THE FESI INTERNATIONAL BULLETIN ON STRUCTURAL INTEGRITY

Where Now For Structural Integrity - Michael Burdekin OBE, FRS, FREng,

Energy ~ Materials and Mechanisms - John Knott OBE, FRS, FREng

Development of Structural Integrity Assessment Technology and Methodology in China - Qun Peng Zhong, Academician of the Chinese Academy of Engineering Sciences

Volume 3 Issue 3

Contents

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EDITORIAL

This is the third issue of the FESI International Bulletin on Structural Integrity. The Bulletin is produced annually as part of FESI's role to provide a forum for exchange of information and experience in structural integrity across industry sectors. This issue contains a number of articles, including an overview on the subject by Professor Michael Burdekin, an HSE sponsored Guide to Plant Ageing authored by Dr Philippa Moore of TWI, and keynote papers by the co-chairs of the ESIA9 Conference, Professor John Knott and Professor Zhong. This Conference, held in Beijing in October 2007, was a major new venture for FESI in partnership with Beijing University of Aeronautics and Astronautics, and was supported by The Royal Academy of Engineering and The Chinese Academy of Engineering. Professor Su Jun Wu has provided an overview of the Conference.

In 2008, FESI organised three successful Professional Development Workshops; on Hydrogen Assisted Cracking (NPL), on Quasi-brittle Materials (Royal Academy of Engineering), and on Developments in Engineering Structural Integrity (University of Manchester). In this issue, there is a report on the RAEng meeting and on the panel discussion at the Manchester meeting. In addition, FESI has co-sponsored several events organised by other institutions and societies.

During the year we have welcomed two new corporate sponsors: Fraser-Nash Consultancy and The University of Sheffield. In addition, The Health and Safety Executive has become a named Supporter. Four new members of the FESI Council have also been appointed: Dr Phil Horrocks (ESR Technology), Professor John Yates (U Sheffield), Andy Holt (HSE), Keith Wright (Rolls-Royce).

EMAS Publishing, the publishing arm of FESI, has had a successful year with the publication of John Draper's book "Modern Metal Fatigue Analysis". Other books are scheduled for publication in 2009 and these will be detailed on our publishing website www.emas.co.uk .

All readers of the Bulletin are encouraged to utilise the network which is FESI and any questions, comments, and other contributions are always welcome.

Brian Tomkins

Who's FESI?

Over the past 10 years, a UK group of interested industry parties has organised a successful series of biennial international conferences, held on the subject of ESI, which has sought to examine the status of the technology and its effectiveness in application. More recently an associated programme of teaching seminars has developed, using senior expert academic staff, to propagate good practice and awareness in areas such as risk based tools and methods, and the quantification of failure. This collective experience has been brought together under the UK Forum for Engineering Structural Integrity (FESI).

The aim of FESI is to provide opportunity to facilitate the effective development and implementation of ESI technology across industry sectors. We believe that this will be achieved through the following means:

- The organisation of teaching seminars on developments in ESI technology and its application.
- The organisation of one day topical discussion seminars on interdisciplinary and/or cross industry sector issues in ESI.
- The organisation of specific industry discussions/meetings/seminars on ESI, on request.
- The organisation, as appropriate, of international Conferences in the UK on Engineering Structural Integrity Assessment concerned with the dissemination of ESI technology and its application across industry sectors.
- Liaison with other bodies involved in significant ESI R&D and applications programmes (e.g. EPSRC, European Structural Integrity Society (ESIS), EU/JRC Networks, International Institute of Welding).
- The organisation, jointly with collaborators, of similar national conferences/seminars in the UK and other countries.

Through these activities, the Forum seeks to encourage technology transfer across industry sectors and the development of technologies which will support the safe and cost-effective design and operation of major engineering plant, structures and components. Its activities will cover a range of industries including aerospace, petrochemical, oil and gas, power generation, automotive, transport and construction. Technology integration includes inspection, monitoring, diagnosis, analysis, materials, IT and assessment methods.

Who's Who on the FESI Council

There are four new members of the Council: Professor John Yates of the University of Sheffield, Keith Wright from Rolls-Royce plc who replaces John Howson, Dr Phil Horrocks from ESR Technology and Andrew Holt from the HSE (NII).

John Edwards MBE is a consultant with many years experience in testing technology, and was a lead assessor National Accreditation, Measurement and Sampling (NAMAS) in mechanical testing.

Professor Peter Flewitt FREng is Consultant Professor within Magnox North Ltd. He has worked on a range of structural integrity topics in the power generation industry amd undertakes research into fracture and locked-in stresses at Bristol University.

Dr Brian Tomkins FREng is a consultant and an expert in engineering plant integrity and safety.

Professor Ferri Aliabadi holds the Chair of Aerostructures and is the Head of Aerostruture Section at Imperial College, London. His particular expertise is in the areas of computational structural mechanics, fracture mechanics and fatigue, materials modelling, and boundary and finite element methods.

Philip Heyes is Head of the Engineering Control Group at the Health and Safety Laboratory.

Dr Phil Horrocks is the General Manager of ESR Technology's Asset Integrity Group. The group's activities encompass all aspects of integrity management in design and operation of assets predominantly in the Oil & Gas and Chemicals industries delivering projects ranging from high level integrity focused management consultancy to detailed assessment of defects and inspection technology performance.

Professor John Knott OBE, FRS, FREng is the Feeney Professor of Metallurgy and Materials at the University of Birmingham with a particular interest in fracture and crack arrest.

Dr Iain Le May is President of Metallurgical Consulting Services Ltd., Canada. He is a renowned expert witness in Canada and USA in the areas of materials and materials science, and the analysis of failures.

Dr Henryk Pisarski is Technology Manager - Fracture in the Structural Integrity Technology Group at TWI, Cambridge, UK, concerned with the application of fracture mechanics testing and flaw assessment procedures (Engineering Critical Assessments) to welds.

John Sharples is responsible for a team of fracture mechanics specialists working on various research and development projects including the R6 Development Programme within Serco Assurance's Structural Integrity Assessments Department.

Professor Andrew Sherry is the Director of the Material Performance Centre at the University of Manchester.

Professor David Smith is Head of the Solid Mechanics Research Group in Bristol University's Department of Mechanical Engineering with particular interests in fracture of materials and locked-in stresses in engineering components. He is also a non-Executive Director of VEQTER Ltd.

Professor Rod Smith FREng heads the Future Railway Research Centre at Imperial College, London. He is an authority on fracture and fatigue particularly in the Rail industry.

Dr Alan Turnbull is a Senior Consulting Engineer at the National Physical Laboratory, specialising in corrosion and fatigue.

Professor Gordon Williams FRS FREng is a Senior Research Investigator in the Department of Mechanical Engineering at Imperial College. He is a world expert on polymers.

Keith Wright is currently a Structural Integrity Specialist in the Nuclear Sector within Rolls-Royce and is the Structural Integrity Strategy Owner for the Naval Nuclear Research & Technology work. Keith has recently become an ASME committee member of the Design Analysis and Fatigue Strength subgroups.

Professor John Yates FIMechE, CE is Head of Mechanical Engineering Department at the University of Sheffield. He is Director of the White Rose Centre for Excellence for the Teaching and Learning of Enterprise, a Co-Director of IMMPETUS (Institute for Microstructural and Mechanical Process Engineering: The University of Sheffield) and Editor in Chief of the Blackwell Science international journal Fatigue and Fracture of Engineering Structures and Materials.

Andrew Holt is an Inspector of Nuclear Installations working for the Nuclear Installations Inspectorate of the Health and Safety Executive.

Where Now For Structural Integrity

Professor Michael Burdekin OBE, FRS, FREng

WHAT DO WE MEAN BY STRUCTURAL INTEGRITY?

It is necessary firstly to be clear on what we mean by 'Structural Integrity'. I take as a working definition:
"The ability of a structure or component to perform its required service duty safely for the required design life, taking account of all reasonable loadings and potential degradation mechanisms to which it may be subjected."
Thus the key requirements of ensuring structural integrity are

(1) a satisfactory basic design
(2) use of suitable materials
(3) satisfactory manufacturing and fabrication procedures
(4) control of operational conditions in service
(5) periodic inspections in service to check that no unexpected and unacceptable degradation is occurring.

Many of these requirements are encapsulated in design codes for specific applications, based on previous experience and established good practice. These considerations are almost invariably based on an assumed 'perfect structure or component', perhaps with some arbitrary allowance for tolerances in fabrication.
When it comes to consideration of the effects of imperfect fabrication or degradation in service, it is necessary to have a detailed understanding of the potential mechanisms of failure. Thus it is necessary to be able to consider the effects of physical defects of different types and the mechanisms by which they may grow, as well as changes in material properties that may occur in service. Some mechanisms of failure are controlled by crack tip stress fields or conditions whilst others are controlled by average stresses on the net cross section. This is where the experts in fracture mechanics play an important role. However in any structural integrity assessments it is essential that expertise is available in stress analysis, materials behaviour, non-destructive testing, failure mechanisms as well as overall design and service experience of the component or structure of concern. This will often require a team of different individuals to be assembled. Regrettably there are some occasions where erroneous conclusions are reached by an inexperienced assessor based on text book understanding!

RECENT TOPICS BY OTHER STRUCTURAL INTEGRITY COMMITTEES

TAGSI

TAGSI stands for the Technical Advisory Technical Group on Structural Integrity for the UK Nuclear Industry. The Main Committee consists of nine independent members and representatives from each of the sponsors: British Energy Group plc, British Nuclear Group plc, Ministry of Defence and HSE (Nuclear Installations Inspectorate). TAGSI responds to requests for authoritative guidance in response to specific questions raised by one or more of the sponsors. These responses are usually published in the open literature and form important contributions to statements of the current understanding of particular problems.
The following are examples of recent deliberations by TAGSI:

Fracture Toughness of Steels in the Transition Region
The 'Master Curve' representation of the variation of fracture toughness with temperature from the reference temperature T_0, includes an adjustment for the thickness of the component being considered, B, or more correctly for the length of crack front involved, as follows:

$$K_{JC}(B)=K_{min}+[31+77\exp(0.019(T-T_0))-K_{min}](B/25)^{1/4}[-\ln(1-p)]^{1/4}$$

TAGSI was asked to advise whether there was an upper limit to the value of 'B' that needed to be considered and whether there was a less conservative approach.
TAGSI's view was that an upper limit to the thickness/crack front length correction was reasonable. After examining a large data base of experimental evidence on A533B/A508 plate and forgings, TAGSI concluded that the Master Curve expression fitted the data for median toughness up to 100 mm thickness and $T_0 \pm 500^{\circ}C$ but that there was no consistent effect of thickness on lower bound fracture toughness.

Peer review of Impact Procedures
TAGSI was asked to review the nuclear industries R3 procedure for evaluating the likelihood of failure of steel and concrete structures under a range of hazards including missiles, whipping pipes and dropped loads. TAGSI was supportive of and endorsed the procedure for carrying out simplified assessments but considered that more sophisticated methods may be required and were now generally available for more complex problems.

Current work
TAGSI has been asked to comment on revised proposals for calculation of creep damage interactions with fatigue, in particular making allowance for dwell periods in the overall history. The proposed new approach is a stress modified exhaustion of ductility method that allows for whether the dwell period precedes or follows a maximum strain condition. It distinguishes between creep strains that occur under maintained stress conditions and those that occur as a relaxation under fixed displacement conditions.
TAGSI is also currently considering questions related to characterisation of defects and their interaction, and to the applicability of structural integrity assessments to fully ductile applications to ASME III.

GTAC

GTAC stands for the Graphite Technical Advisory Committee. It consists of nine independent members and responds to questions put by the Nuclear Installations Inspectorate on a wide range of issues concerned with graphite in Magnox and AGR reactors. Many of these questions have a structural integrity background and the committee involves members with a range of backgrounds from material aspects of graphite to stress analysis and structural integrity in steels and other materials. The problems in graphite are extremely complex and there is much to be learnt from the behaviour of these different materials. Yet the general structural integrity community and the graphite community seem to operate in independent arenas with little or no exchange of expertise except that achieved through the GTAC committee.

TAGSI SYMPOSIA

In alternate years, TAGSI organises technical symposia on structural integrity issues, the objective of which is to provide a forum for debate and exchange of experience across different industries. The following symposia have been held in recent years:

2003 - **Design Margins and Safety Factors Related to Structural Integrity**.
2005 - **Residual and Secondary Stresses in Structural Integrity Assessment Estimation, Measurement and Assessment**.
2007, the Seminar was a joint one between TAGSI and FESI on the topic **Structural Integrity under Dynamic Loading.**

ONGOING STRUCTURAL INTEGRITY REQUIREMENTS

The following brief notes are examples of the way in which structural integrity methods can and are being used and of potential requirements for ongoing research work.

Materials Aspects

Structural Integrity Assessment methods can be used to determine material property specification requirements for particular situations to suit design stress levels and standards of fabrication. This is particularly the case where new materials are proposed or where existing materials are proposed for new applications. An example of particular importance is the use of higher strength materials where determination of fracture toughness and fatigue crack growth properties should be regarded as an essential pre-requisite to use for new applications.

Dynamic Loading Aspects

The whole field of dynamic loading is a fruitful one for ongoing research into structural integrity assessment. Although there are improvements in simplified models and in the ability of properly constituted finite element analysis models to represent effects of dynamic loading on structures, only limited work has been carried out on effects of defects and degradation on structures subject to impact, earthquake or blast loading. Whilst there are general principles that there will be a dynamic amplification of stresses dependent on the ratio of the rise time or frequency of the applied loading to the natural frequency of the component, and the properties of the material may be strain rate dependent, calculation of specific cases with a broad frequency spectrum may be very complex. Simplified methods to determine equivalent maximum static loading conditions would be extremely helpful.

Residual and Secondary Stresses

Effects of residual stresses have been well known for many years (at least since the middle of the twentieth century). Yet there is still much research being carried out to try to predict the effects of residual and secondary stresses. Some older research workers may feel that this is an example of the wheel coming round again and younger researchers re-discovering things that have been known for years. However, this would be an unfair criticism. What is happening, and what is needed, is that the rapid improvements in the ability of finite element programs and high powered computers to calculate residual stress distributions and their effects are providing much better accuracy in predicting levels of residual stresses such that previous conservatisms may be reduced.

Fatigue and Environmental Crack Growth

There are still a number of failures that occur due to fatigue and/or environmental crack growth. Sometimes these are due to incorrect design assumptions. However, the interactions of particular materials with specific environments are such that this remains a rich field for ongoing theoretical research into mechanisms and experimental research into susceptibility and effects on growth rates. The problem of predicting accurately the effects of cyclic load interactions on rates of fatigue crack growth for specific load spectra, with or without environmental effects, remains one that has not been solved satisfactorily but is much needed.

Uncertainties, Risk and Safety Margins

The position will always remain that there are scatter in materials data and uncertainties in loading, stress analysis and assessment methods. It is therefore essential for structural integrity assessments to make appropriate allowance for such uncertainties without making excessively conservative assumptions that lead to unrealistic conclusions. The two approaches to this are either probabilistic fracture mechanics treatments where an acceptable probability of failure is linked to the consequences through a risk assessment, or the use of partial safety factors calibrated to achieve the same effect. There is ongoing scope for further development of both of these approaches, particularly in relation to less well developed areas of structural integrity assessment such as response to dynamic loading.

Strain Based Methods of Assessment

One of the disadvantages of the failure assessment diagram approach of the R6 methodology, also adopted in BS7910, is that the structure or component is deemed to fail by plastic collapse when the net section stress reaches to yield or flow strength of the material. There are situations where loading may be displacement or strain controlled and there are also cases where contained yielding may occur at local stress concentration regions or in redundant parts of the structure. In such cases the structure may have significant capacity beyond a condition where a simple local assessment deems it to be unacceptable. The original crack tip opening displacement 'design curve' from the 1970s related crack tip driving conditions to applied strain and to the size of crack present. A similar approach was published at the ESIA-5 conference in Cambridge in 2000, linking the applied J integral value at the crack tip to applied strain and defect size. There has been a recent addition to the R6 procedure document putting forward an approach for strain based assessment but this appears to require a specific finite element stress analysis to carry it out. I hope that the R6 panel will consider the alternative simpler approach from the ESIA-5 conference paper.

