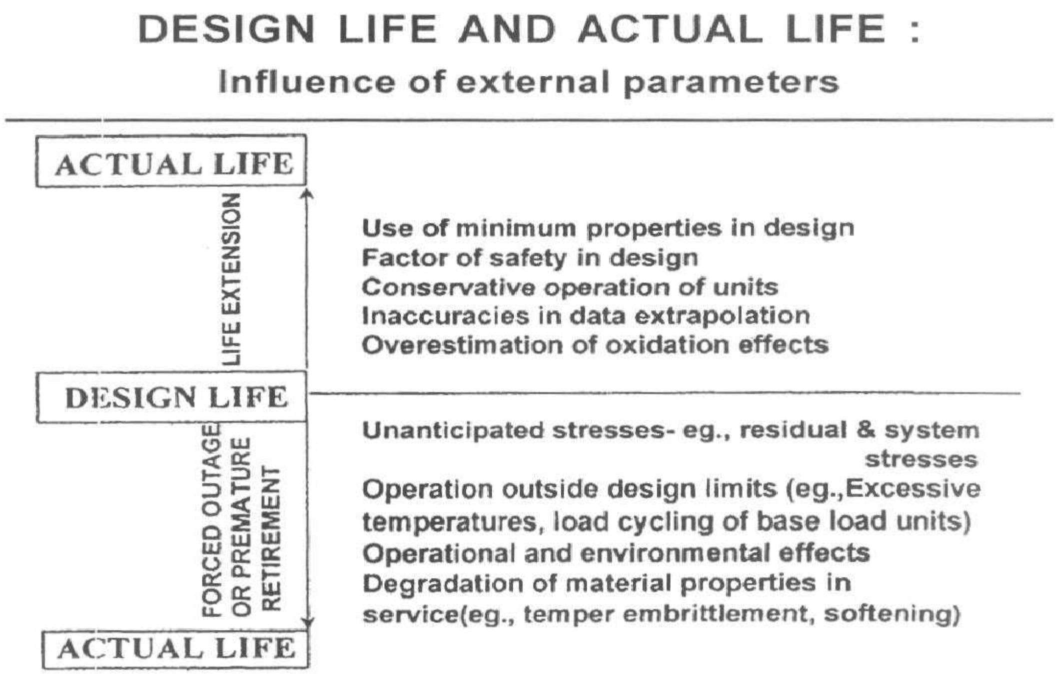

Fig 6 : Factors that determine the "Actual Life" of Engineering Component

initial micro-structure and certain internal and external defects, after service for a certain fraction of its life may have a different chemical composition; an alloy put in a nuclear reactor would have seen many nuclear transmulations. It may have a new microstructure. Some of the ferritic steels would have been graphitised. The component may have new defects. Old defects would have grown and new service related defects would have been introduced. You need information on all this and we must take into account degradation of the material and we must take into account that the permissible defect size also comes down. Inspite of all this, because of the use of a conservative factor of safety in design, catastrophe fracture is often avoided. This is a happy situation. There is still a safety margin but on many occasions it happens that the crack growth is accelerated or material damage is severe and pre-mature failure takes place (Fig. 6). These things do happen in engineering components. Quite often we are able to extend the life beyond the design life because the safety margin is still there. Refurbishing a plant is more economical than building a new plant. However, when a pre-mature failure occurs, you have a shut-down and loss of valuable plant-days. Here rem nant life assessment comes into very great significance.

Periodic In-Service Inspection (ISI) is very important for assessing remnant life and in making decisions on life extensions or avoiding plant shut-downs. The role of NDE techniques in ISI needs to be emphasised[1-3].

In addition to giving valuable quantitative information on defects and 'damage' for assessment of structural integrity and remnant life, in-service inspection data should also be used for establishing the interval for the next ISI. A look at the data along with data from previous ISI campaign and fabrication history will be extremely useful to assess the rate of deterioration during service and a more useful input for remnant life assessment and analysis.

CONCLUSION

It is seen that considerable progress has been made in non-destructive testing techniques for defect detection and characterization over the last two decades. Today, NDT & E methods can give accurate information regarding quantification and sizing of defect by using new methodologies of imaging, signal/image processing etc. and meet the challenging demands towards total quality management and life extension programmes for safe, reliable and economic performance of components and structure. In many of these areas, progress and contributions from India have been significant.

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