The Application of Condition Assessment and On-line Monitoring to the Evaluation of Continued Service of Critical Components in Petro-Chemical Facilities

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Abstract

Increasingly, the continued use of critical plant components under original and modified operating conditions requires that suitability for service be demonstrated. Evaluations for continued service integrate nondestructive testing inspections to determine current state of damage in the component, engineering analyses to predict the rate of damage accumulation, and on-line damage monitoring to establish suitability for continued operation. In addition, these assessments provide for cost-saving optimization of component maintenance and determination of re-inspection intervals and requirements. This paper describes the various techniques applied to component condition assessment technology. Specifically, replication is discussed as a method to perform on-site metallurgical evaluation of components and identify damage mechanisms without costly and time consuming sample removal and repair welding. The uses of nondestructive testing techniques such as magnetic particle testing and ultrasonic testing, for the detection and sizing of defects, is reviewed with specific examples. Analytical approaches including closed-form solutions, finite element stress analysis, and fracture mechanics calculations to predict future rates of damage accumulation and/or defect growth, are reviewed. Finally, a damage monitoring system is discussed that provides on-line component-specific measurement of operating conditions and damage progression so that cost-optimized decisions can be made regarding future maintenance and re-inspection intervals.

Introduction

Condition assessment or remaining life programs consist of an integrated approach using metallurgy, nondestructive testing, stress analysis, and fracture mechanics technologies. It is, therefore, necessary for engineers of each of the above disciplines to have a fundamental understanding of the principles of each discipline as applied to condition assessment programs. Clearly, the relative contribution of a technical area or discipline is dependent on several factors, such as the specific component being assessed, the operational and maintenance histories of similar components, and/or the specific condition or damage state of a component. As an example, a baseline assessment of a high temperature component primarily relies on a program structured around nondestructive testing techniques and metallurgical replication. However, a program for the assessment of a high temperature component with known problems may consist of more analytical approaches (stress analysis, fracture mechanics, and predictive models). It is, therefore, necessary to first establish program protocols for a variety of critical components in combination with a variety of assessment goals.

The initial phase of a condition assessment program consists of reviewing the operational environment and typical materials of construction for selected critical plant components. With an understanding of the component materials and service environment, this step is to identify the possible damage mechanisms and susceptible locations in a given component.

As an example, with the realization that thermal transients can initiate and propagate cracking in thick-section components at regions of thickness transitions and geometric stress concentrations, focus would be on inspection techniques to interrogate the internal surface of the component; while an evaluation of piping girth weld cracking requires an analytical treatment of the steady state piping and support system loads, and metallurgical treatment of weldment aging. So for each selected component, evaluations should center on developing an understanding from a metallurgical and stress perspective, of the locations most susceptible to damage and, as importantly, the mechanism(s) responsible for the damage. Mechanisms to be correlated to component service environment include:

- Creep
- Fatigue - Thermal and Mechanical
- Erosion
- Corrosion - Various Forms
- Metallurgical Degradation - Graphitization, Sheroidization, Decarburization
- Hydrogen Damage - Various Forms

Once an understanding of the potential damage mechanisms and susceptible locations is established, it is necessary to evaluate the applicability and limitations of various inspection techniques, for the detection and characterization of the subject damage. Specifically, replication, nondestructive testing methods (dye penetrant, magnetic particle, ultrasonic, and remote visual), and dimensional methods will be covered to develop an understanding of the integrated inspection approach. The following provides discussion of the typical techniques used in a condition assessment program.

Nondestructive Testing

The first step in the field performance of a condition assessment plan is the nondestructive testing examination of critical locations on a component. Again, prior to the actual examination, the appropriate examination method (i.e., dye penetrant testing, magnetic particle testing, ultrasonic wall thickness measurements, ultrasonic shear wave examinations, etc.) should be established for the detection and characterization of the anticipated damage. In addition, nondestructive examinations assist in the identification of locations for subsequent evaluation using metallurgical replication.

In general, examinations performed for the detection of macro surface-connected defects consist of dye penetrant testing and magnetic particle testing. The selection of the most appropriate technique is based on the materials of construction, available testing time, and desired level of sensitivity. The examination of nonmagnetic materials (austenitic stainless steels, nickel- and cobalt-based alloys, titanium, etc.) imposes the requirement for dye penetrant testing (PT). Many methods exist for penetrant testing of in-service components; however, the most common are visual and fluorescent methods.

For the characterization of component wall thickness, ultrasonic methods are almost exclusively used. However, a wide range of methods and equipment exists for these measurements. Specifically, wall thicknesses may be determined from simple hand-held meters that provide only a digital read-out of thickness at a single point. Alternatively, fully automated systems that include robotic scanners and digital data acquisition systems that provide two- and three-dimensional maps of wall thicknesses may be used. These automated systems are being used more extensively due to the increasing demand for rapid-scanning of large areas with readings taken at discrete intervals. Computer color-presentation of the data provides a convenient means to interrogate large volumes of data and readily pinpoint problem areas. Figure 1 shows some examples of how measurement data may be displayed. Computer data acquisition and archival capabilities also allow for the determination of component wall-thinning rates, using data collected over successive inspections. These wastage rates can subsequently be projected into the future to estimate remaining life.