Education! Education! Education!

One of the problems that I meet fairly regularly is where people who do not understand the principles of fracture mechanics methods try to apply the BS7910 or R6 methods and get it wrong! There is no alternative but to ensure that there is an adequate supply of 'Engineers' who have included in their education a proper appreciation and training in structural integrity assessment methods. In the 2006 John Player Lecture to the Institution of Mechanical Engineers the author made the case for having at least one Masters course including specialist modules in structural integrity supported by those industries with a strong dependence in this subject area for safety or success of their business. I close by repeating this plea!

ESIA9 Conference - Report from Beijing

Professor Su Jun Wu

ESIA9 - 9^{th} International Conference on Engineering Structural Integrity Assessment, hosted together by the Chinese Academy of Engineering, the Royal Academy of Engineering, Beijing University of Aeronautics and Astronautics (BUAA) and the Forum of Engineering Structural Integrity (FESI), was held in the Conference Centre of BUAA from October 15^{th} to 19^{th}, 2007. The vice president of BUAA, Professor Xu Huibin, presided over the opening ceremony. The Academician of the Chinese Academy of Engineering (CAE), Chairman of the conference (China), Professor Zhong Qunpeng, made the opening speech, in which he highlighted the functions and significance of the Conference, expressed his high expectation for the success of the Conference.

Professor Q P Zhong
Academician of the Chinese Academy of Engineering Sciences
Co-Chairman

Professor John Knott OBE FRS FREng
Co-Chairman

Fellow of the Royal Society (FRS) and Royal Academy of Engineering (FREng) Professor John Knott representing RAE, the Academician of Chinese Academy of Engineering Professor Du Shanyi representing CAE, the president of BUAA and Academician of Chinese Academy of Science (CAS), Professor Li Wei, the Advisory member of ESIA9 Committee and Academician Gao Zhentong, the Secretary of Planning, Science and Technology Division of the State Administration of Work Safety, Mr Yang Fu, the Head of the Special Equipment Safety Supervision Bureau of the State Quality Inspection Administration (AQSIQ) Mr Zhang Gang, addressed the opening ceremony. The Conference Co-Chairman Professor John Knott (UK) presented the first conference plenary report titled "The Integrity and Durability of Structures and Machines", followed by other three Plenary Reports presented by Professors Dai Shuhe, Robert O. Ritchie and Zhong Qunpeng. Carrying the theme of "Engineering Structural Integrity-Research, Development and Application", the international conference held in BUAA was the ninth of such series with Xu Kuangdi being the Honorary Chairman, and Professor Zhong Qunpeng (China), Professor John Knott (UK) being the Conference co-chairmen. All areas related to the integrity assessment of operating factories and mines, structures, components and the like were discussed, including the technology, methods, criteria, management and regulations for assessment, referring to most of the main industrial departments as Aeronautics and Astronautics, Energy, Communications and Transportation, Mechanical, Petrochemical Industry, Civil Engineering and Construction. Over three hundred experts, scholars and students in this academic field from more than twenty countries attended this conference, including two academicians of CAS, three of CAEs, five FREngs (of which Professor John Knott also being a Fellow of the Royal Society (FRS)), one member of the National Academy of Engineering and one from Finnish Academy of Engineering. The conference proceedings are divided into two volumes containing three hundred and thirty-nine papers, some of which were going to be recommended to SCI journals to publish after formal review.

The conference lasted for five days, during which the representatives discussed structural integrity topics in sixteen sessions, paid a visit to the university and held an open discussion about the potential cooperation and communication and other issues interested in the future. In the end, about twenty experts were invited to a Panel Meeting for extensive discussions on the present development status, current issues and future direction and trends, which would be of great value for the subsequent researches and development of safe production and management of integrity. This Conference initiated a preliminary cooperation intention between China and other countries like UK, Germany, France, Austria, etc, paving the way for further cooperation and communication.

The ESIA Conferences are a series of international conferences themed on engineering structural integrity assessment and are regarded as one of the leading forums in this field, serving as a central communication platform for academia, industrial sector, regulatory system and standard institutes. The other eight conferences were all held in the UK and the ninth one was in China, providing us with a great opportunity to exchange most current achievements with other advanced countries.

Dr Su Jun Wu
Professor of Metallurgy and Materials Science
Beihang University
Beijing, PRC

The Opening Ceremony of ESIA9 - Engineering Structural Integrity - Research, Development and Application

Appreciation given to Professor Zhong's Plenary Presentation

FESI Seminar Reports

Understanding Quasi-Brittle Material and its Behaviour through Modelling and Probabilistic Approaches

5 June - Royal Academy of Engineering, London

A combined meeting of ESIS Technical Committee 12, (Chairman Dr R Moskovic), with a FESI Seminar/Workshop was organised by FESI on 5 June 2008 at the Royal Academy of Engineering in London. Approximately 30 people attended from the UK. The meeting addressed the issue of understanding quasi-brittle fracture of materials and their behaviour through modelling and probabilistic approaches.

In introducing the meeting the chairman Professor P Flewitt (Magnox Electric and Bristol University) identified several issues that needed to be addressed:

- Are we clear what materials fall into this category.
- What is the experimental evidence for this type of brittle fracture.
- Do we have adequate models to describe quasi-brittle fracture behaviour.
- Do we have input data for supporting and validating models.
- Is fracture data available for supporting deterministic or probabilistic structural integrity evaluations.
- Do we have appropriate procedures or methods for evaluating the safe and economic service life of structures and components.

Professor Bhushan Karihaloo (Cardiff University) introduced Session 1, **Quasi-Brittle Fracture Modelling,** with his presentation which posed the question -

What is Quasi-brittle Fracture and How to Model Its Fracture Behaviour:

"There are many materials of great engineering significance, e.g. concrete, that are regarded as brittle to be used only under compression. Yet when attempts were made as far back as the 1950s to apply classical brittle fracture theories of Griffith and Irwin to concrete, these proved unsuccessful in the sense that the onset of fracture could not be quantified uniquely by the critical stress intensity factor or the critical energy release rate (i.e. fracture toughness). It was however observed that the behaviour of hardened cement paste with its fine microstructure was close to the predictions of linear elastic fracture mechanics (LEFM), but the behaviour deviated the more from the LEFM predictions the coarser, or the more heterogeneous, the microstructure of concrete became."

Professor Ron Stevens, Bath University then went on to consider **Porous Ceramics**:

"Virtually all ceramics contain porosity often as a result of the manufacturing process but it can sometimes result from the starting materials. In engineering ceramics the nature and the amount of porosity present can have a significant effect on many properties of interest to the engineer; density, strength elastic modulus, fracture toughness, thermal conductivity and even machinability are of relevance. More recently porosity has been introduced into ceramics to control these properties and even used to induce biocompatibility into hydroxyapatite bone substitutes."

Dr Andrew Hodgkins of Serco TAS considered the **Behaviour of Graphite Fractures**:

"Graphite is often cited as a classic example of a brittle material; its strain to failure is commonly measured in fractions of a percentage. However the porous aggregate microstructure means that its fracture behaviour cannot be characterised well using Linear Elastic Fracture Mechanics methods."

Dr James Marrow of Manchester University concentrated on **Fracture Observation of Graphite**:

"Graphite is used as the moderator and also for structural components in first and second-generation carbon-dioxide gas-cooled nuclear fission reactors, such as the AGR reactors in the UK. It is also to be used in the next (third) generation of high temperature helium gas-cooled nuclear reactors. A well-founded, quantitative understanding of the behaviour of the microstructure under stress is important; a research aim is for the structural integrity of large graphite components of complex geometry to be predicted reliably from the assessment of relatively small test specimens."

Dr Gareth Neighbour, Hull University, began Session 2 - Structural Integrity Applications,with a presentation on **Mechanical Characterisation and Scale of Data Used in Assessments**:

"What do we mean by mechanical characterisation? Can a material be adequately characterised for a given situation? Material properties are often described as being characteristic and are quoted as such irrespective of scale. However, although the testing of materials is sometimes assumed to be a mature field, there are issues related to the appropriateness of the test, the inherent suitability of the assumptions in determining the material property value, and indeed inherent microstructure of the material concerned. Quasi-brittle materials by their very character show deviation from a truly elastic material and so challenge some of the assumptions being made

Dr Robert Moskovic of Magnox Electric considered the **Inputs of Integrity Assessment of Graphite Core Bricks**:

"The structural integrity leg used in the assessment of Magnox reactor core bricks has been described by Ellis and Staples. The arguments are based upon a comparison of the service stresses for the bricks and the strength of the material to establish a likelihood of cracking. To date no cracking has been observed within the bricks contained in operating reactors. The strength of graphite decreases with loss of mass by radiolytic oxidation. It is recognised that the PGA graphite used to fabricate the bricks can fracture in laboratory tests with quasi-brittle characteristics, namely the cracking is progressive stable and relieves stresses."

The final presentation was given by Professor John Knott of Birmingham University, who posed the question - **High Performance Engineering Ceramics: fact or fiction?**:

- The presentation highlights some aspects of the assessment of the fracture behaviour of brittle materials related to the theme of the meeting.
- Fracture under mixed mode (I and II) loading. Brittle fracture runs normal to the maximum principal stress and is governed by a critical value of this stress (examples: oolitic limestone, PMMA). The critical energy criterion based on a combination of K_I^2 and K_{II}^2 appears not to apply. Using results from experiments on ferritic steel, mixed mode testing can serve as a diagnostic to distinguish between fractures controlled by tensile stress and those controlled by critical shear strain.
- The role of (Weibull) volume sampling in (3-point and 4-point) bend and tensile test-pieces. The role of stress gradient here is contrasted with that of the non-uniform loading of surface–breaking cracks in stress gradients. A consequence of the tensile stress criterion for brittle materials is that, for cracks at an angle other than 90° to the surface, the mode I and mode II components of the stress field ahead of the crack need to be evaluated separately and subsequently combined. Choice of the more appropriate approach plausibly relates to the size of the fracture-initiating defect, relative to a). the size of the test-piece; b). the scale of the 'micro'-structure.

- The general principles are examined for the specific case of a SiC ceramic, tested in uni-axial tension, in plain 4-point bend, and in pre-cracked SEN 4-point bend fracture toughness tests. Comparisons of the K_{Ic} values and the bend strengths suggest a critical defect size in the range 7-24 mm (99%/1% limits), mean 10mm, comparable to the grain size of the material and very much smaller than test-piece dimensions. Concomitantly, comparison of 4-point bend and tension results supports the volume sampling argument.
- Some examples are given of ceramic matrix composites (CMCs) in modern aerospace applications. Finally, the proposal is made that there is a good case for using SiC/SiC CMC turbines in helium-cooled high temperature ("Generation IV") nuclear reactors."

Presentations were followed by a discussion led by Prof. J Knott with contributions from, in particular, Professors Gordon Williams from Imperial College and David Smith from Bristol University. It was concluded that unlike brittle materials, quasi-brittle materials exhibit tension softening which is characterised by increase in deformation with decreasing tension capacity past the ultimate strength. This is one of the main reasons for the lack of success of LEFM in explaining the behaviour of quasi-brittle materials. Scaling of strength measurements obtained on laboratory sized specimens to structural components is one of the main challenges that need to be resolved for these materials.

Poul Gosney
FESI

Developments in Engineering Structural Integrity

19 November 2008 - Manchester
Round Table Discussion
Chair: Dr Brian Tomkins
Panel: Prof Peter Flewitt (Magnox North Ltd and Bristol University), Dr Phil Heyes (Health and Safety Laboratories), Dr Iain Le May (Metallurgical Consulting Services, Canada), Mr Keith Wright (Rolls-Royce plc)

Programme

09:45 **Introduction – Where are the challenges coming from?**
Dr Brian Tomkins – FESI
Andrew Holt – HSE

10:25 **Current Structural Integrity Assessment Procedures – BS 7910, R6, FITNET and API 579**
Dr Isabel Hadley - TWI

11:05 **Non-Destructive Examination – what are we doing to improve input data for methodologies**
Bernard McGrath – Serco
Prof Chris Scruby – RCNDE/Imperial College

11:45 **Fracture Mechanics-based Methodologies – identifying weaknesses and challenges**
Prof Andrew Sherry – University of Manchester
John Sharples - Serco

13:30 **Residual Stress – accommodation in assessment methodologies**
Prof Phil Withers – University of Manchester
Steve Bate - Serco

14:10 **Risk Based Methodologies/Life Management**
Dr Phil Horrocks – ESR Technology

14:50 **Corrosion – management and mitigation of corrosion, particularly in the chemical and process industries**
Pauline Parker - ABB

15:45 **Round Table Discussion – Chaired by Dr Brian Tomkins**
Panel members will include: Prof Peter Flewitt FREng, Magnox Electric; Dr Phil Heyes, HSL; Prof Iain Le May, MCS Ltd; Keith Wright, Rolls-Royce

Following Dr Brian Tomkins' introduction, Prof Peter Flewitt opened the Round Table Discussion by thanking all concerned for their excellent presentations. Prof Flewitt drew attention to a theme which had emerged from the day's workshop presentations: an emphasis on the need for an integrated approach when assessing the safe and economic operation of plant. Prof Flewitt referred to Mr Andy Holt's discussion of his HSE experience in a regulator's view of assessment tools and their application, which highlighted the need for organisations to achieve a balance between a robust safety culture and the economic drivers of their business competitiveness. Another recurring theme noted by Prof Flewitt was the requirement for a system of structured feedback with regard to emergent problems identified during the assessment process, and he suggested that FESI could have a role in the dissemination of learning derived from this source.

Prof Flewitt challenged the audience to consider the maturity of the discipline of Structural Integrity (SI):

- Was it their perception that the workshop had covered the full range of SI challenges existing within their organisations, or were there yet other issues to be addressed?
- What were the specific issues concerning their organisations' safety culture?
- Where are the audience's organisations positioned in terms of their safety culture?

Prof Flewitt went on to say that mechanistic and microstructural understanding needs to be enhanced in order to underpin failure-avoidance practices and that, overall, the success rate of failure avoidance needs to be improved. In general the engineering and technological communities are good at explaining failures but less able to predict overall of components and structures, hence the need for appropriate safety factors in codes and procedures.

Mr Holt responded that mechanistic modelling did indeed increase understanding and he emphasised, as he had in his presentation, how important it is that SI and industry codes should not be 'blindly applied' in organisations. He identified one positive outcome of improved mechanistic understanding as the increase in operators' confidence in their tools, and another as the accumulation of accurate information about the residual stresses in welds and in the practice of welding, both for assessment and in design. Mr Holt went on to say that SI is a strong 'supporting leg' for safety models.

Mr Keith Wright gave a summary from Rolls Royce's perspective on Structural Integrity, which is awarded a high priority within the organisation. He went on to comment that Design Codes (e.g. ASMEIII) assume that structures are defect-free but, to demonstrate a higher level of reliability ('incredibility of failure') than can be claimed from code compliance alone, then there is a need for defect tolerance assessments via the R6 failure avoidance procedure in the structural integrity assessment. The UK is investing in the next generation of nuclear submarines and the requirements of a modern standards safety case have led to a significant investment in terms of R&D expenditure. The design of the vessels needs to include a design of welds for reduced residual stresses and Rolls-Royce is working in partnership with Serco to be able to deliver this. The investment in SI is in excess of £10m per annum which includes research on various issues including environmental effects. Environmental fatigue evaluations, using some of the latest design curves with a dependency on strain rate amongst others, suggest increases in fatigue usage factors of x15 to x20 but this has not been reproduced in real plant operation. Hence the support to the need identified in Prof Andrew Sherry's presentation, Fracture Mechanics-Based Methodologies, to investigate the behaviour of real materials containing real defects under real loading conditions, and the need for the testing of representative component features. He also pointed out that design codes such as ASMEIII included design by analysis methodologies based on 1960s technologies. There is much work to be done to update the codes and their acceptance criteria in particular for application to 3D finite element models

Mr Holt commented that different industries have different perspectives and hierarchies of needs. While SI is a high priority at Rolls Royce and the nuclear industry in general, it is, unfortunately is not regarded as important at a senior level in other organisations. Mr Holt emphasised that SI must be seen as a vibrant community and not given mere lip service. It is not HSE's role as a regulator to prescribe to organisations, but it is the job of industry and academic bodies to decide where SI goes from here. HSE supports industry in a manner consistent with its remit and has produced pamphlets intended to disseminate the HSE's learning on various topics including RBI, and it pump primes projects such as PANI 1, 2 & 3, discussed in Mr Bernard McGrath's presentation, Non-Destructive Examination.