To implement a current condition assessment and establish future serviceability, it is often necessary to detect and characterize volumetric defects, especially in weldments. In this case, the preferred examination technique is ultrasonic testing; specifically, either shear wave examinations or time-of-flight diffraction (TOFD). Both methods have the required attributes to detect and provide estimates of defect size, although to different degrees. Recent advances in both hardware and software have increased the inspection speed, detection limits, and sizing abilities of TOFD techniques, particularly multi-channel systems, making TOFD the preferred technique for detection inspections.

Characterization of detected indications refers to the evaluation(s) performed to quantitatively size indications. Characterization is an important step in the dispositioning of detected indications. The characterization should include identification of the nature of the indication (weld geometry, entrapped slag, porosity, cracking), the location of the indication (ID, midwall, OD, in the volume of the weld metal, or at the weld interface), and accurate measurement of the indication size (length and radial extent). The accuracy and confidence of subsequent analytical assessments, particularly fracture mechanics calculations of crack growth and time to failure, is highly dependent on the initial flaw sizes. The most quantitative NDE technique for these characterizations is currently focused ultrasonics. Examples of defect images using a focused UT inspection system with advanced image processing capabilities are provided in Figure 2. In addition to providing a presentation of UT data in a format that assists in the interpretation and sizing of indications, these images provide archival data that can be used with subsequent inspections to quantify damage growth predictions and refine remaining life predictions.

Metallurgical Replication

Replication is a field-implemented technique that allows for the nondestructive evaluation of material microstructure and metallurgical condition. In lieu of replication, a metallurgical evaluation of material condition or identification of damage mechanisms requires the removal of material samples from a component, submittal of the samples to a metallurgical laboratory, preparation and analysis of the sample, and repair of the sampled component; all tasks that require significant time and expenses to complete. Replication allows for the metallurgical analysis of large numbers of locations on a timely basis without the need for repair.

Metallurgical replication is performed following standard metallographic techniques used in a laboratory; however, replication is performed in-situ on the component under examination. Specifically, portable equipment is used for the grinding stages to prepare the surface for subsequent polishing. As with the grinding, polishing is carried out in progressively finer steps to remove scratches and eliminate artifacts that can interfere with detailed microstructural interpretation. After the polishing is completed, the prepared surface is etched with a suitable etchant solution to reveal the features of interest. Once the preparation is complete, a thin piece of acetate film is moistened in acetone and applied to the prepared surface. The acetate will conform to the surface, 'duplicating' the surface features. Once the acetate film is dry, it is removed and placed on a slide for analysis using a standard metallograph or portable microscope. Following proper procedures, replicas can be produced that can be interpreted using optical microscopes with magnification up to 1000X, or scanning electron microscopes with up to 5000X magnification.

The characterization of microstructures, with emphasis on identifying fabrication history (forging, casing, welded construction), heat treatment history (stress relieved, renormalized, as-fabricated), and typical structures (decarburization, quenched structures, long term spheroidization, graphitization) can be carried out on-site with the use of replication. Characterization can also include the separation of benign fabrication-induced defects (laminations, reheat cracking, slag, porosity, liquation cracking) from service-induced damage. Service-induced damage mechanisms could include spheroidization, graphitization, creep (short term and long term), fatigue (mechanical and thermal), hydrogen cracking, and corrosion. Each mechanism can be identified so that repair or reconditioning can be carried out only where necessary to minimize unnecessary maintenance efforts.

Metallurgical replication is used extensively for the evaluation of microstructural degradation in components (such as thermal softening, spheroidization, precipitate formation, graphitization, and decarburization) that occurs due to long term exposure to elevated temperatures. It must be realized that these changes could also effect critical properties (such as creep ductility and creep strength) of the material, and this can effect the service life of a component. These microstructural changes, once observed, can effect the material properties selected to be used in subsequent analytical assessments. Therefore, replication can provide assistance in the selection of critical material properties to be used in the analytical prediction of crack growth (fracture mechanics) or remaining life prediction (such as Larson Miller parameter for creep life in the absence of cracking). An example of microstructural degradation (graphitization) detected by replication in a carbon steel pressure vessel is provided in Figure 3. This replica was subsequently used in quantitative image analysis to determine the volume fraction of graphite nodules in the material and shape factors. These quantitative measurements became the baseline against which future inspection results could be compared to establish component specific degradation rates.

As an additional example, techniques are available for the use of replicas to predict the useful life of a component subject to creep damage. Specifically, creep is a progressive damage mechanism that begins in the incipient stage as isolated grain boundary cavities. As the damage progresses, the density of cavities increases until microcracks form. Microcrack development is then followed by macrocrack formation and propagation. Figure 4 shows creep voiding detected in a field replica.

Creep damage development can be described using qualitative or quantitative approaches such as the Neubauer System (Table 1) and Life Fraction System (Table 2), respectively. More specifically, the Neubauer system allows rapid classification of creep cavity and cracking that, when used with general correlations of life fraction, allows for the qualitative development of re-inspection intervals and serves as a baseline to estimate damage rates based on subsequent inspection results.

An alternate method that provides a quantitative assessment of damage state and progression is the 'A' Parameter approach. In the 'A' parameter method, quantitative metallography is performed on each creep damaged microstructural zone (i.e., fine-grained heat affected zone (HAZ), coarse-grained HAZ, base metal or weld metal) to statistically determine the number of damaged grain boundaries in the region of interest. The 'A' parameter is calculated from this statistical measurement of damage density, and compared to similar data generated from interrupted creep rupture tests to estimate a consumed life fraction and predict remaining life. Although the 'A' Parameter method requires more effort and thus increases the replication costs, it does provide an objective approach for classifying creep damage, minimizes differences between different inspectors, and provides for a quantitative measure of the change in creep damage between inspections.

Analytical Approaches to Condition Assessment

Analytical approaches to condition assessment may be employed prior to component NDE and/or metallurgical condition assessment inspections, to identify, prioritize and schedule critical components and component locations for inspection. More importantly, once examinations are performed and damage or cracks detected, analytical techniques allow for an assessment of the severity of the damage, and a subsequent decision concerning continued service, repair, replacement, and/or reinspection of the component.

As with NDE techniques, various techniques are available for analytical assessment of component life. For components subject to wall loss due to erosion/corrosion mechanisms, analytical-based life prediction may involve nothing more than a future projection of historical wall loss rates to estimate the expected time until wall thickness is reduced to a critical thickness for failure. The critical thickness for failure can be estimated via limit load analysis in consideration of material yield and tensile strength properties, geometry, and applied loads and stresses. For components subject to time-dependent failure mechanisms such as creep and fatigue, damage index (i.e., Life-Fraction-Expended) calculations may be performed to estimate the percentage of life consumed and the corresponding additional operating time for crack initiation. These calculations require knowledge of the component operating history (i.e., service hours and duty cycles), operating conditions (i.e., temperatures, pressures), stresses, and material strength properties.

For components with known or postulated defects (i.e., original fabrication-related flaws or service-induced cracks), analytical life prediction methodologies invariably rely on the concepts of fracture mechanics. These evaluations are intended to determine the following:

1) Critical Crack Size - This is the flaw size, or depth, for onset of rapid, unstable crack propagation leading to either a through-wall leak condition or potential

catastrophic failure. Depending on the component material, temperature and applied loads, unstable crack propagation and fracture may occur in a brittle manner, involving little or no plastic deformation of the material, or may occur in a ductile manner, involving appreciable plastic deformation. Linear Elastic Fracture Mechanics (LEFM) and Elastic Plastic Fracture Mechanics (EPFM) methodologies are used for the evaluation of brittle fracture and ductile tearing failure modes, respectively.

2) Subcritical Crack Growth - For detected flaws less than the critical crack size, controlled *subcritical* crack growth may occur during service due to creep, fatigue, stress corrosion or corrosion-fatigue. Predictions of this in-service crack growth rate, coupled with the calculated critical crack size and the anticipated operating interval until the next planned inspection, allow run/repair decisions to be made for detected flaws (i.e., what is the maximum size flaw which can safely remain in a component and not grow to critical size in the operating interval until the next inspection). For components with no known defects, it is common to perform crack growth evaluations for postulated defects with size equal to the minimum detection limit of the applicable NDE testing technique employed in the examination of the component. The results provide a quantitative basis for establishing safe reinspection intervals for damage-free components.

3) Leak-before-Break Potential - Once a flaw attains the critical flaw depth and subsequently propagates through-wall causing a leak, it may result in a sustained 'detectable leak' or in instantaneous rupture. EPFM evaluations can be performed to determine the critical length of a 'through-wall' flaw for rupture. Comparison of this critical through-wall flaw length to actual flaw length and depth dimensions determines the *leak-before-break* (LBB) potential of the flaw. Assurance of LBB reduces the risk associated with continued operation provided that a reliable means for early detection of leaks is available, and that a leak condition for a limited time period is not objectionable in the subject component (based on the contained fluid and other considerations).

Fracture mechanics technology has evolved over the past 30 to 40 years to specifically address components containing flaws and has gained wide acceptance in the power generation, aerospace, defense, automotive and other industries. Regardless of the industry, the component, or the applicable damage mechanism, a fracture mechanics-based evaluation requires input in three primary areas, namely; current flaw size, applied loads and stresses tending to initiate and propagate the flaw, and material behavior and properties for the component containing the flaw. Flaw size, shape, location and other characteristics are determined through NDE and metallurgical examinations as have been discussed previously. With respect to material behavior, typical properties required for a fracture mechanics analysis are as follows:

- Yield and Tensile strength
- Elastic-plastic Stress-Strain relationship
- Fracture Toughness
- Crack Growth Rate properties for fatigue, creep, stress corrosion or corrosion-fatigue, as applicable

Property data is available in the open literature for the majority of materials encountered in petro-chemical plant components, but, in many cases, can exhibit significant scatter. In the absence of component-specific data, evaluations can be performed using assumed 'worst case' properties from the literature, which produce conservative but reasonable results. In some cases, limited testing of the material may be possible, to provide evidence to justify the use of less pessimistic material properties. Examples are the use of replication to characterize the material microstructure, portable hardness testing, portable alloy analyzers, and removal of miniature samples for material testing.