Dr Phil Heyes commented that risks do not remain static, and that risk must be assessed as "low as reasonably practical for today". Dr Heyes referred to the mining industry, which still uses codes developed in the 1950s although these have not been reassessed to take into account the numerous developments in practice and technologies.

Dr Iain Le May addressed the need to use tested techniques such as metallography in fracture mechanics and to tie these techniques in with inspection procedures. A further issue for the industry is, he said, the tolerance assumed in industry codes for 'no defects'; not only is this impossible to achieve, but codes continue to specify this although it is clear that in reality there can be no such thing. This ambiguity can have significant implications, one instance of which being when failures lead to legal interventions. Dr Le May cited two legal cases on which he had consulted, where complications arose from the inadequate wording of codes. He suggested that codes and standards must be much more considered in their phraseology and need to be more specific to retain their relevance. He commented further that while RBI itself cannot assure risk avoidance, it has a role in risk reduction.

Mr Holt reiterated the message from his presentation: organisations must apply SI for "the right reasons".

Dr Le May raised two further issues; namely that 1.- in industry there is only a limited time window in which inspections can take place, and as an outcome the reality is that not all defects can be discovered or will be identified, and 2.- there is a need to maintain and keep proper records so they can be referred to later.

Dr Heyes agreed that there is a need for inspection records to be accurate, and added that he had witnessed instances where inspection records had contained fictitious information.

Dr Le May commented that he had seen cases where inaccurate inspection records had been carried forward without amendment and were thus useless in the identification of subsequent problems.

Prof Flewitt threw a question open to the floor: Why are probabilistic methodologies not, apparently, being developed?

Dr Isabel Hadley, TWI, responded that she was not aware of any developments, but confirmed that there is a need research in this area. She mentioned that a deficiency in assessment methodology is because there is no lower threshold for measurement, as in, for example, fracture toughness, where there is no lower band. Dr Hadley also emphasised the need to acquire the correct input data for use in these assessments. At present such data are limited.

Dr Tomkins introduced a philosophical discussion regarding the nature of engineering: in the past assessment factors had been dependent on and derived from 'expert opinion' and experience from within the industry, and assessment methodologies reflected this. Now, however, there is a need for quantitative and mechanistic methodologies, and meanwhile NDE and other analyses must be much more rigorous. Traditionally, engineers tended to focus on and work within specific industry sectors and thus accumulated a broad experience base; latterly this was supplemented with technical underpinning. However, now the industry is increasingly technology-driven and there is a need for sound scientific knowledge.

Dr Heyes commented that this appeared to be the case in the railway industry, where it seems that aspects of SI are considered to be covered, by and large, by the experiential knowledge of employees.

Dr Tomkins indicated that he saw a need for the engineering industry to find mechanisms for sharing their learning across all sectors.

Dr Le May commented that there is also a need for quantitative methods of data collection, and he questioned the quality of materials available today: What are their properties? How reliable are they? He stated that there is a constant worry about getting materials with the right properties for purpose, and noted that inferior products are sometimes passed by quality control but these are often for an organisation's export market.

Dr Heyes suggested that it would be appropriate for FESI to run an SI workshop which drew in all industry sectors, so that their experiences could be exchanged and shared. He indicated that the HSE has spent some £40m on pump-priming and other activities and, although not intended to solve industry's problems as that is not HSE's role, the focus was on assisting an improvement in performance. Dr Heyes raised two further concerns; 1, the role of 'human factors' in NDT because of the variability of the inspectors' performance, and 2, how it would be possible to raise the quality of human performance.

Mr Bernard McGrath, Serco, responded, that when his project team canvassed NDT vendors, the biggest issue identified was the lack of information from clients. He suggested that there is an urgent need to improve communications between practitioners and clients.

Prof Chris Scruby, Imperial College, London, raised a further issue which will impact assessment: demographics. Current NDT inspectors will not be around in ten years time. Low-cost, automated assessment techniques are currently being researched to good purpose but, he noted, the continued development of high-end solutions will raise standards across the board. Ultimately, solutions will determined by market size because of the cost implications.

Dr Heyes asked if a way of addressing the 'human factors' issues in assessment might be by having an accreditation scheme for inspectors, and wondered if there are any courses which currently offer such accreditation.

Dr Tomkins responded that, historically, this was not a component of engineering courses.

Prof John Yates, Sheffield University, commented that this is a supply and demand issue, and that in general the level of awareness is not high. He noted that there are two issues to be considered: 1, there are very few home students with the necessary funding, and 2, what should the educational focus of SI be – what should its content be, and how would it be assessed? Exams may not be a realistic means of assessment.

Dr Tomkins noted that there is a need for a much better connection between industry and education.

Dr Hadley offered that the Open University has available a module in SI, but that it probably does not exist at graduate or post-graduate levels.

Prof Flewitt noted that a Structural Integrity course must be truly multi-disciplinary, and include an NDT side. While conservatisms should be built in, it is still necessary to determine the correct level of conservatism.

Mr Wright, Rolls-Royce, pointed out that the University of Strathclyde is involved in hosting a new series of Structural Integrity webinars that covers all the elements of the SI field. Roll-Royce has recently made use of this.

Dr Tomkins reverted to discussion of the proposed FESI cross-sectoral industry workshop: Would there be a demand? What should the course structure be?

Mr Wright commented that there is a difficulty in finding graduates with experience in Engineering Critical Assessments. (It is a term used in BS7910 for a fracture assessment.)

Dr Tomkins asked where consultancy personnel come from?

Dr Phil Horrocks, ESR Technology, replied that in his experience they are difficult to find, and his organisation is constantly seeking to locate suitable personnel.

Dr Tomkins related how useful he continued to find Prof Michael Burdekin's 20-year old notes on SI and the range of issues they covered, and wondered if they could be used as the basis for a customised SI course.

Dr Horrocks commented that there is a perception that SI will be applied in-service, whereas most companies don't carry out maintenance in-service, and this acts as a barrier to the application of SI.

Dr Tomkins replied that this barrier to SI is being eroded. There are OEMs at design base, and the growth of consultancy and technology support has aided with SI participation.

Andrew Wasylyk, a PhD Student delegate from Manchester University, described the SI perspective from his viewpoint as a recent graduate. He drew attention to the need to raise awareness of SI within universities: What do graduates either see or know of SI? Where can they go to find out about research and job opportunities? Moreover, what would an SI engineer actually do? What would the job entail? He suggested that there is a need for the SI community, and FESI, to connect with under-graduates and recent graduates.

Prof Chris Scruby commented that while available funding is mainly directed at ESRC, they will sometimes lend an ear to industry. There are, however, schemes such as the four-year EngDoc award , an alternative to the traditional PhD, which is aimed at post-graduates who wish to pursue a career in industry. EngDoc opportunities exist in Manchester and Birmingham Universities. EngDoc centres are attempting to provide some of the outcomes discussed around the table; however, these centres are not increasing in number and someone must lobby for this to happen. Prof Scruby suggested that this might be a task for captains of industry, as they will need to address the skill shortage which will result from a shortfall of suitably qualified personnel for industry.

Dr Tomkins regretted that the time allocated for the Round Table Discussion had expired. He noted that the discussion indicated that there is potential for a number of publishing opportunities for FESI, including the development of practical handbooks and manuals. He encouraged those present to liaise with FESI, who would appreciate the audience's input and suggestions. He reminded the audience that FESI is a not-for-profit organisation owned by its members, and therefore all profits are fed back into the organisation for its benefit.

Prof Flewitt commented in closing that FESI has a role in addressing the key issues raised and in disseminating learning about them to the wider community involved in SI.

Dr Tomkins agreed, with the caveat that it is not FESI's role to launch a new journal.

Dr Le May noted that FESI could add value to its activities by providing updated references to SI drawn from various existing journals and conference proceedings.

Dr Tomkins encouraged everyone present to send information on these and the other issues raised during the day to Mr Poul Gosney at FESI. He asked delegates to note that the FESI website at is becoming increasingly interactive and could provide a useful resource.

Prof Flewitt closed the Round Table Discussion with a reminder that the FESI Conference, Engineering Structural Integrity Assessment: Present Goals – Future Challenges, will take place in Manchester on May 19 and 20, 2009. He added that, in the light of the remarks about student participation and the need for their raised awareness of SI, as many students as possible should be encouraged not only to attend the conference BUT also submit papers. As an incentive, he confirmed that there is a cash prize to be awarded to the best student paper/presentation at the conference and that the Conference Organising Committee was still accepting Abstracts. For all Conference information go to the FESI website.

Finally he said that the notes of this discussion would be recorded and made available to all attendees.

Elisabeth Deckker
Metallurgical Consulting Services Ltd, Canada

Energy - Materials and Mechanisms

Professor John Knott OBE, FREng, FRS

Introduction

The paper describes some of the main changes in the UK energy strategy which have taken place over the last ten years, leading in 2001 to a 2025 vision of approximately 80% electrical generation by gas, and the rest by a combination of renewable sources and imports, with only a small amount of nuclear generation [1]. By 2006, this vision has been modified to countenance the possibility of a higher proportion of nuclear [2]. There is likely to be a shortfall between demand and supply over the next 5-10 year period, which provides incentives for “plant life extension” of existing systems, but justification for life extension must be set in the background of the recently introduced New Electricity Trading Agreement (NETA), the effect of which is potentially to increase the amount of cyclic loading experienced by plant. The effects of such operation, and other materials issues relating to life extension, are described for two main generation systems: gas turbines and pressurised water reactors (PWRs). Some attention is paid to advanced nuclear systems and to renewable sources.

Socio-Political Background

At the beginning of the 21st Century, the UK Government's vision for electrical energy supply up to 2025 was based on a DTI document [1] which indicated a running-down of coal-fired stations to zero (oil-fired stations having already been eliminated), an increase in gas-fired systems to generate some 80% of the total, nuclear down to about 3% (Sizewell B), and the remainder coming from renewable sources (mainly wind, possibly some wave power, solar cells) and imports. The DTI document also pointed out that demand for North Sea gas would exceed supply in 2006/7, but gave an arguably optimistic view of future gas supplies: from Norway/The Netherlands; from Russia; from Libya and Algeria. These options were not examined critically in terms of either the future cost of gas, or of the security of supply. One consequence of this vision was that wind-farm schemes were given financial incentives by the Government. Pleas from the nuclear licensees to maintain the nuclear contribution at ~20% (the existing figure at the time) were effectively ignored. Although one of the drivers was the commitment given by Britain to the Kyoto Agreement, analysis of the effects of the strategy on carbon dioxide emissions was not fully considered: replacement of coal by methane reduces emissions, but replacement of nuclear by methane increases emissions.

Five years later, there has been a re-appraisal of the strategy, spurred by a sharpened perception of the need for adequacy and security of gas supply. A point that has not been made strongly is that, in an overall supply system including, say, 10% wind-power, there needs to be 10% over-capacity available to draw upon at times when the wind-power fails. This is likely to pose problems for a fully devolved, privatised power industry, not necessarily identified with altruistic principles; in particular for companies who could feel aggrieved that wind-power had already benefited unduly from Government measures. The nationalised CEGB had a remit to generate a supply of electricity adequate for the nation's needs, in a safe and efficient manner. It is not clear who now bears this responsibility: if it is a body such as OffGem, it is not clear how it can actually fulfil its responsibility. In 2006, the Government instituted a major consultation on how to address energy issues, one result of which was to countenance the possibility of 'new build' nuclear generation plant [2].

It is within the background of this socio-political framework that I address issues of modes of electrical power generation, the demands on materials that these place, and the consequences with respect to through-life management that are then implied. It is clear that the main means of generation will be gas-fired stations; but there is the issue of 'open cycle' or 'combined cycle' operation. It is likely that nuclear 'new build' will become reality, but crucial planning time has already been lost, and it is unlikely that much new plant will be delivering power before 2015. There could well be an increasingly significant shortfall between demand and supply from now until that time and there will therefore be increasing efforts to 'fill the gap' by 'plant life extension' of existing plant, whether fossil-fuelled or nuclear.

Plant life extension implies operation beyond the original design intent and therefore invokes revisiting the safety-case assumptions relating to structural integrity assessment, inspection and monitoring. These issues, and those relating to design life of new systems, are compounded by a relatively recent change (NETA) in the system for pricing electricity, which is now 'traded' in half-hour slots, bid for 3.5 hours before delivery. This system is applauded by some main customers, such as hospitals/NHS, but provides serious problems for through-life management of older plant. Up to the mid 1990s, the management, by the CEGB, of electrical power provision followed a standard pattern. The main, day-to-day provision was carried by 'base-load generators': nuclear and large (efficient) fossil-fuelled stations. When demand increased, due to predictable events (such as colder winter temperatures), less efficient, smaller, fossil-fuelled stations were brought in to meet demand, and, for sudden surges, such as half-time at a televised Cup-final, (open cycle) gas-turbine generation would be used to 'top-up' the supply. The NETA 'trading' arrangements and a privatised industry, only some of which combines generation with a customer base, have changed this situation dramatically. The demands to 'trade' in short time-slots makes it near-impossible for large units to come 'on-steam' and 'off-steam' with sufficient rapidity. The result is that 'open cycle' gas turbines, which can respond rapidly (within a minute) to changes in demand tend to be seen as more attractive than conventional, fossil-fuelled or nuclear systems.

In addition to these general concerns, there are issues relating to the efficient generation of electricity by turbo-alternator systems, whether gas-turbines or steam- turbines. The maximum thermodynamic efficiency is given by {(T_{max} T_{min})/T_{max}}, where T_{max} is the entry gas/steam temperature and T_{min} is the exit temperature. The newer CEGB steam turbines, having a high-pressure steam temperature of 565˚C, achieved some 40-45% efficiency and this is matched by Advanced Gas-cooled nuclear reactors (AGR), which were designed to deliver steam at the same entry temperature. The Magnox nuclear stations and the Sizewell PWR achieve efficiencies of order 30-32%, because the steam temperatures are significantly lower, approx. 300˚C. Although gas entry temperatures for the gas-turbine (GT) are very much higher (see below), the efficiencies achieved in 'open cycle' operation are again only of order 30-33%, because the exit gas temperatures are high, approx. 500˚C. Efficiencies up to 60% can be achieved by operation in 'combined cycle' mode, which involves passing the hot exit gas through steam generators and coupling the GT to a steam turbine (see fig.1). The disadvantage of this is the loss of flexibility to respond rapidly to changes in demand through the NETA trading system. In terms of both economic use of gas and reduction in emissions per kW generated, combined cycle systems would seem to be the obvious, 'prudent' way forward for the nation, but the 'free market economy' tends to adopt a short-term, parochial response. The consequence is that much 'open cycle' (rapid response) operation is likely to continue, despite the lower efficiencies. If there are serious shortages in electricity supply in the 5-10 years horizon, there may be continued operation, even of coal-fired plant, because the nation has become extremely reliant on the continuing provision of electrical power: as one example, all e-mail communications (banking, on-line purchasing, travel bookings etc.) are utterly dependent on the supply of electricity.