With respect to stresses, through-thickness stress profiles at the known or suspected location of cracking in a component are required to determine critical crack sizes and in-service crack growth rates. In many cases, these stresses can be determined using standard closed-form solutions. A common example is the case of a pressure vessel, storage tank or other cylindrical component subjected primarily to internal pressure and possibly thermal transient loadings, and susceptible to cracking (caused by thermal fatigue, stress corrosion or corrosion fatigue) at circumferential or longitudinal seam welds. Through-thickness internal pressure stresses can readily be determined for this geometry using closed-form solutions. With knowledge of the expected magnitude and rate of temperature change, reasonable estimates of thermal stresses can also be generated using closed form solutions or available computer-based numerical techniques.

Geometric discontinuities such as thickness transitions, nozzles and other penetrations in pressure vessels serve as stress concentration sites where service-induced cracking is common. For such complex geometries, closed-form solutions are often not adequate for reliable prediction of stresses. In such cases, computer-based Finite Element (FE) modelling and stress analysis techniques are utilized for detailed determination of stresses. Figure 5 is an example of a FE model generated to determine stresses in a pressure vessel experiencing cracking in the attachment welds for a group of nozzles. Through-thickness stresses determined from this FE analysis provided input to a crack growth evaluation performed using a personal computer-based general purpose fracture mechanics program.

On-line Monitoring

In many cases, the service-induced damage and cracking experienced in plant components is strongly dependent on the time histories of process variables such as temperature and pressure. In such cases, stress analysis and fracture mechanics evaluations, as described above, can be performed using estimates of the most likely temperature and pressure operating conditions. However, significant improvement in predictions of damage accumulation, crack growth and remaining useful life can typically be attained, if account is taken of the exact temperature and pressure histories of the component. Computer-based on-line monitoring systems, which track process variables on a continuous basis and relate this data to stresses, damage and crack growth rates in the monitored equipment, have been developed in recent years for this purpose.

With respect to petro-chemical processing plants, these facilities are required to operate at high levels of availability/reliability (typically greater than 95%). For these facilities, the financial ramifications of an unscheduled or extended shutdown caused by a component failure or unexpected repair are large. The financial incentive further exists to increase the interval between plant maintenance shutdowns and to decrease the duration of these shutdowns. These conditions place increasing demands on condition assessment programs aimed at ensuring the safety, availability and reliability of plant components. The improvements in component life prediction and increased knowledge of detrimental plant operating conditions afforded by on-line monitoring can be used to optimize condition assessment efforts to meet these increasing demands.

On-line monitoring systems as described above have been developed and applied to the monitoring of critical plant components in nuclear and fossil utility power generating stations. With respect to fossil utility plants, the **Creep-FatiguePro** system developed by Structural Integrity Associates and the Electric Power Research Institute, tracks creep and fatigue life consumption in thick-walled plant components subjected primarily to pressure and thermal loadings. This system accesses instrument data such as temperature, pressure and flow rate from the plant computer system on a continuous basis, and processes this data to determine component stresses and creep/fatigue life consumption rates. Examples of typical stress and crack growth predictions from this system are shown in Figure 6. In addition to deterministic remaining life predictions, the software considers potential variabilities and uncertainties in the primary input variables such as material properties or current flaw size estimates. Probabilistic remaining life analyses accounting for this uncertainty can be performed and typical output is shown in Figure 7.

Geometry-dependent *stress transfer functions*, which convert instrument readings (i.e., temperature, pressure, etc.) to component stresses are specifically determined through closed-form solution or FE analyses, and placed in user-configurable databases for each **Creep-FatiguePro** installation. All material property data for creep and fatigue life consumption calculations are further maintained in configuration databases which can be modified or extended as necessary to suit a particular application. As such, the monitoring system can be readily adapted to petro-chemical plant components where service-induced damage can be related to process variables such as fluid temperatures, pressures and flow rates.

Summary

Condition assessment and suitability for service evaluations of critical plant components rely on an integrated program of nondestructive testing, metallurgical examinations, and analytical assessments of expected future damage accumulation rates. This paper has reviewed various alternative techniques available for these assessments as applied to petro-chemical plants. Ultrasonic testing techniques for monitoring component wall loss, and for detecting and characterizing fabrication or service-induced defects, have been discussed. The use of in-situ metallurgical replication for the detection of microstructural material degradation mechanisms has been introduced. Lastly, stress and fracture mechanics based life prediction techniques, and on-line monitoring options, have been reviewed.

TABLE 1
Neubauer Classification System - A Qualitative Approach

Level 0	New material.
Level 1	Service exposed, no detectable voids.
Level 2	Isolated creep voids.
Level 3	Oriented creep voids.
Level 4	Creep microcracking.
Level 5	Creep macrocracking.

TABLE 2
Life Fraction System - A Quantitative Approach

Damage Class	Consumed Life Fraction Range	Remaining Life Equation Minimum	Remaining Life Equation Maximum
1	0.00 - 0.12	$t_R=7.33t_S$	Unknown
2	0.04 - 0.46	$t_R=1.17t_S$	$t_R=24.0t_S$
3	0.30 - 0.50	$t_R=1.00t_S$	$t_R=2.33t_S$
4	0.30 - 0.84	$t_R=0.19t_S$	$t_R=2.33t_S$
5	0.72 - 1.00	Failed	$t_R=0.39t_S$

Where t_R is the remaining life and t_S is the cumulative service life of the component.

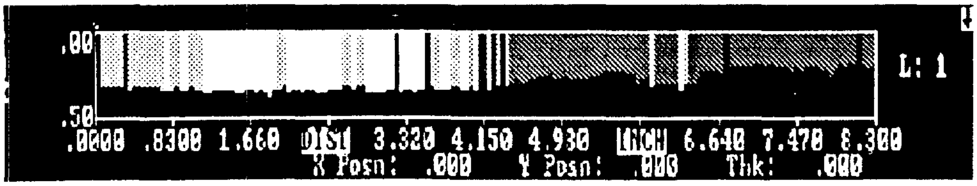

Figure 1A. B-scan of measured piping tube wall thickness

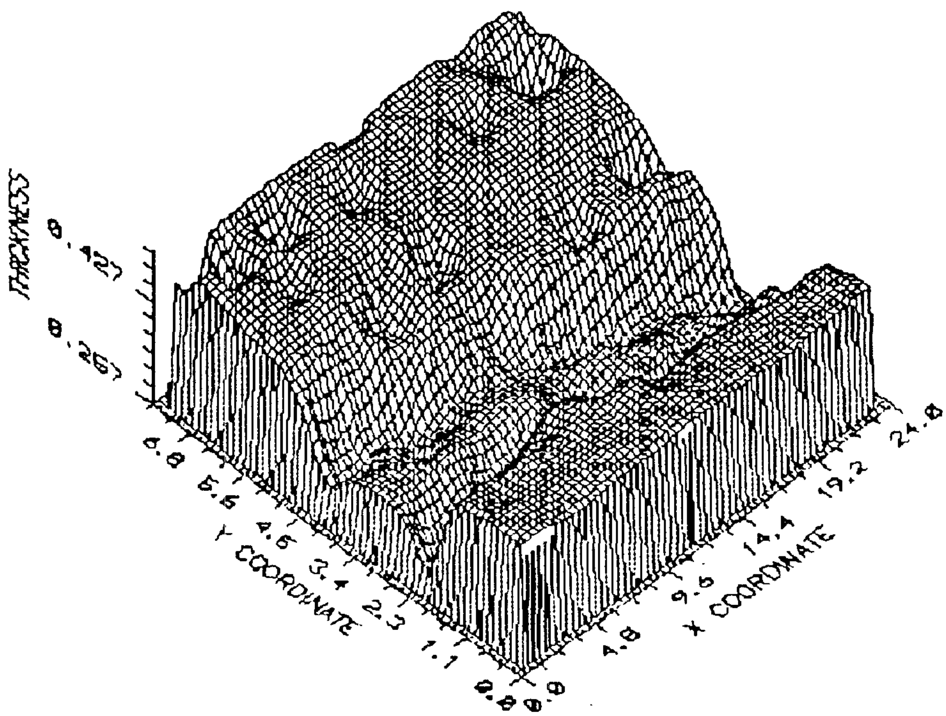

Figure 1B. 3-D image of measured piping elbow thickness

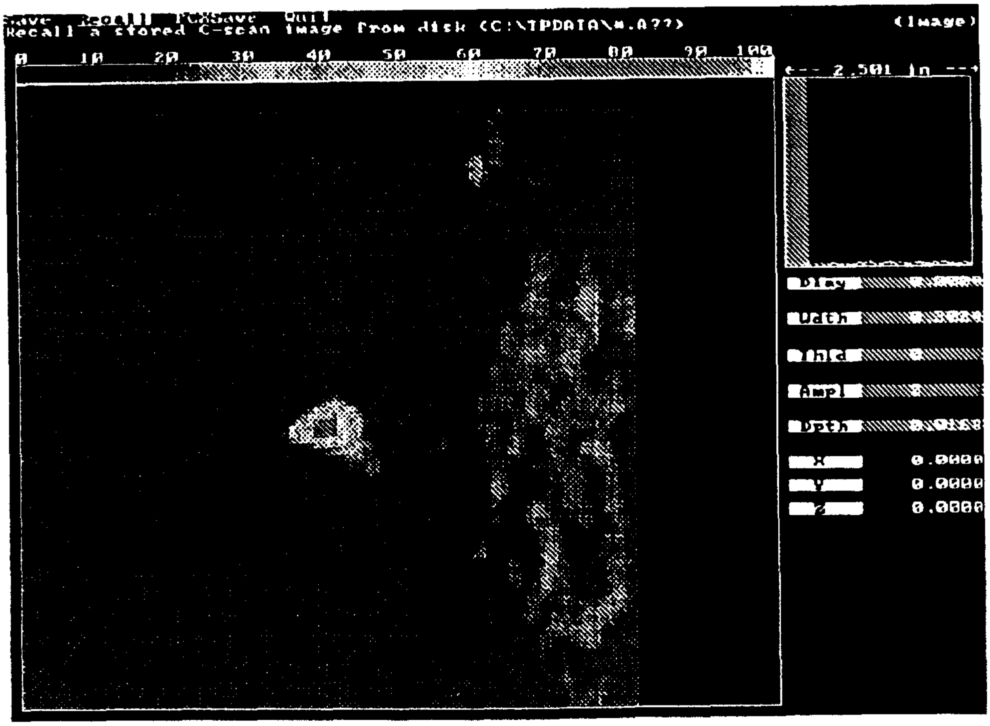

Figure 2A. Focused UT image of weld defect detected in a weldment.

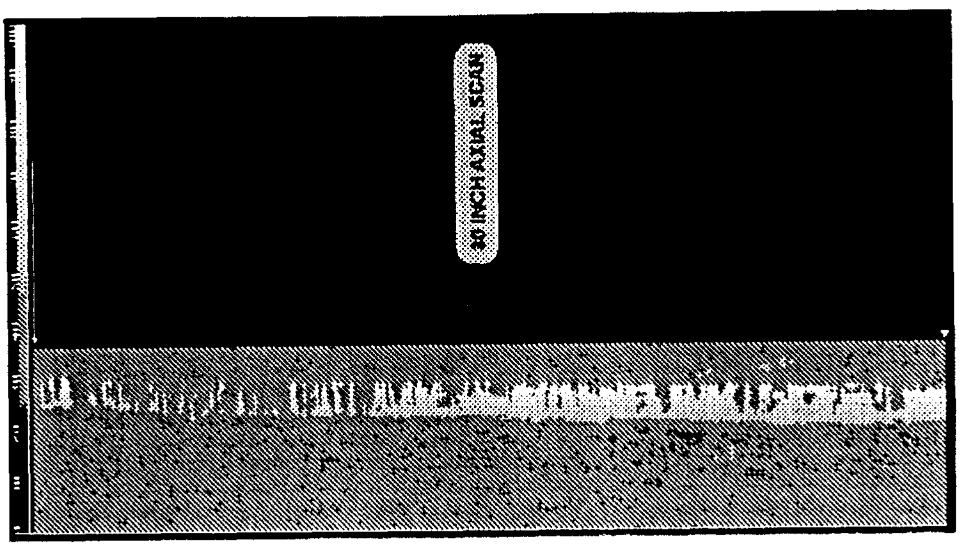

Figure 2B. Focused UT image of cracking detected in a service weld.