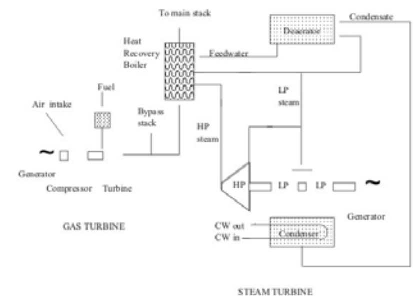

Fig :1 Combined Cycle System - schematic

Gas Turbines

The land-based, industrial gas turbine for power generation (fig. 2) resembles that for an aero-engine, but with the fan replaced by a re-designed compressor and the combustor designed to minimise carbon monoxide and NOx emissions. In the compressor, air is heated adiabatically to ~600˚C, and then feeds into the combustor, in which the gas is burnt. Current turbine entry temperatures (TETs) for the combusted gas stream are of order1400-1500˚C, but there are incentives, in terms of efficiency, to increase these to ~1700˚C. In terms of minimising CO/NOX emissions, however, a temperature of around 1430˚C is optimal. The demands on the high-pressure blades (HPT) and the discs that support them are extremely boundaries, are no longer needed. The drive has been to increase creep resistance, and additions have been made of dense, high melting point metals, predominantly W and Re. Alloys containing Ru are being explored. Current calculations suggest that there is an upper limit to the density of the alloys of about 9 Mgm^{-3}. Beyond this, the higher centripetal forces (which are given by $mr\omega^2$, where m is mass, r is radius and ω is angular velocity) outweigh the advantages of higher creep strength. A second point is that the Cr content of the alloys has been much reduced. This relates to the fact that as Mo, W, Re etc. are added, there is a tendency to form 'topologically close-packed phases' (TCPs), such as Laves phases and sigma phase. These are brittle, having no well defined slip planes, but can be avoided by lowering the Cr content. The disadvantage of this is that the alloy's 'natural' oxidation resistance (initially, with ~18% Cr) is destroyed and oxidation resistance has to be provided by coatings. Two current compositions are, for internally cooled HP turbine blades: CMSX4, which contains 6.5Cr, 10Co, 0.6Mo, 6W, 5.6Al, 1Ti, 3Re, 0.1Hf%, and, for un-cooled, hollow IP blades: RR3000, having a composition 2.3Cr, 3.3Co, 0.4Mo, 5.5W, 6.3Re, 5.8Al, 0.2Ti, 8.4Ta, 0.03Hf%. Blade cooling is achieved by {a.} casting internal channels into the blade and bleeding cooling air (at compressor exit temperatures of ~600˚C) into these channels; {b.} drilling holes through to the channels from the blade surface to achieve a cooling-air 'wash' across the blade surface.

Since the alloys melt at approx.1450˚C, which is the turbine entry temperature, integrity can be maintained only by a combination of an environmental barrier coating (diffused-in platinum and/or MCrAlY coating) and a thermal barrier coating (TBC), based on yttria-stabilised zirconia, some 250mm thick. The TBC acts to give a temperature at the blade surface of ~1100˚C for a gas temperature of ~1450˚C, but provides no barrier to the ingress of oxygen. It is of interest that the solid-state electrolyte favoured for solid-oxide fuel cells, running at ~950˚C is also yttria partially stabilised zirconia, because it allows the ready passage of oxygen anions at that temperature (see below). In gas turbine service, an oxide layer (predominantly alumina) gradually builds up at the TBC/EBC interface, until it reaches a critical thickness, at which it spalls off, laving the blade unprotected. The spalling process is exacerbated by thermal cycling, because every cool-down from temperature subjects the layer to compressive stresses, which

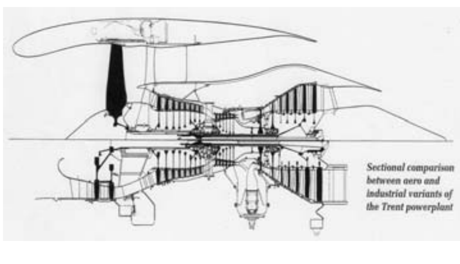

Fig 2: Cross-section through the Rolls-Royce Trent Aero-engine and the Trent Industrial Gas Turbine

promote buckling or shear cracking. Hence, the duty-cycle of the GT is a major factor in the lifing assessment, and assumptions made as little as six years ago (pre NETA) may no longer be relevant to current operation. The impurity content of the gas is also of relevance: elements such as sulphur or vanadium are particularly detrimental to the integrity of the “oxidising” layer.

The blade material is conventionally 'lifed' in terms of creep properties, but frequent 'load following' may induce sufficient fatigue cycles for creep/fatigue interactions to become an issue. The blades are fixed to wrought nickel super-alloy discs by fir-tree root fittings and the lifing of these has to include a fatigue component - note that, because of the high centripetal forces, the fatigue is associated with a high stress-ratio, R. The discs themselves are relatively conventional polycrystalline superalloys, such as In718, which contains 18.5% Cr, 3% Mo, 5% Nb, 0.4% Al, 0.9% Ti, 0.04% C and 18.5% Fe (to reduce cost) bal Ni. or Udimet 700 with 15% Cr, 18.5% Co, 4.3%Nb, 4.3% Al, 3.5% Ti , 0.08% C, 0.04% B bal Ni. In Udimet 720Li (low interstitial), attempts are made to limit intersititials, such as carbon, to prevent selective oxidation of carbide stringers. Such discs might operate with rim temperatures of order 600˚C. As TETs increase, and the blades become hotter, the disc rim temperatures will also increase and it becomes necessary to develop alloys to withstand these higher temperatures. Addition of dense, high melting point, metals, as for blade development, makes it more difficult to forge cast discs, and alloy-rich/alloy-lean 'banding' tends to be observed. To produce more uniform meso-structures, recourse may be made to the consolidation, via hipping/forging routes, of (inert) gas-atomised powder. An alloy which Rolls-Royce have developed for aero-engine discs is RR1000 (to withstand 1000K = 727˚C) having the composition 15% Cr (for oxidation resistance), 18.5% Co (solid solution strengthening and lowering the stacking fault energy), 5% Mo (solid solution strengthening), 3.6% Ti, 3% Al, 2% Ta (g' formation and lattice parameter mismatch control), 0.06% Zr, 0.027% C, 0.02% B (for grain boundary modification).

Future trends may include ceramic combustor linings and the powder-formed (and forged) turbine discs, but one of the major issues remains the precision of lifing for coatings under realistic present-day and future duty-cycles and gas composition. For a discussion of lifing issues, see ref. [3].

An innovative possibility is to replace the conventional combustor by a solid-oxide (yttria partially stabilised zirconia) fuel cell operating at ~950˚C, in which carbon and hydrogen, from the gas stream, interact with oxygen ions diffusing through the oxide (see above re TBCs) to form water vapour and carbon dioxide. It is then possible to draw DC current from the fuel cell, in addition to the AC current from the GT, giving an overall efficiency of ~70%. One main issue is the reforming of methane to produce carbon and hydrogen, combined with the sensitivity of catalytic reforming material to impurities (particularly sulphur) in the gas stream.

There is one interesting point of contrast between the UK vision of the main provision being accomplished by gas turbines, and that of parts of Continental Europe, which are continuing with new build of fossil-fuelled steam-turbines. To achieve greater efficiency in these, they have been trying to develop creep-resisting steels to allow higher steam entry temperatures. For economic reasons, these are ferritic steels, with some 10-12% Cr and additions of elements such as Mo and W. The evaluation of creep properties for new compositions of this sort demands an extremely large, and long-term, testing programme. For the UK 'combined cycle' vision, it is not clear that the 'hand-over' temperature from gas to steam is particularly critical in terms of overall system efficiency and it may be that it is satisfactory to continue with conventional 2.25Cr1Mo or 9Cr steels, obviating the need, not just for alloy development, but for large-scale testing. For example, in the 900MW combined cycle gas turbine power station at Killingholme, the base load gas turbine outlet temperature (from four gas turbine units) is 553˚C and the boilers are designed to produce HP steam at 522˚C. The overall efficiency is ~50%, 287MWe from the gas turbines and 161MWe from the steam turbine [4]. There are suggestions that efficiencies up to 60% would be achieved if steam temperatures could be raised to the order of 640˚C. Not only would this demand the advanced steels, but it implies high levels of service duty for the heat-exchanger/steam-generator, particularly if attempts are made to operate in 'load-following' mode.

Life Extension Other Existing Plant

Plant-life extension issues for fossil-fuelled steam-turbines can be considered in terms of tried and tested methodologies relating predominantly to creep failure and creep-crack growth for high-temperature components, fatigue issues in rotating parts at all temperatures (both initiation/stress concentrations and fatigue crack growth, with appropriate monitoring systems) and the potential for environmentally-assisted cracking, EAC, (leading perhaps to brittle fracture) in the low-pressure (low temperature turbine. Whereas the materials for discs can be selected to be resistant to creep for high temperature components (usually CrMo steels) and resistant to brittle fracture for low temperature components (NiCrMoV steels), conventional plant has single shaft from the HP turbine through to the alternator. There has been some exploration of the feasibility of a welded “dual steel” shaft, joining a CrMo high temperature section to a NiCrMoV low temperature section, choosing a welding consumable with 'average' composition. The lifing assessment of any such component has to take account of the duty likely to be experienced in future operation, since this may include more frequent “on-off” cycling than assumed previously. It is important also to determine the fatigue properties of a full-scale weldment, since the through-diameter stress gradient in this will be much shallower than those in small test-pieces.

In addition to conventional structural steel issues, mainly concerned with the performance of 316-type austenitic stainless steels at temperatures up to 600˚C, continuing operation and plant life extension for AGR plant has to address a further materials issue: that of the occurrence of cracks in the graphite moderator [5]. The assessment methodology has concentrated on the potential incidence of cracking from the sharp roots of keyways around the outside of individual channel blocks (suggesting that the first significant occurrence of these would be observed after ~29 years of operation), but, from 2001 onwards, there have been observations of a number of cracks on the inside bores of channel blocks. The prime driving force for this is the shrinkage of graphite under neutron irradiation (indeed, the pattern of cracks bears some resemblance to that of a 'crackle glaze' on Chinese pottery, which is produced by thermal shrinkage of the glaze material on cooling), but the situation is complicated by the simultaneous (gamma-ray) irradiation-enhanced oxidation of the graphite. The presence of the cracks as they exist at present does not provide any threat to structural integrity, but there are concerns that their future development with time could conceivably allow sufficient movement in the core as a whole for safe operation to be challenged. Concern is such that three years ago, the NII set up a Graphite Technical Advisory Committee (GTAC), akin to the industry-funded Technical Advisory Committee on Structural Integrity (TAGSI), to give independent advice on the issues.

The Pressurised Water Reactor (PWR)

The principle of operation of a PWR is that light water, which acts both as moderator and 'coolant' (heat-transfer-medium) extracts heat from the fission reactions in the core, which is comprised of uranium dioxide pellets contained in a large number of small diameter zircaloy tubes, spaced such that the water can flow past freely. The moderating effect of the water is to slow down energetic neutrons to sustain a chain reaction. The heated water is pumped around a primary circuit (starting at a temperature of ~300˚C) to a heat exchanger, in which it heats water in a secondary circuit, which then converts to steam and drives a steam turbine/alternator to generate electricity. Maintenance of liquid water in the primary circuit at such operating temperatures demands high pressures, which must be contained by the reactor pressure vessel (RPV) and associated pipe-work.

The vessel (see fig.3) has a (vertical) cylindrical “barrel” section surrounding the reactor core, a hemi-spherical bottom dome with penetrations for instrumentation, a 'nozzle ring' to which is welded the inlet and outlet pipe-work carrying cooler water to, and hotter water from, the reactor, and a detachable hemi-spherical head, with penetrations for the control rods, which can be raised and lowered to regulate the operation of, or shut down, the reactor. The head is bolted to the top of the nozzle ring, but all other joints are welds. The hoop stress generated in the cylindrical barrel section under normal operation is moderate (~170MPa). Following conventional pressure vessel codes (with a safety factor of 2), this requires steel with a minimum yield strength of 340MPa at the operating temperature of 290˚C, and it must be readily weldable. The requirements are met by steels conforming to specifications A533B for plate material, A508 for forgings, or European equivalents, such as 22NiMoCr37 or 20MnMoNi55. These steels contain 0.8-1.5 Mn, 0.5-1.0 Ni, 0.5-0.7 Mo, with maximum carbon of ~0.25% to meet weldability criteria. Early vessels were fabricated by forming pieces of A533B plates and welding these into rings, which were joined by circumferential welds. This entailed some axial welds (normal to the hoop stress) and the welds in each ring were staggered to avoid a continuous axial weld running the length of the vessel. Later vessels were fabricated from forged A508 rings, which avoided any axial welds. The UK Sizewell 'B' RPV has a particularly large ring forging in the barrel section, such that no weld is subjected to the very high neutron exposure associated with regions around the reactor core (referred to as the 'belt-line' region). It should be noted, however, that one of the more severe threats with respect to fracture: the so-called 'loss of coolant accident', or LOCA generates equi-biaxial stresses, so that, here, a circumferential weld experiences the same stress as does an axial weld.

A major concern has been the possible failure of the RPV by catastrophic brittle fracture. The sequence of events leading to the hardening and subsequent embrittlement of RPV steel under neutron irradiation has been understood in broad terms from the beginnings of the nuclear power programmes begun well over fifty years ago., A neutron interacts with a U235 atom and causes this to split into two product atoms, typically of atomic masses ~97 and ~136 plus one or two highly energetic neutrons: energies of 1-2MeV or above. The role of the moderator is to provide sufficient (low atomic mass) atoms to cause the energetic neutrons gradually to lose energy to levels such that they can interact with further U235 atoms to generate a 'chain reaction', which will produce further energetic neutrons, which will again be moderated to provide a self-sustaining sequence. The PWR oxide fuel is enriched (by gaseous diffusion or centrifuging techniques) to ~2.5% U235, which enables light water to be used as a moderator. For present purposes, there are three relevant effects of the moderating events. The primary effect is that 'slowed-down' neutrons interact with U235 in the fuel to sustain the chain reaction. The second is that the energy lost in (water) moderation processes is carried away as heat by the (water) coolant to generate steam. The third relates to the irradiation embrittlement of the RPV steel.

A PWR RPV steel is bombarded by neutrons of a wide spectrum of energies, ranging from highly energetic (those that have avoided any interaction with moderator atoms) down to low levels (those that have undergone many interactions). There is also a spectrum of g-rays of differing energies. The net effect of this bombardment is to produce 'damage' in the steel, which is primarily the displacement of atoms from their normal lattice sites to produce vacancies and 'interstitials'. (These are 'self-interstitial' iron atoms forced to occupy non-lattice positions, not carbon or nitrogen atoms in interstitial sites). An energetic neutron displaces, and transfers kinetic energy to, an iron atom through an elastic collision this is termed a 'primary knock-on' or PKA. The PKA then collides with further iron atoms to produce a displacement cascade of clusters of vacancies and (self-) interstitials, although some re-combinations may occur after the PKA has passed. For less energetic neutrons, causing displacements but not transferring so much energy, the 'damage' may be in the form of 'Frenkel pairs' of vacancies and interstitials; at lower energies still, a neutron may not be able to transfer enough energy to effect a displacement (the energy transferred to the iron atom must exceed 40eV for it be displaced) and the effect is to excite thermal

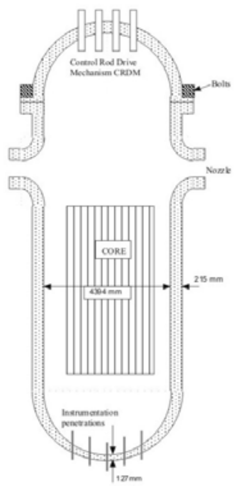

Fig 3: PWR Pressure Vessel - schematic

vibrations. Damage is best defined in terms of displacements per atom, dpa, recognising that the main effect on properties is that of hardening the matrix, and that this hardening is due to the fact that the clusters, in particular, provide barriers to dislocation movement through the lattice [6]. The hardening, in turn, affects brittle fracture behaviour, as described below. There are issues concerned with relating the neutron 'bombardment', with its spectrum of energies, to the end-effects on damage. The term 'fast neutron fluence' implies a number of neutrons per unit area having energies greater than an agreed boundary level, e.g. 0.1MeV. This is a coarse descriptor of the energetic neutron spectrum, although it has been used widely (with different boundary levels). What is now done in codes is to split the neutron spectrum into a large number of narrow energy bands and to calculate the dpa produced by each band, finally summing these to give the total dpa for the whole spectrum. The gamma ray energy spectrum can be treated in a similar manner [7].

An increase in hardness is associated with an increase in the notched impact brittle-ductile transition temperature. This can be explained in terms of comparable behaviour in slow notched (four-point) bend tests, for which it is possible to calculate the local fracture stress below the notch, s_F, knowing the fracture load and the yield strength at the test temperature: see fig. 4. In general, s_F=Q.s_Y, where s_Y is the yield strength at the temperature at which fracture occurs, and Q is a factor known as the 'stress intensification'. For fracture coincident with general yield, Q=2.5. The 'transition temperature' for fracture at general yield for unirradiated material is given by the intercept of 2.5 s_Y with s_F. If the steel is hardened by neutron irradiation, the yield stress increases to s_Y^+ and the point of interception of 2.5s_Y^+ with sF is now at a higher temperature, so that there is an increase in transition temperature, DTT_1. To relate the increase in yield strength to the temperature shift, the sF line may be taken as horizontal. The 2.5_Y and 2.5s_Y^+ lines are strictly non-linear curves, but if they are reasonably parallel to each other and the transition temperature shifts are not too large, there will be a monotonic, if not quite linear, relationship between DTT and the increase in yield strength induced by irradiation hardening.