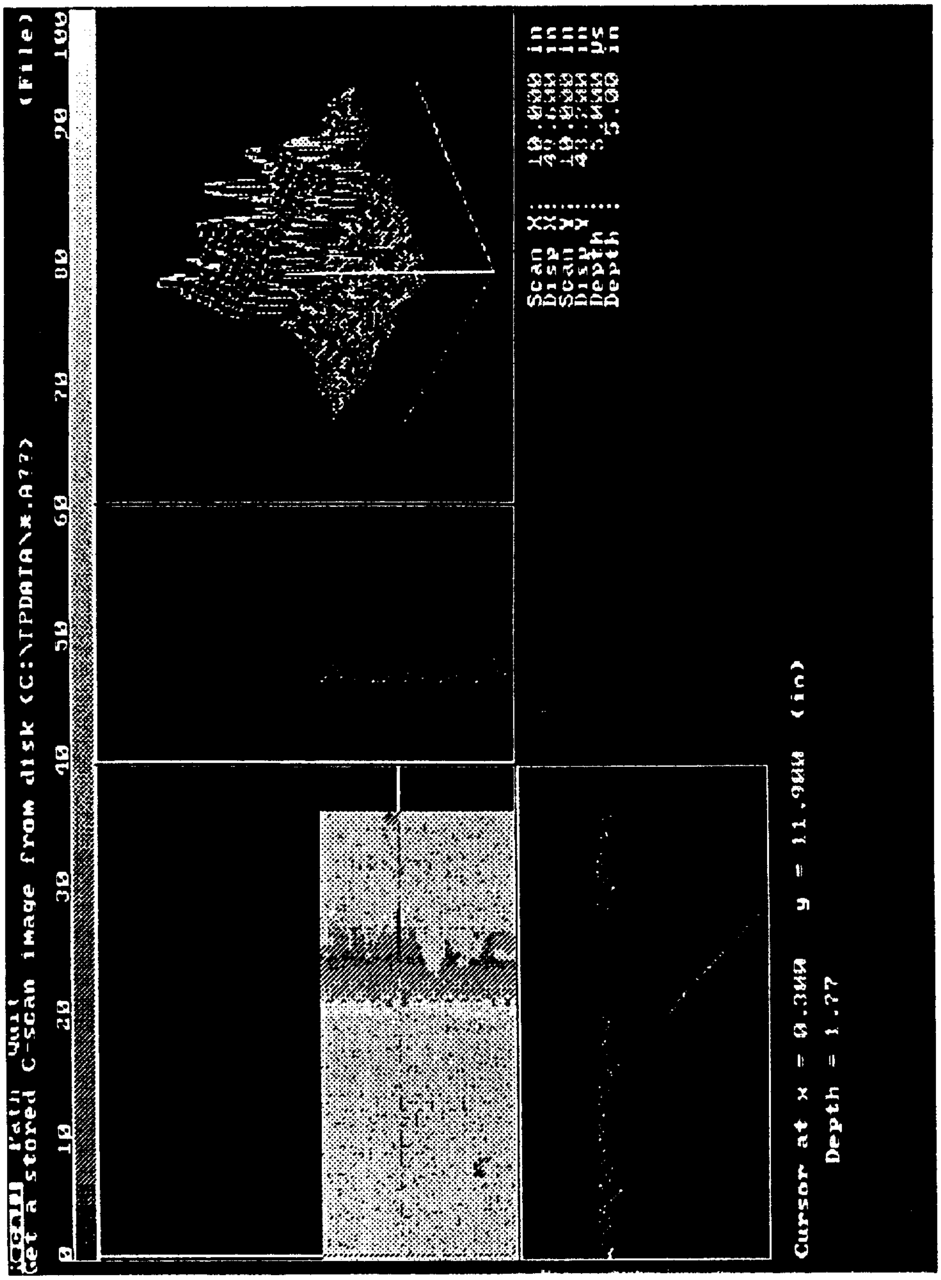

Figure 2C. Cracking shown by UT B-scan and 3-D imaging.

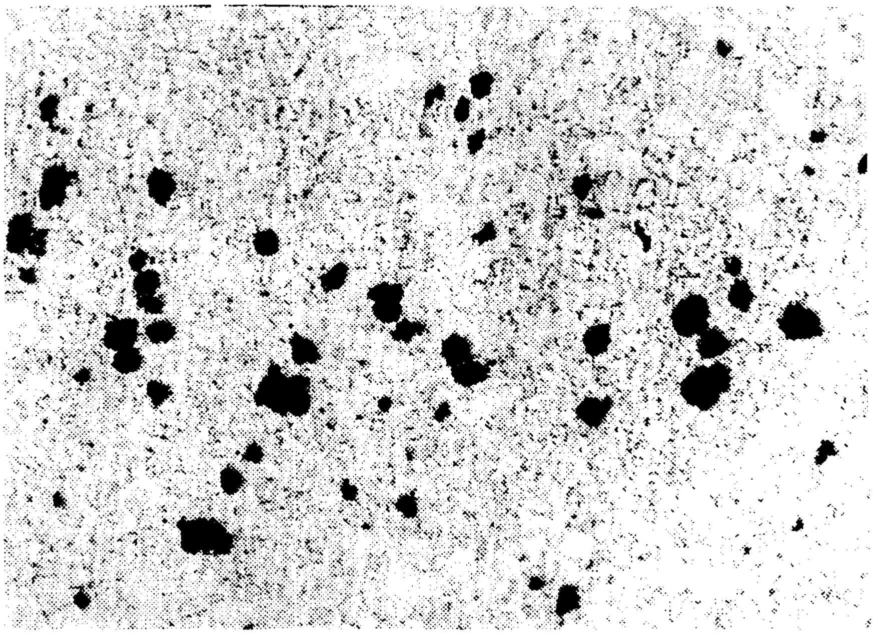

Figure 3. Replica Micrograph showing graphitization in a carbon steel vessel

Figure 4. Replica Micrograph showing microstructural creep damage

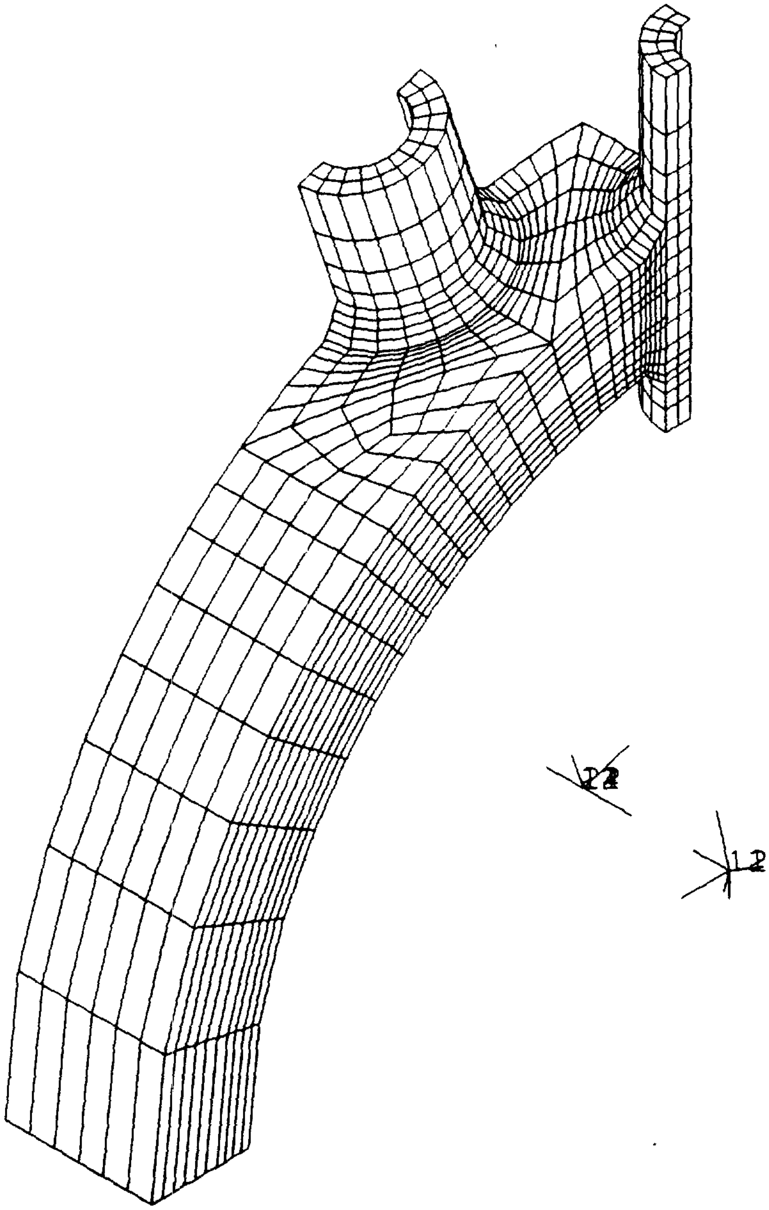

Figure 5. Typical FE Model used for Detailed Evaluation of Component Stresses