In recent years, it has been found that hardening in submerged arc welds induced by exposure to the fluence may be attributed to two separate causes. The first is the generation of obstacles provided by the clusters of point defects; the second is a component due to copper precipitation hardening [6].This finding was initially surprising. It was known that copper could produce precipitate hardening in steels but the ageing temperatures were in the range 450-550°C, whereas the temperatures of interest in the reactors were less than ~ 350°C. The critical point is that the point defects generated by irradiation increase diffusion rates such that copper can become mobile at these lower temperatures. When the copper component is removed, it is found that the hardening (as deduced from transition temperature shifts) depends on the square root of 'damage', D, expressed as dpa.

Two effects of trace impurity elements on the occurrence of inter-granular fracture during stress relief/tempering have been recognised: during the heating cycle and during the final slow cool to room temperature. Susceptibility to cracking during the heating cycle ("stress-relief cracking" or "reheat cracking") has been traditionally associated with the flow properties of the matrix, especially for secondary-hardening steels. When the joint is heated, the yield strength begins to decrease, but,

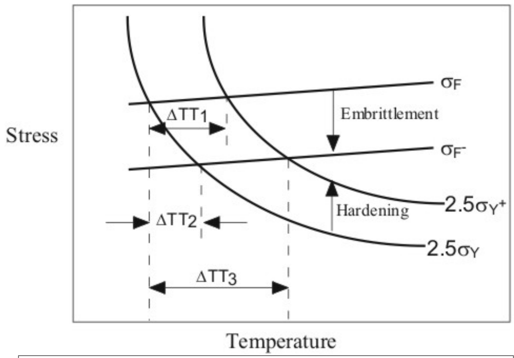

Fig 4: Fracture Stresses and Transition Temperatures

at temperatures of order 500°C, fine-scale carbo-nitrides re-form and harden the steel matrix. The residual stress is then relieved, not by plastic flow, but by cracking. There are various empirical expressions relating susceptibility to cracking to the steel's chemistry, emphasising the role of secondary-hardening elements. Additionally, however, trace impurity elements, such as P or Sn are taken into solution at the high austenitising temperatures and are retained in solid solution after cooling. At temperatures of about 500°C (whilst the steel is still hard), they can segregate to grain boundaries and reduce the inter-granular cohesion. The effect of this can be seen in fig.4. If s_F is reduced to s_F- by segregation, there is an increase DTT_2 for unirradiated material, which increases to DTT_3 when both irradiation-induced hardening and segregation are included.

Similar cracking problems were experienced with "under-clad cracking". The cladding here refers to a layer of austenitic stainless steel, some 5 mm thick, which is deposited, by the equivalent of a fusion welding technique, all around the inner surfaces of the RPV. The design purpose for the cladding was to minimise the risk of corrosion products blocking cooling channels. The cracks were found in the ferritic steel just below the clad interface, of some 5-6 mm extent normal to the interface. Again, metal is heated to >1200°C, cools rapidly and is then subjected to a stress-relief heat-treatment, The residual stress field is different in detail from that for a simple fusion weld, because the thermal expansion coefficients for ferritic and austenitic steels differ, so that thermal mismatch stresses are induced. A second feature is that inter-diffusion can occur across the dissimilar metal interface during cooling after deposition of the clad. In particular, chromium from the austenite can interact with the carbon in the ferrite to form a small region which transforms to a hard martensite. A second area in the reactor where this can occur is in the "safe-end" welds where austenitic pipe-work is welded to nozzles in the nozzle ring.

The avoidance of both stress-relief cracks and under-clad cracks by controlling trace impurity elements to low levels is recognised and the specification of the A508 steel for Sizewell B gave close tolerances for impurity elements: 0.008 P;

0.008 S; 0.01 Sn; 0.008 Sb. An added benefit may be that low levels of impurities are beneficial with respect to resistance to environmentally assisted cracking (EAC). Such specifications lead to added cost, and it is likely that, in any "new build" scenario, the need for such tight specifications will be subjected to close scrutiny. In fact, the control of water chemistry in modern PWR systems is so good that it is possible to contemplate un-clad RPVs, and the question of whether any potential "new build" PWR would be clad or unclad remains open.

The 'new build' options for nuclear plant will almost certainly focus on two systems: the European Pressurised Water Reactor (EPR) similar to that being constructed in Finland, and the Westinghouse Advanced Pressurised Water Reactor (AP1000) recently licensed in the USA. The AP1000 includes many 'passive' safety features, such as natural waste heat removal in the event of a shut down for safety reasons, and is designed on a modular basis, with many components being interchangeable. The design life is set at 60 years. Sizewell B was built to exceptionally high standards, with meticulous attention paid not only to the fine detail of steel composition, but, in particular to the number, and multiplicity, of pre-service inspections undergone by the pressure vessel. In the environment of 'free market' 21st Century Britain, the necessity for such a detailed, costly, appraisal will be challenged. Indeed, the NII is now proposing that regulation might proceed by approving the generic design and paying further individual attention only to the specific site conditions. This is radically different from the traditional UK approach, which had to deal with some twenty nuclear stations, almost all of which had significant differences between them, but is not dissimilar for what would be done by the Civil Aviation Authority in clearing a new aircraft or aero-engine. What is needed critically is to assess where the attention to fine detail is of paramount importance and where general (already high) industry standards will suffice. Unfortunately, in the absence of firm bids for nuclear 'new build' systems, funding for such appraisal work has not yet been made available. As noted above, one set of issues is likely to involve the effects of trace impurity elements and heat-treatment/welding conditions on resistance to EAC in PWR water. Here, it is also necessary to evaluate the possible effect of (gamma-ray) irradiation enhancement on the corrosion processes, to determine the magnitude of any radiolytic component.

Other Nuclear Systems

For the future, other possible nuclear systems are the high temperature reactor (HTR), the fast reactor and the fusion reactor. Of these, it is possible that the HTR could enter service, somewhere in the World, by 2015-2020. One version: the Pebble Bed Modular Reactor (PBMR); has reached a high state of development in South Africa. It works on the Brayton cycle, with helium gas as coolant, flowing through an assembly of 'pebbles' formed by the agglomeration of a large number of micro-spheres composed of a core of graphite and a number of deposited 'shells' of ceramic (SiC) and further graphite. The gas entry temperature is ~500˚C and it is heated to ~900˚C as it leaves the pebble bed assembly. It is compressed and then drives a conventional turbine, before cooling and being pumped back to the pebble bed. The system is designed to give a completely safe shutdown, with natural heat decay. There is no clear evidence of major structural integrity issues at this stage: one suspicion is that, in commercial service, it may be difficult to prevent helium leaks; this is more likely to be a commercial concern than a safety hazard.

An opportunity that seems available for the PBMR is to replace a conventional nickel-base turbine system with a ceramic turbine (SiN, SiC or composite). This would be much lighter (remembering that helium has low density, hence limiting the kinetic energy available), yet able to operate comfortably at 900˚C in an inert gas atmosphere.

Fast reactors, based on transmutation of U238 to Pu239, followed by radioactive decay of the Pu, have been in existence for potential civil power generation for over twenty years. Studies for the European Fast Reactor (EFR) were being made in the late 1980s. Japan has plant operating at Monju. The main issue is not the transmutation or radio-active decay aspects (production of plutonium for bombs has been continuing since the Second World War), but the safe and reliable generation of electrical power. The primary circuit coolant is liquid sodium and this is passed, at ~500˚C, through a steam-generator, to raise steam from water. The sodium passes through tubes of perhaps 30m length, ~10mm diameter and 2mm wall-thickness. On the other side of these tubes is liquid water. Any sodium leak into the water will cause a violent chemical reaction. The number and closeness of spacing of such tubes provides major challenges to assembly and makes in-service inspection non-viable. In one design, ~38 km of tubing is drawn through hard-faced spacer plates, separated at ~1 m intervals. Guaranteeing that no tube is scratched to one quarter (0.5 mm) or even one half (1mm) is a daunting task: the only form of monitoring available is to measure the drawing force. Given the 400˚C temperature differential in the workable PBMR and an equal (if not greater) temperature differential between 500˚C and 100oC/RT in the fast reactor, it is tempting to suggest that one might explore a fast reactor heat source, liquid sodium coolant, but an inert gas (argon) plus compressors to drive the turbine. The fusion reactor is still in the research stage and, almost certainly, will not be producing electricity for the nation in the 2025 timescale. The plasma, in which the deuterium/tritium fusion processes take place, is electrically charged and can be confined in a toroidal magnetic field. The generation of electrical power is achieved, however, not by any coupling with the plasma, but by the fact that, in the nuclear reactions, a number of neutrons are produced. These are highly energetic (up to 14MeV) and, because they are uncharged, they can escape from the confining magnetic field and 'shoot into' the so-called 'blanket material', which is a large cylindrical block of steel surrounding the plasma. The displacements and thermal vibrations induced in the blanket produce heat, which is extracted (at about 500˚C) by water flowing through longitudinal holes running through the blanket. The blanket material is likely to be a steel of the 9-12 Cr type, but Mo can be activated by the neutrons, and so the steel may contain Nb. Mention has been made of internally oxidised alloys, but the fabrication of very large blocks may not be easy to achieve. The interior, plasma-facing 'front wall' of the block has to be constructed from a material that will not erode too rapidly under bombardment from the neutrons: tungsten is one favoured option.

There are recent excellent reviews on materials for advanced nuclear power plant by Little [8] and on plasma-facing materials by Cottrell [9].

Renewables

Under this heading, there are several postulated systems: including water turbines (for both conventional hydro-electric generation or wave-power) tidal basins and/or barrages, solar cells, and, of course, wind. Bio-mass fuelled systems are 'renewable' but generate carbon dioxide in their combusted products. Fuel cells can run on hydrogen alone, but the commercial systems are planned to run on reformed methane or similar hydrocarbons for electricity generation, or methanol for transportation. The prospect of hydrogen as a clean fuel is extremely appealing, but hydrogen needs to be generated by electrolysis of water, which implies a source of electrical power! The overall prospect, as far as the UK is concerned has been elegantly summarised by Thompson in his paper "Energy in the Landscape" [10]. He calculates the size of system needed to meet the UK's total electrical power demand for each of the various methods. On conventional hydro, for example, the UK has very little water at heights greater than 1000 m above sea level, yet would require an area some ten times that of the British Isles; a tidal basin would need to be roughly the size of (all) Ireland. With converters of 100% efficiency and continuous sunshine from a clear sky, the total area of solar panel required is about 50% bigger than the Isle of Wight: current efficiencies for silicon-based panels are of order 10%; the sun does not shine continuously; and silicon-based panels are not just expensive, but need significant amounts of energy to produce. For 2 m high waves, the catchment needs to be approximately three times the length of the South Coast: for a 20 knot wind, it is the length of the South Coast and 500 m high! It is clear that our existing fossil-fuelled or nuclear generation systems at least have the virtue of being relatively compact.

The generation of electricity by wind power is not a new development: Nansen had a wind generator on board the "Fram" in 1894 when he went "Farthest North". The Netherlands have been using significant wind generation for some years. Over the last five years, the UK Government has actively encouraged the development of wind-power generation by offering financial incentives. Large wind farms have appeared, often on moor land, sometimes verging on sites of natural beauty. Offshore sites are also being developed. Remote sites tend to be more difficult to access for inspection, maintenance and repair and these aspects will assume more importance as we generate higher percentages of electricity by wind-power and as the systems 'mature' (i.e. age). In October 2006, the "World's biggest offshore turbine" was towed out to the Beatrice field in the Moray Firth, Scotland. The 1000 tonnes structure measures 120m above sea level, with blades 63 m long. It will generate 5 MW of electricity. It is clearly necessary to have 200 such turbines to generate 1000MW of electricity and the associated monitoring, inspection and maintenance of such a large assembly is likely to be much more labour-intensive than that for a conventional station.

The material for blades of these large sizes (2x63 = 126m is greater than the size of most cricket fields) is most likely to be a glass-fibre/epoxy composite, with a volume fraction of some 50% fibres. Carbon fibre composites are too expensive for components of this size, but another potential system is a wood/epoxy laminate. The design parameters relate to strength/weight; stiffness/weight and fatigue strength/weight. The strength/weight ratio for the glass/epoxy is ~25% higher than that for the wood/epoxy, which makes the wood/epoxy ~25% heavier. On the other hand, the stiffness/weight ratio for glass/epoxy is only ~90% of that for wood/epoxy. This effect is amplified in bending, where the tip deflection for a blade made in wood/epoxy is only 75% of that for glass/epoxy. The fatigue strength/weight ratio is identical for the two options. Superficially, blades are not particularly complex structures and there is experience of wind farm operation. Structural integrity issues for normal, land-based wind farms should be readily manageable, although some blade failures have occurred. Concerns exist mainly with the absolute size of the large blades and with the conditions encountered in offshore operation. There have been some spectacular failures of large, sea-going catamarans built from glass-fibre/epoxy composites, although, arguably, these have been associated with the failure of fixing points where the linking cross-spars join the hulls. There may also be issues with an offshore farm, as opposed to an individual turbine, if the array of blades produces anything in the nature of a vortex. The importance of monitoring, inspection and maintenance is emphasised.

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'The Plant Ageing Guide: Management of Equipment Containing Hazardous Fluids or Pressure', - HSE Research Report RR 509.

A review by Dr Phillpa Moore of TWI on behalf of the HSE

INTRODUCTION

Many UK industrial companies are seeking to maximise the life of their equipment containing hazardous fluids or pressure, and fewer installations are being replaced with new-build. Equipment therefore needs to be kept working safely and reliably for longer. In order to address concerns over the way some parts of UK industry is managing equipment that is degrading by time-dependant mechanisms the Health and Safety Executive (HSE) commissioned 'The Plant Ageing Guide: Management of Equipment Containing Hazardous Fluids or Pressure', published as HSE Research Report RR509. The document is a practical guide discussing the issues to be considered for managing ageing equipment, and its aim is to help those responsible for equipment containing hazardous fluids or pressure to understand and assess the risks of accumulated damage and deterioration, and to manage their equipment over time to ensure that it stays safe and reliable.

RR509 has been publicly available from the HSE website since November 2006, and a number of related seminars on the management of ageing plant have been run by the IMechE and ABB. This paper aims to provide an overview of the main content of the Guide. However, at over 100 pages, the Guide itself contains substantially more information, and covers topics in more depth than is possible in this paper. RR509 is presented in four distinct chapters, covering the main steps in the management of ageing equipment, and this article summarises some of the key elements from each section:

- Awareness of ageing: “Could my equipment be ageing?”
- Identification of ageing damage: “How can I tell if ageing is happening?”
- Addressing ageing: “What do I do about it?”
- Getting organised for managing ageing: “How can my organisation be prepared?”

AWARENESS OF AGEING

It is important to appreciate that ageing is not about how old your equipment is; it's about what you know about its condition, and how that's changing over time. Those who have responsibility for owning and operating equipment often find that they wish to run it beyond the original stated design life, to change its operating conditions, or to purchase and operate second hand equipment. However, there is also a need to ensure the equipment's ongoing structural integrity and safety. An awareness of the risks of accumulated damage and deterioration of equipment is vital for these situations and many others.

Much of the assessment is good engineering judgement, but it is required over a broad range of disciplines, and many of the topics interlink.

One model for understanding ageing is to consider the four stages of equipment life:

Stage 1 is 'Initial' when the equipment has been commissioned and installed, and has a probability of failures occurring due to issues such as shake-down, faults that were not anticipated during design, or problems with the installation such as bolting or valves leaking.

Stage 2 is 'Maturity' when the equipment is operating within it design limits, and routine maintenance is carried out. Most of the equipment's life will be in Stage 2 when the probability of failure is lowest.

Stage 3 is 'Ageing' when the equipment's design life has been used, or when degradation becomes evident, and a justification must be made for continued service. A change of service conditions may also put equipment into Stage 3. At the Ageing stage, equipment needs regular inspection, and repairs or modifications may be necessary.

Stage 4 is the 'Terminal' stage, when accelerating and accumulating damage to equipment means that repair and/or replacement is necessary. The equipment has reached its end-of-life, when no further service can be justified on safety or financial grounds.

Understanding where equipment may be in its lifetime, relative to the four stages, is an important step in managing equipment ageing.

IDENTIFICATION OF AGEING

The symptoms of ageing cover a large number of indicators and damage mechanisms. Many of these will be obvious to day-to-day operators when equipment starts to suffer from leaks, vibration, drips, valves seizing up, reduced pumping efficiency, noise, repeated problems, impurities in the product or ultimately, breakdown. Other symptoms of deterioration such as wall-thinning, wear, corrosion, numerous types of cracking, blisters or fretting may need to be detected from inspection and non-destructive testing (NDT). Those with a good awareness of ageing should consider carrying out inspection for the latter set of symptoms when one or more of the former set of symptoms is evident. Understanding what kind of degradation and damage the equipment may be at risk from will play a big role in tailoring the type of inspection carried out.

In addition to detecting the damage, there are a number of risk factors that can also make deterioration more likely. The risk can be increased, for example, when equipment is under cyclic loading but without a fatigue assessment (either if it was constructed to an old code, or has exceeded its original fatigue limit), or from changing the service conditions without revalidation. A lack of knowledge can also increase the risk of deterioration - if there is no awareness of the possibility of ageing, then the risk is that is occurring will not be avoided. In addition, an absence of information, such as when purchasing second hand equipment, may not provide sufficient confidence that the condition of the equipment can be known.

NDT and inspection plays a vital role in managing ageing equipment, when it is necessary to ensure equipment integrity to justify continued service. The type of inspection carried out will depend on the stage of the equipment within its lifecycle. In Stages 1 and 2 the inspection will be 'confirmatory', but will become more 'deterministic' in Stage 3 and 4. Confirmatory inspection is when the expected condition of the equipment is simply confirmed, typically using techniques such as routine manual ultrasonic testing (UT) and magnetic particle or dye penetrant testing. When equipment in an unknown condition needs to be monitored, or it becomes necessary to quantitatively measure flaw sizes, deterministic inspection is done, possibly using methods such as automated UT techniques. The scheme of examination must therefore be reviewed at suitable intervals, as the equipment passes through the stages of its life when a different approach to the inspection becomes necessary. The topic of NDT and inspection is discussed in more detail in the Guide.

ADDRESSING AGEING

By this point, with a good awareness of the risk of equipment ageing, and knowing what damage to look for and how to detect it, those responsible for equipment containing pressure or hazardous fluid should be in a good position to address any ageing damage that is found. Any action taken needs to be carefully considered, depending on the damage found. There are only a limited number of options to choose from, and sometimes more than one will be chosen:
:

- Do a fitness-for-service, or remaining life assessment
- Remove the damage, possibly without further repair
- Repair the vessel (may be either a temporary or permanent repair)
- De-rate the vessel service conditions
- Monitor the vessel to ensure rate of damage accumulation does not compromise safety
- Scrap the vessel

A fitness-for-service assessment can be a good first step to determine what further action is necessary and can be carried out to assess damage such as fatigue cracking, locally thinned areas or dents and gouges. It can assess whether the damage is tolerable and may be left, or needs to be repaired. Alternatively, it can determine a safe lower service stress for which the flaw is tolerable.

When surface and near surface flaws are found, the most common approach is to remove the flawed material by grinding. After grinding and subsequent NDT, the remaining wall thickness can be measured to determine whether it is still sufficient, without further repair welding. When making weld repairs to existing equipment, the potential for defects to be introduced may be greater than when the item was new. For weld repairs, appropriately qualified and experienced personnel are essential. There are specialist welding techniques which can carefully control the repair weld heat input to offset the disadvantages of a lack of post weld heat treatment.

Repair is not necessarily the most cost effective method of dealing with damage to equipment. Consideration can also be given to the possibility of revalidation to justify changes to the operating conditions of the equipment, which can then preclude the need for any repair. Examples where revalidation for changes of service conditions or equipment modifications is particularly critical are; the operation of ferritic steel equipment at lower temperatures where the material might show a significant drop in fracture toughness; changes to the contents or environment such that unforeseen damage mechanisms could occur (e.g. stress corrosion cracking); or physical modifications that would limit access to critical locations for inspection.

Equipment will not be able to continue in service for ever, and ultimately the equipment will need to be scrapped or replaced. The decision for when this will occur is often based on financial considerations, when the cost of ongoing operation, repairs and revalidation, along with the combination of risk and consequences of failure, becomes greater than the cost of replacement.

GETTING ORGANISED FOR MANAGING AGEING

The management of ageing equipment requires knowledge and expertise across a wide range of disciplines, found in a team of people, be it all in-house, or through selected sub-contractors. The competencies required include:

- Awareness of safety codes and regulations
- Pressure/chemical plant engineering
- Familiarity with the equipment concerned
- Design and construction codes
- Metallurgy and corrosion
- Inspection, NDT and maintenance
- Structural integrity
- Welding engineering
- Management, teamwork and organising
- Communication skills.

The principal additional managerial issues are covered by the following questions (which RR509 helps to provide answers to):

- Who is responsible? Responsibility may be shared by more than one person.
- What competencies do they have? Competence is both having and demonstrating the necessary knowledge, skills and experience to do a particular task within a particular context.
- How are individuals' competencies demonstrated? Is there a company culture of problem awareness? The person who notices the problems may not be the one who understands the implications. A culture of communication, and shared responsibility, without blame, can be effective.
- What is known about the history of the equipment? Who knows about it and how is information transferred or passed down? A lack of knowledge about the equipment's condition is a risk factor for ageing.
- When will the equipment's design life end?
- Has an end-of-life date been set and what strategies will be used to manage the equipment up until, and possibly beyond this date?

Often the most critical link in safety management is the people who are responsible for equipment containing hazardous fluid or pressure. There are challenges to the recruitment and retention of sufficiently skilled personnel. As well as dealing with people's knowledge there are also documents and records that need good management. The principal tool for this is the equipment inventory, so you know exactly what equipment you have got. Good inventory control will also record any modifications and repairs. This, in combination with a complete set of inspection and maintenance records, can be invaluable; skilled interpretation of the data stored in these records allows trends to be identified, and hopefully, future problems to be averted.

CONCLUSION

The management of ageing begins with an awareness that ageing is taking place all the time, and the factors that are influencing ageing. Once the symptoms of ageing are understood and detected using NDT methods, a decision can be made how to proceed. The options include putting together a case to justify continued service, re-rating the equipment, repair, or scrapping the equipment. In addition to the engineering aspects, it has been shown that there are important managerial issues that should be considered related to ageing equipment. The effect of staff demographics, along with skills and competencies, are discussed.

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Wintle, J., Moore P. L., Henry N., Smalley S. and Amphlett G. The Plant Ageing Guide: Management of Equipment Containing Hazardous Fluid or Pressure, HSE Research Report RR509, November 2006.

http://www.hse.gov.uk/research/rrhtm/rr509.htm

Dr Phillipa Moore is the Senior Project Leader in Fracture Integrity Management within the Structural Integrity Technology Group at TWI Ltd. This is a summary of the paper she gave at ESIA8 - Throughlife Management of Structures and Components in October 2006 in Manchester. The title of the paper was: ***Guidance for the Management of Ageing Equipment.***

FESI Forthcoming Conferences and Events

ESIA10 - Engineering Structural Integrity Assessment: Present Goals - Future Challenges
19 - 20 May 2009, Manchester

This FESI Conference will be based around the theme of "**Engineering Structural Integrity Assessment: present goals - future challenges**" and will:

- examine current needs in terms of sustainable management concepts, strategies and methodologies, regulatory requirements, economic benefits and societal impact,
- address the development and deployment of condition evaluation and assessment tools; integration into methodologies and their application to the current situation and future planning, both deterministically and probabilistically based; operational challenges of life cycle management for newly designed plant,
- consider case histories demonstrating the applicability to specific plant problems to the improved life management of existing and new structures and components (papers here will be particularly welcome),
- consider all major industry and business sectors, including energy, transport, process and civil engineering.

Conference Programme - Current

Tuesday

Setting the Scene

Present Goals - Prof John Knott, OBE, FRS, FREng
Future Challenges - Prof Rod Smith FREng
HSE's Generic Design Assessment of New Nuclear Reactors - Dr Andy Cadman, Head of Nuclear Engineering Assessment Unit, Nuclear Directorate

Risk and Reliability [Life Management Issues]

Life management - Dr Phil Horrocks, General Manager, ESR Technology**Risk-based Spares Inventory** - **Ujjwal Bharadwaj**, TWI
Asset Management, Failure Avoidance and Human Factors - **Elisabeth** Deckker, MCS
Risk Informed In-service Inspection - Progress in the European Nuclear Industry - Adam Toft, Serco TAS
Reliability and Lifetime Analysis For a Cracked Cylinder of Giant Ammonia Unit Compressor - Szabolcs Szávai, Institute for Logistics and Production Systems, Hungary

Methodologies

Challenges to Produce Materials for Use in Fusion Reactors - Prof Steve Roberts, Oxford University
Overview of Achievements of Recent European Projects in the Area of Fracture Analysis - Dr David Lidbury, Serco TAS
Fitness-For-Service from FITNET - Dr Isabel Hadley, TWI
Energy Based Failure Evaluation of Isothermal and non-isothermal Mechanical fatigue tests - Gemma Hennings, Serco TAS
The Measurement of Stresses of Oxides grown in a RT22 Coated Super Alloy - Gabrielle Hilson, Fraser Nash Consultancy
Estimation of Elastic Follow-up in Structures - Saeidi Hadidi-Moud, Bristol University
Analysis Techniques for the Design of ITER and Future Fission Reactor Systems - Peter Sherlock, AMEC Ltd
Unified Measure of Constraint - Mahmoud Mostafavi, Bristol University
The Influence of Compressive Plastic Pre-strain on the Creep Deformation and Damage Behaviour of 316H Stainless Steel - Dr Catrin Davies, Imperial College, London
Development of Doplex CT Fracture Toughness Specimen to Investigate Crack Behaviour in Heterogenous Materials - Brain Daniels, Serco TAS

Wednesday

Assessments

Modelling of Stresses in Weldments - Prof Tom Hyde, Nottingham University
Material Modelling to Predict Life of Components - Prof Rachel Thompson, Loughborough, University
New Developments in Modelling Related to Durability Challenges for Aerospace Structures - Prof Ferri Aliabadi, Imperial College London
Fatigue Life Evaluation - Prof John Yates, Sheffield university
Probability and Statistical Methods for Modelling Material Property Data - Dr R Moskovic, Magnox Electric
The life Cycle of Nuclear Graphite in Generation IV High Temoerature Reactors - Prof B Marsden, Manchester University
Failure Analysis of Expansion Loops in a Hospital Pipeline System - Dr Roberto Lascalle, Cantabria University
Determination od Lack of Penetration Tolerance in Circumferential Butt Welds of Wind Towers - Dr S Cicero, Cantabria University
Assessment Techniques using R6 - Peter Frost, Fraser Nash Consultancy
Virtual Design Validation of High Temperature Components Automotive Engine Exhaust Manifold Case Study - B Daniels, Serco TAS
Dating of Fatigue Cracking Based on Oxide Analysis - Roberto Pascual, MCS

Health Monitoring and Inspection

Title to be confirmed - Prof S J Wu, Beihang University
Risk-based Repair and Inspection for North Sea Platform - Dave Sanderson, MMI Engineering
Is Your Decision to Extend a Pressure Vessel Internal Examination Interval Properly Justified? - Dr Philippa Moore, TWI
Are You an Intelligent Customer of Non Destructive Examination? - Bernard McGrath, Serco TAS
A Fullscale Structural Health Monitoring Demonstrator - Dr Elena Barton, NPL
Development of Bridge Manintenance Decision Making Process Considering Existing Condition - Dr Q uz Zaman Khan, University of Engineering and Technology, Taxila, Pakistan
Condion Monitoring and Defect Detection of Engineering Structures Using In-plane Laser Shearography - Leon Lobo, Laser Optical Engineering
The ACLAIM Project Structural Health Management for Composite Components and Structures - Richard Lee, ESR Technology
A New NDT Technique for Residual Stress Measurement - Ennio Curton, Italy

Review and student award

Please visit our website for the latest information on the conference: www.fesi.org.uk and click on the link

Development of Structural Integrity Assessment Technology and Methodology in China

Professor Q P Zhong

Introduction

This paper reviews the development history and main research achievements of engineering structural (pressure vessel and pressure piping etc.) integrity assessment theory, technology, methodology, criteria and standards in China, from the point of view of failure mode, criteria of evaluation, assessing technique and assessing conditions. Following an introduction of the successful applications of the regulatory and standards of the safety assessment and failure analysis on the pressure vessels, pressure piping and engineering trusswork in the industries of aeronautics, mechanical, special equipment, petrochemical and port mechanical, the research developments and prospects of engineering structural integrity assessment theory and technology in recent years are summarised. The paper concludes by describing the theories, technology and applications of engineering structural integrity in China and abroad from the macroscopic view while the outstanding innovative points of which are proposed.

Development of the technologies and methodologies of engineering structural integrity assessment in China

From 1970s, investigation and research on safety assessment of pressure vessels and some engineering structures have been carried out in a few Chinese colleges and research institutions. After research on structural integrity assessment and its engineering application for over forty years, it can be summarized in eight aspects which are failure mode, the objects to be assessed, the assessing criterion of fracture failure, the technology of safety assessment, basis of safety assessment, the working condition and environment of safety assessment, assessing range and the professionals related to safety assessment, each of them experienced respective developing process.

Fracture failure mode

In the field of fracture failure mode, safety assessment research in China has successively experienced three development phases: linear elastic fracture, elastic-plastic and plastic instability.

1) From the beginning of the 70s, studies in China mainly focused on the theory of linear elastic fracture mechanics and the testing method of the fracture toughness parameter K_{IC}. Sun[1] studied the effect of heterogeneity on the fatigue crack propagation process and fatigue life of materials. Lai[2] discussed the physical meaning of K_{IC} and its significant influential factors, from both macroscopic and microscopic point of view. Chen[3], Huazhong University[4] and the Fracture Study Group of the Chinese Institute of Mechanics[5] carried out research on the effect of the mixed mode loading on the testing and the calculation of the fracture toughness values. Li[6] investigated the application of the linear elastic fracture mechanics to the design of the spherical pressure tank. Wang[7] analysed the fracture of pressure vessels with defects in the wall. In 1978, China published the first edition of the Chinese Standard[8] for the testing and measurement of the fracture toughness value K_{IC}.

2) The elastic-plastic structure integrity assessment theory and technology has been studied in China from the end of 1970s. The technical route mainly refers to two aspects: one is COD theory and another is R6 method based on the J integral. The main research work includes: the testing and studies of COD resistance curve (R-curve) [9]; the assessing procedure based on the COD theory and the comparison analyses between the procedure in China and abroad[10]; the high strain area crack tip opening displacement COD expression[11]; the safety and reliability analysis of CVDA design curve[12], its research results have formed the industry standard " safety assessment for pressure vessels containing defects, CVDA-84 [13]. Studies have also been carried out on the new R6 method of English CEGB and the American EPRI method, namely elastic-plastic fracture theory on the basis of the J integral theory, such as study [14] on the J_R R-curve for different materials, studies on general failure assessing curve based on the J integral criterion[15~16]. The researchachievements have formed SAPV95, the first draft of Chinese standard GB/T19642-2004.

3) On the foundation of the research of above two assessing theories and the EPRI project method, EPRI engineering evaluation optimization method [17, 18] has been brought forward in China at the end of 90s, through which an assessing method for area defects, namely an evaluation method based on the instable ductile fracture load theory (plastic instability theory) was formed. This method has already been integrated into Chinese national standards GB/T19624-2004 appendix F[19].

The assessing objects

The research on safety assessment was carried out for the pressure vessels first, then for the pressure piping and further for equipment and plant in complete set.