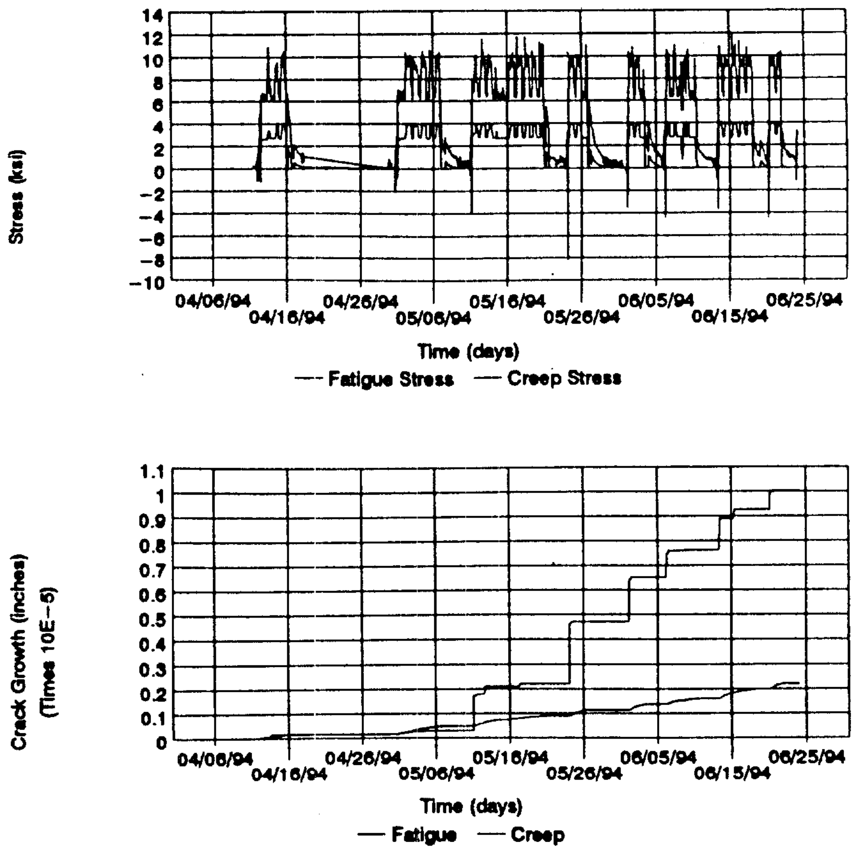

Figure 6. Typical Creep-FatiguePro Output for Monitored Stresses and Predicted Crack Growth

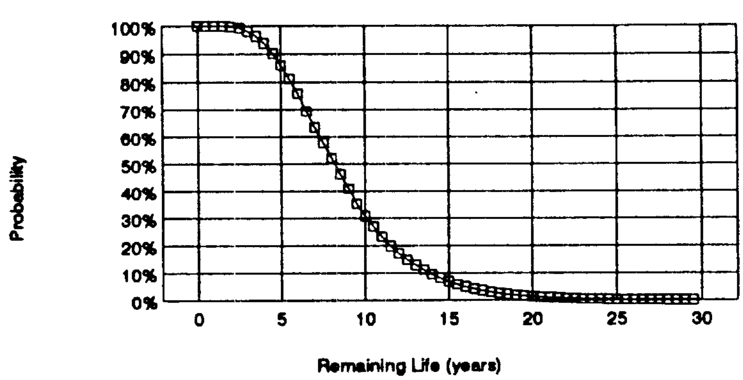

Figure 7. Typical Creep-FatiguePro Output for Probabilistic Remaining Life