1) At the beginning of 1970s, when the structure integrity assessment research work was just developed, the main object of its application was the pressure vessels, also including some other simple components bearing pressure, like welding pipe connection in sea platform, gun barrel, astronavigation vessel, and so on.
2) From mid 1980s to later period of 1990s, with the development of elastic large plastic theory, the application was mainly shifted to the pressure piping with complex structure loadings. Pressure valve and other pressure components are also included.
3) Afterwards started the research on the structure integrity assessment of the entire equipment or plant, including power plant equipment and sea platform, airplane, chemical industry device and so on.

Fracture assessing criterion

In the fracture failure criterion, elastic fracture assessing criterion is introduced first, then the COD design curve in our country, next developed the studies on R6 failure assessment curve, finally carries on the research and the application of the ductility tearing instability stress.

In 1984, the Pressure Vessel Division of the Chinese Mechanical Engineering Society (CMES) and the Machinery and the Automated Division of the Chemical Industry and Engineering Society of China (CIESC) worked out "safety assessment for pressure vessels containing defects"(called CVDA-84 for short) [13] according to the earlier research results. This standard had ascertained the fracture failure criterion on the foundation of COD.
The CVDA design curve is shown in Figure 1 and its expression is as follows:

$$\phi = \frac{\delta}{2\pi a \varepsilon_s} = (\varepsilon/\varepsilon_s)^2 \quad (\varepsilon/\varepsilon_s \le 1);$$
$$\phi = \frac{\delta}{2\pi a \varepsilon_s} = \frac{1}{2}(\varepsilon/\varepsilon_s + 1) \quad (\varepsilon/\varepsilon_s \succ 1) \qquad (1)$$

where δ is crack opening displacement, the half length of penetrated crack, the strain, the yield strain.

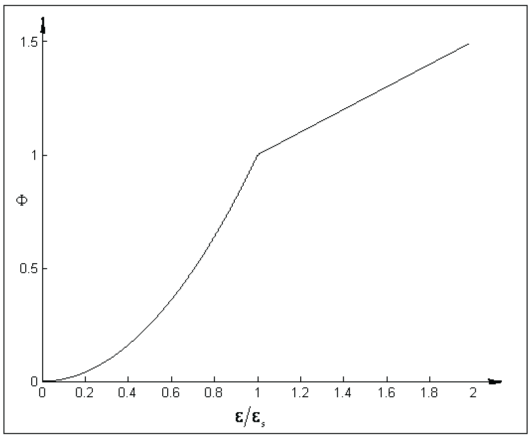

FIGURE: 1 - CVDA-84 FAC

CVDA-84 had reflected the technical level in China at that time. Compared with the standards of other countries which used the COD theory as the foundation at that time, it was quite reasonable. Moreover based upon the performance of the commonly used pressure vessel steels in China and the large plate safety experimental studies, the COD curve in the standard CVDA-84 has madesome modifications compared to the COD curve shape between $S_r=\delta_r=0.8\sim1.2$ (where δ_r fracture ratio, S_r stress ratio) as shown in Fig.2, which is to conform to the actual situation of Chinese produced steels, therefore it has certain advanced aspects in the standard in the 80s initial period.

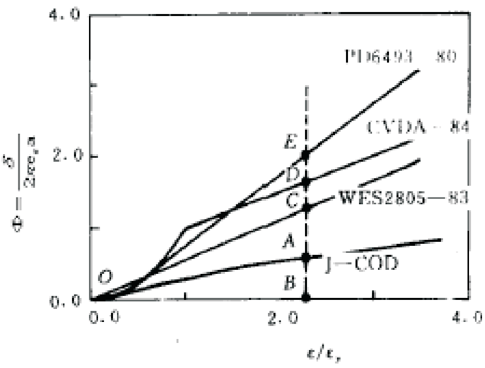

FIGURE: 2FAC in different standards

Along with the worldwide development of the safety assessment technology for pressure vessels containing defects, massive research work on the most advanced elastic-plastic fracture analysis method has also been carried out in China in recent years. Simultaneously research works on how to apply the overseas up-to-date achievements to the vessel steels with long yielding platform which were most often used in China were conducted. To the 90s studies on elastic-plastic fracture analysis and failure assessment curve with the J integral theory as the foundation had made significant progress. China Key Technologies R&D Program (1992-1995) sponsored a key project which obtained more than eight hundred failure assessment curves (FAC) from thousands of specimens processed by different manufacturers with different heat treatment, thickness of plate, testing temperature and crack shapes (as shown in Fig.3). From the research it was found that around the point of Lr=1, most of the testing curves are below the R6 curve. Among them, general failure assessment curve equation for long yield point jog steel is defined as $Kr=(1-0.211L_r^{1.32})[0.1+0.9\exp(-1.72L_r^{10.4})]$ (where Kr is the

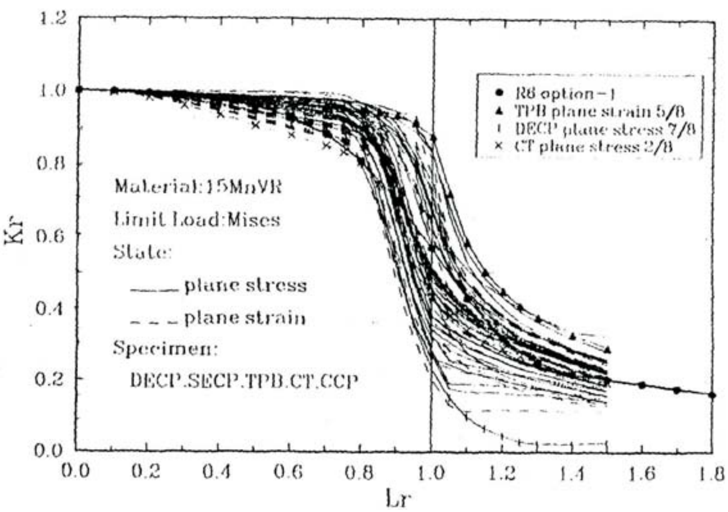

FIGURE: 3-15MnVR tested FACs for steels with long yielding platform fracture ratio, Lr is the stress ratio), the curve is shown in Fig.4. The cut line of the curve is L^{max}.

The general failure assessment curve R6 is safe and reasonable for the pressure vessel steels without long yield point jog and with yield point above 400MPa and austenitic steel. In order to match the international failure assessment curve, the general R6 curve was used in China's standard GB/T 19624-2004.

4) To ascertain plastic instability stress on the plastic deformation condition, from the 90s, much research work has been done according to the EPRI fracture plastic instability criterion [19], The plastic collapse loads of four kinds of cracks have been given: radial crack in the vessel internal surface, full circular radial crack in the vessel internal surface, the internal surface axial crack and the internal surface major axis to the crack which formed a set of China's unique fracture failure stress assessing technology and method.

Technology of safety assessment

As for technology of safety assessment, it went from safety assessment expanded to the risk assessment, and then developed into the safety security technology research and application

As mentioned above, since the beginning of the 70s, China has carried out the study and practice of structural integrity assessment for nearly 40 years.

In 1995, Pan Jiahua introduced comprehensively the United States pipeline risk management handbook which aroused wide concerns among the Chinese academic community. From then on, a certain discussions regarding the fuel gas pipeline risk assessment methods have been made in China. A series of practical risk assessment method were proposed profited from the overseas research results. There were also many fruitful studies on remaining life of the corrosion pipeline, pipeline reliability under multi-factor influence, pipeline aspects and the quantitative risk assessment for piping conducted which has helped solve the actual practice problems.

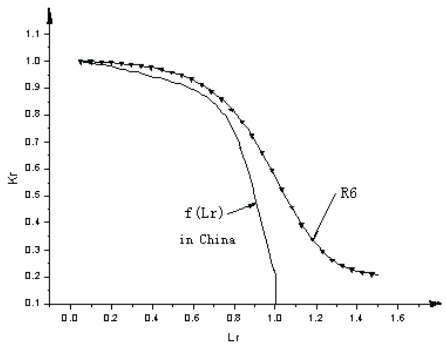

FIGURE:4 FAC for steels with long yield platform

Around the 21st century, researches on the safety security techniques have been carried out in China, like the city buried the fuel gas pipeline and the safety security technique engineering research for the industry special bearing pressure equipment, including the related significant dangerous source appraisal, risk assessment, pipeline corrosion protection, online detection technology and so on. This research advanced the transformation of research results to the production practice.

Basis of safety assessment

The development of the safety assessment has experienced various stages, i.e., the empirical assessment, the deterministic assessment, and the probabilistic assessment.

In China the method of the safety assessment was based on experience in early time, such as some safety inspection standards provided in the 1980s "Pressure Vessel Inspection Rules".

In the 1990s, technical specification, CVDA84, was mainly based on the theory of COD, but COD theory has its own inherent weaknesses. Along with the development of safety assessment technology for pressure vessels containing flaws in the world, recent years massive research work in China has been done on the advanced elastic-plastic fracture analysis theory and method, and focused on quantitative and deterministic method.

At present many researches carried out in China are related to the probability, fuzzy and so on. The research of probabilistic safety assessment based on the probability fracture mechanism for pressure vessels and piping systems in China includes two areas: one is the analysis of the distribution of main variables influencing the probability of failure [20] (namely study on the probability distribution of safety assessment parameters, such as studied on the ability to NDT, the probability distribution analysis of defects parameter[21-23], on the probability distribution analysis of general mechanical properties and toughness, on the stress random uncertainty analysis of the pressure vessels and equipment such as pipes); the other is the study of the approaches determining the probability of failure of structural components, mainly based on the probability of fracture mechanics of the Full Distribution Approach, Monte-Carlo method and first order second moment approach[24], Edgeworth method [25, 26], Bayesian method [27] and fuzzy methods of safety assessment study [28]. Some encouraging results have been achieved [21-28].

Safety assessment at various working condition and medium

In working condition and medium of safety assessment, the structural integrity assessment technology in China has experienced the development from the air to high-temperature, then to corrosion medium.

In the 70s and the 80s, the working conditions of the research components is generally under the air, namely only the performance of materials under air and room temperature was consider.

In the 1990s, more studies on the performance assessment of materials under various temperature were carried out in China. The range of the research covered the high temperature detection technology, thermo elastic-plastic-creep analysis and the damage of pressure vessels, the application of creep stress in the safety assessing, high-temperature component life prediction, high-temperature fatigue theory, high-temperature defect classification safety assessment methods [29-30]. Currently the main areas of research focused on two aspects: the structural integrity theory of high-temperature damage based on the damage theory and the theory of high-temperature structural integrity based on the fracture theory [31].

The study on stress corrosion and corrosion fatigue of some Chinese produced steels was started in the 90s which including the performance research of materials suffering the stress corrosion and the corrosion fatigue, the corrosion rule and the corrosion rate under the different corrosion environment and so on [32-34].

The relevant research results of safety assessment technology about stress corrosion and high-temperature creep have integrated to China's national standards" Safety assessment for in-service pressure vessels containing defects "GB/T19624-2004.

Safety assessment range

In safety assessing range, it experienced a technical study to the development of standards, and then technology and the application of the standards development process in China.

Study and application team of safety assessment

The Study and application team of safety assessment concentrated in the industry of pressure vessels and piping first in China, then expanded to the other industries, now it is a nationwide organization.

The research of engineering structural integrity concentrated in the pressure vessels at the beginning. Afterwards it expanded to the pressure piping, at present the research works for the equipments on harbor, amusement park, airplane etc. have already started. The series research results have been widely used in many aspects in China. So the study and application team of safety assessment has become a nationwide organization.

Main technical progresses of engineering structural integrity assessment in China

The main technological progresses of engineering structural integrity assessment can be summarized in the following 10 aspects.

Failure Assessment Diagram Technique based on COD Curve

The first level assessment is called the simplification assessment in China standard GB/T19624-2004[19], which inherited the essence of CVDA-84[13]. The COD design curve (Figure 1) has been transformed into failure assessment diagram in the first level assessment[19], in which

$\sqrt{\delta / \delta_c}$ (where δ_c is the critical COD for a crack) is

taken as the ordinate, $\delta=\delta_c/2$ as critical conditions

(namely $\sqrt{\delta_r} = \sqrt{\delta / \delta_c} = 0.7$), and $S_r=L_r(\sigma s+\sigma_b/2\sigma_s)$

as the abscissa, $S_r=0.8$ as the boundary cutline in the rectangular line failure assessment diagram (Figure 5).

It can be seen from the wide plate test results that, when , the fracture points often fall above the Bürdikin design curve (see Figure2 PD6493 curve) and below CVDA design curve.This phenomenon shows that the CVDA-84 design curve represents the better agreement with the experiment results in China compared with BSI PD6493-91, which indicates that the CVDA design curve is more practical [35~37].

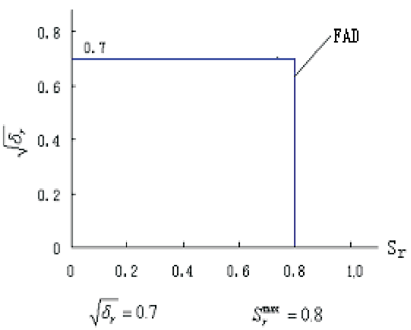

FIGURE: 5 FAD of first level assessment in GB/T19624-2004

Engineering optimization technology of EPRI fracture instability assessment

Researches on engineering optimization technology of EPRI fracture instability assessment were carried out in China. The research achievements have formed an assessment method for area defects. The J integral is used as the fracture parameter directly in this method which is the strictest elastic-plastic fracture mechanics assessment method. The whole fracture process in which from crack initiation on the pressure vessels, to its limited tearing and instable tearing can be assessed accurately by this method.

The option 3 and level 3 of R6 assessment method can make the precise assessment. Another assessing method similar to the option 3 of R6 method also can do the precise assessment in which the instability condition is $J(\sigma,a) = Jr(\Delta a)$ and

$$\frac{\partial J(\sigma_R, a)}{\partial a} = \frac{\partial J(\Delta a)}{\partial a}$$

, the stability assessing diagram is proposed by EPRI, the instability point should be determined by the tangent point of resistance curve and the driving force curve. The tangent point, however, is difficult to determine. In the Chinese standard, an "optimisation" method is used to find out the instability stress. Given a Δa_k value, the corresponding stress σ_k can be determined based on the equilibrium condition $J(\sigma,a)=j_R(\Delta a_k)$, the maximum value of σ_k is therefore considered the instability stress. The process is computerized using a software developed in China. This method is called the EPRI engineering optimization assessment method which reflects China's achievement in this area[17, 18].

Analysis and assessment need a lot of detailed first-hand information, such as the reliable J integral solution and entire resistance curve of materials. There are, however, only parts of J integral solutions for structures containing crack. Therefore, the analysis assessment method is mainly applied to the important large containers and its components containing defects which cannot be assessed by the conventional assessment and difficult to repair. It is also the technical basis and the important means to study, develop, and evaluate the conventional evaluation methods [35, 36].

Joining technology between fracture conventional assessment and analysis assessment in CVDA-84 and GB/T19624-2004

The different level of safety coefficients was introduced to safety simplified assessment, conventional assessment and analysis assessment. Selecting appropriately the safety coefficients can solve the reasonable compatibility problem between different assessment levels, including conventional assessment and analysis assessment, simplified assessment and conventional assessment of pressure vessels containing planar defects. This technique can prevent the "reversal" phenomenon, in which the flaws can pass through the simplified assessment while cannot pass through conventional assessment, or can pass through conventional assessment while cannot pass through the analysis assessment. It guarantees that the three level elastic-plastic assessment method of planar flaw becomes a relatively complete system [35,36,38].

Assessing technology of instability limit load for voluminal (pits) flaw

The assessing technology of instability limit load for pits flaw of pressure vessels was carried out in the "8.5" Key Technologies R&D Program. Figure 6 shows the limit load of single notched plate specimen under the plane strain tension and bending mixed loading condition[39].

The pits are the common flaws of pressure vessels. Pits can be caused by corrosion, mechanical damage, or form from the surface crack due to polishing or other superficial flaws. Pits are generally less dangerous than crack. The provision of the reliable safety assessment method for pit flaws can avoid welding repair and then avoid the occurrence of new cracks formed during the welding process. Therefore, the method has the great practical significance.

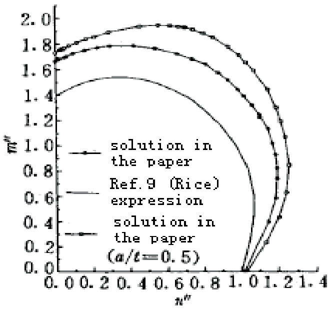

FIGURE: 6 limit load of unilateralism slotted under plane strain and stretch and bending force plate comparison between the Rice J

The pit plastic failure mode is possibly the overall plasticity collapses, or partial plastic failure on the bottom of pit. The research results obtained from elastic-plastic analysis, the limit load analysis, the stable load computation and experiments of all the plates, spherical and cylindrical shells with large number of pit flaws[40] showed that the plastic limit bearing capacity of vessels was influenced by the following two parameters: Z/B and, $X/\sqrt{RB}$, where Z is the pits depth, B the thickness of spherical shell, X the half length of pits, R average radius of vessels.

The limit load of the spherical shell with pits may be the expressed conservatively as,

$$(P_L/P_{L0}) = 1-0.6\frac{Z}{B}\frac{X}{\sqrt{RB}} = 1-0.6G_0 \qquad (2)$$

where is the limit load with pits, the limit load without pits.

The concept of the assessment method for voluminal flaws is clear and the application is easy to handle. Therefore, the method is widely used in engineering projects. It is an innovative engineering approach in China, which can "liberate" a considerable number of pits from repairing.

If there is no planar flaw (crack for example) among pits, this proposed practical method is conservative and safe enough [35, 38-41].

Plastic modifying factor K_r of crack tip when Secondary Stresses conservation

Supported by "8.5" Key Technologies R&D Program in China, research was carried out on the problem that Rice J integral is no longer conservative with the presence of the secondary stress. Figure 7 is the comparison between the Rice J integral, J' integral test results and the fracture toughness J_{IC} of 16MnR plate specimens with center penetration butt-welding crack under tensile load. It can be seen that Rice J integral is significantly below the fracture toughness J_{IC}, while J 'test results and the fracture toughness J_{Ic} are in good agreement. This proves that when secondary stress exists J integral fracture criterion is no longer $J=J_{IC}$, which is based on Rice J integral, but should be $J'=J_{IC}$ based on J' integral.

The revised J integral and its computational procedure was proposed in China for the conditions where secondary stress exists. On the basis of it an advanced crack tip Kr plasticity modifying factor was instructed. The experiments showed that the application of the factor is safe and reliable.

Simultaneously the research work on this aspect showed that secondary stress coefficient Xr in CVDA - 84 is not a constant and varies in wide range. So in GB/T19624-2004 the secondary stress coefficient Xr in fracture simplified assessment for planar defects was amended to make it agree with the engineering practice [42].

Modifying coefficient for Multi-crack elastic-plastic interaction

The elastic-plastic analysis of crack interference effects was studied in China. Practically defect does not always exist in isolation. Generally two neighboring cracks are taken as one large penetrated crack when the stress intensity factor increased to a certain extent in the most standards abroad. It is found that in "8. 5" Key Technologies R&D Program the elastic-plastic crack interference effect $\sqrt{J_{double}/J_{single}}$ is much more than elastic interference effect K_{double}/K_{single}, and related to the constitutive relationship of the material and the load level. For example, when the distance between two adjacent cracks is more than the crack length, according to the old norms no mutual influence for both cracks should be considered.

But elastic-plastic analysis of double crack interference shows that, for material A533B, when $L_r>1$, the elastic-plastic interference effects G = $\sqrt{J_{double}/J_{single}}$ can reach to 1.40, and for materials 16MnR, when L_r-1, G can go up to 2.1. Obviously neglect of the interaction will bring unsafe consequences.

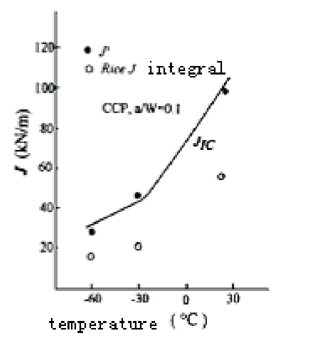

FIGURE: 7 comparison between the Rice J integral, J 'integral test results and the fracture toughness J_I

The research works supported by "8.5" Key Technologies R&D Program in China demonstrated that the general failure assessment curve can be used for the fracture assessment of defects with elastic-plastic interference effects through multiplying adjacent defects interference coefficient G. The interference coefficient G was calculated according to different stress-strain relationships of materials and listed in the attached forms of Appendix A of Chinese standard GB/T19624-2004 which is convenient to apply [35].

U factor assessing method for pressure piping with circumferential planar defects[43,44]

The studies of U factor

($U = (\sigma_s + \sigma_b)/(2L_r^F \cdot \sigma_s)$, where the yield strength, tensile strength, the L_r^F at fracture initiation) assessing method for Pressure piping with circumferential planar defects were supported by "9.5" Key Technologies R&D Program in China. An engineering assessment method with simplified factor was proposed which can be applied to any materials with various stress - strain relationships, fracture toughness values, and the safety coefficient could be chosen freely. It is a criterion representing the initiation of fracture at the defects. U factor assessing method for Pressure piping with circumferential planar defects is very simple to apply with high degree of accuracy. The circumferential planar defects under mixed loading including tensile stress, bending stress, distorting stress and inner stress can be assessed by the U factor engineering assessing method.

Probabilistic analysis of failure assessment curves of Chinese made steels

As discussed above, major part of the testing curve (mainly for the long yielding platform steel) is below the R6 curve at the point Lr=1, which means the reliability of the R6 curve can not be considered to be 100% or 99% as we usually do. So the reliability analysis was carried out for these failures assessment curves.

First, the distribution of data of failure assessment curves corresponding to different Lr value was analyzed using probability paper method and Kolmogorov test. It was found that the data follow the normal distribution; then, the 50%, 60%, 70%, 80%, 90%, 99% fractile failure assessing curves can be obtained through the statistical analysis; last, the general failure assessing curves for long yielding platform (Chinese produced) steels in different fractile and its expression were obtained using piecewise method (three pieces) and approximation analysis method as shown in Figure 8 and Table1 which will be valuable for probability safety assessment[45].

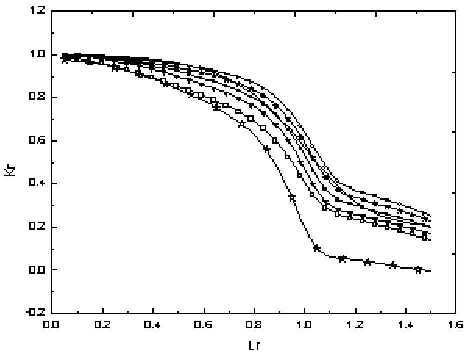

FIGURE: 8 Failure assessing curves on different fractile

Fractile	Fitting equations
50%	$Kr=(1-0.19Lr^{2.47})[0.53+0.46\exp(-0.566Lr^{12.5})]$
60%	$Kr=(1-0.24Lr^{2.05})[0.52+0.47\exp(-0.63Lr^{12.8})]$
70%	$Kr=(1-0.28Lr^{1.8})[0.5+0.5\exp(-0.74Lr^{13.5})]$
80%	$Kr=(1-0.33Lr^{1.6})[0.47+0.54\exp(-0.86Lr^{13.3})]$
90%	$Kr=(1-0.4Lr^{1.4})[0.41+0.6\exp(-1.08Lr^{13.6})]$
99%	$Kr=(1-0.5Lr^{1.8})[0.15+0.83\exp(-1.2Lr^{14.6})]$

Table 1 - Fitting equations of failure assessing curves on different fractile

Synthesis assessing technologies of fracture, collapsing, corrosion and high temperature

In standard [19], it is emphasized in the general remarks that it should take Synthesis safety assessing to the evaluated object. At the same time, a general principle has been set up for "The judgment of failure mode" and "selection of safety assessment methods". Failure Mode judgment should be based on the cases and experience of the failure analysis and safety assessment of similar pressure vessels or structures, on the specific manufacturing and testing data, applying conditions, the physical and chemical testing and physical diagnosis of defects. The possible effects of corrosion, stress corrosion, temperature and environmental conditions on the failure modes and the safety assessment methods should be fully considered. Therefore, the standard GB/T19624-2004 [19] is the Synthesis assessing technologies of fracture, collapsing, corrosion and high temperature.

Technical progress in probability safety assessment

In the theoretical and technical aspects of probabilistic safety assessment (namely PSA), some progresses have been made, including the study on the uncertainty of evaluation parameters and on the probabilistic safety assessment methods.

As for the research on the uncertainty of evaluation parameters, Ref [46] proposed the Bayes method for the probability assessment of nondestructive evaluation ability, namely

$$P[B_1 / A_1] = \frac{1}{1+\alpha \cdot \beta} \qquad (3)$$

where $P[B_1/A_1]$ is the probability of detected defects on a certain size, commonly expressed by the probability of detectable, $P[A_1]$ the probability of detected of the detects, $P[B_1]$ the probability of defects existing on a certain size, $P[B_2]$ the probability of a certain size defects is no exist,

$\alpha = \frac{P[B_2]}{P[B_1]}$, β the ratio of condition, probability of defects has been detected while the preset size defects is no exist. The method can assess the ability of nondestructive evaluation quantitatively.

As for the probabilistic safety assessment methods and technology, the main research work is carried out on the basis of deterministic safety assessment method together with the probability fracture mechanics and Monte-Carlo simulation technique. Some studies have their own characteristics, such as literature [27] proposed the "structural integrity assessment probability R6 method " in which statistical analysis was conducted on the reservation coefficient F_p^l, a probability density function was deduced, in turn the failure rate (also known as "reservations coefficient method") was obtained; Chen [46] proposed a criterion based on the dual criteria of random interference model; Ref[28] proposed a fuzzy reliability evaluation method for pressure pipeline containing defects; Ref[47, 48] gave the reliability safety assessment of the pipeline and safety grading assessment method and technology; Ref[49,50] presented fatigue fracture probability analysis and evaluation methods based on two random variables, and stochastic processes.

Technical progress in risk assessment

Normally, there are two variables to characterize the risk characteristics: the probability of failure and loss of failure. The research and application of risk assessment technology are mainly concentrated on the controllable expression method, variability expression method, application of extendable method and Markov methods.

Awareness of risk Controllability has gone through a long process. Risk control can be divided into two methods: reducing the possibility of their occurrence and reducing losses with its occurrence. The classic risk-control means include risk avoidance, risk transfer, risk undertaking and risk control. Ref [51] suggested that using the power function express risk controllability, and using the controllability power function amend risk size. Effectiveness function is valuable for the awareness of risk nature. But it will not be helpful for the selection of control scheme. Effectiveness function in practice is difficult to apply.

The same risks at different times may have different probabilities and loss of function, or even have different risk control effectiveness function. So Ref [52] introduced parameters to express the risk of variability, the parameters of time t and the role of the extent d, discriminant function DSF (t, d), is defined as follows :

$$DFS(t,d) = \begin{cases} 0, & t \in [0,T] \\ d & t \in [0,T] \end{cases} \qquad (4)$$

This method provides a set of ideas to study the variability of risk and explaining the uncertainty characteristics of risks.

In addition, the literature [53~56] applied matter-element theory and extension set theory to do the risk rating assessment of pipeline which avoid the human error during classification evaluation. Ref [43] applied Markov chain model to the calculation of failure probability of the city buried gas pipeline. The method used four-state Markov chain to describe the actual conditions of the pipeline in which failure rate of the pipeline changing with time can be calculated. It can play the prediction role.

In summary, through the years of research in China, the achievements not only can be used on safety assessment and risk assessment of pressure vessels and piping, but also can prevent the failure of such equipments, and will further improve the scientific research and application of the corresponding theories and technologies.

Applications of engineering structure integrity assessment technolgy in China

The research achievements of structural integrity assessment techniques and methods have been used widely in China especially on the following aspects: the constitution of the standards, defect detection and safety assessment, risk analysis and management, structure failure analysis and prevention, life prediction.

Application in constitution of standards

The study achievements of engineering structural integrity assessment theories and techniques in China have formed a national standard GB/T19624-2004[19] and been incorporated into a number of other regulations and standards, such as "Pressure Vessel regularly test rule" [49], "Industrial Pressure Pipeline Regular Testing Rule" (2003 edition), National Standards "Metal Pressure Vessel Acoustic Emission Testing and Evaluation Methods" GB/T18182-2000, Industry standards " Boilers, Pressure Vessels and Pressure Piping Nondestructive Testing (on application)" JB 4730-2004, "Pressure Vessel Safety Technology Supervision Rule" and National Standards "Blasting Tablets and Blasting Tablet Devices" GB 567 -1999 etc.

Application in defect detection and safety assessment

The research achievements of defect detection and safety assessment have been applied successfully to the special equipment, petrochemical installations, aeronautical facilities and port machineries.

The detection and safety assessment techniques have been used on the following special equipment: urban LNG tanks, spherical tanks of petrochemical industries, catalyst regeneration units, boilers, absorption towers, UHP reactors, coolers, petrochemical pipelines, connection tubes of nuclear power plants [57].

The detection and safety assessment techniques have also been used for the aerospace equipment, such as gas storage tanks, brackets, wings, under carriages and other components [58].

Applications to the major port machinery and equipment include: car dumper, ship unloader, the cranes [45, 57, 58] .

In addition, there are many applications in other industries, such as electric power (generator shaft), construction (tower belt machine), nuclear electric power (pressure vessel, steam generator, etc.) and so on [59].

Application in risk analysis and management[58-62]

Among the development of risk assessment techniques in China, great progress has been made in risk identification and analysis techniques. There are numerous successful applications of the technique: the safety evaluation of mechanical and petrochemical plants, thermal power stations, and cranes; the risk classification of chemical plants, metallurgy and smelting factories; and the hazard identification and risk assessment in electronics industry, the construction industry, the printing industry, mining industry, automobile manufacturing industry.

Simultaneously the risk management found its application widely on gas and oil pipelines, pressure vessels, the major port machinery, nuclear facilities and other large industrial equipment. Meanwhile, it has also been widely used on the massive building projects, such as subway tunnel, constructions, water conservancy facilities where exist a large amount of uncertainty risk factors [60-62].

Application in structure failure analysis and prevention[57]

Engineering structural integrity assessment theory and technique have been also applied to the analysis of large scale failure structures.

For example, in the "9.3" accident, belt elevator of tower belt machine used in one of the key projects in China crashed suddenly, which resulted in serious casualties. The theory and technique of "plastic limit load" was applied in the failure analysis and investigation of this accident. The analysis method was also used to other gas furnace failure accidents.

In addition, there are many failure analysis cases including the parts of cableway, elevators, coal mining equipments, lifting gears, automobile parts, etc.

Nowadays applications of this technique and corresponding standards have found its way to various industries in China.

Application in life prediction

The study of structural integrity assessment theory and technique is inseparable from life prediction research. There are a number of practical applications of life prediction theory and related technique. For example in the literature [63] life prediction model based on the reliability and damage theory was applied to the life forecast of concrete structures; in Ref. [64] life prediction theory was applied to the lifetime prediction of some in-service bridges; failure analysis and life prediction theories were also applied to technical management of petrochemical installations [65]; the high temperature structural integrity assessment was carried out for the life prediction of aviation and petrochemical parts [66] etc.

In a word, the engineering applications of the research achievements of structural integrity assessment have been widely conducted in many industries such as general machinery, chemical and petrochemical, transport, electricity power and energy, construction, aerospace etc.

Prospect of the technology and methods of structure integrity assessment

In summary, the study of engineering structure integrity assessment (including probabilistic safety assessment and risk assessment) in China has been carried out for more than forty years and obtained great achievements. In the following areas, however, further efforts should be made in the future:

1) Optimisation technology of safety factor;
2) Engineering methods of probabilistic safety assessment and the relationship between deterministic assessment and probabilistic safety assessment;
3) Precise fracture assessment technique and methodology;
4) The optimization and dissemination of EPRI engineering evaluation method;
5) Identification technique of the failure modes during integrity evaluation;
6) Engineering application of life prediction technique and methods;
7) Joining technique between safety assessment, risk assessment and life prediction;
8) Safety assessment technology and methodology for complex failure modes resulting from various defects;
9) Safety assessment technology and methodology for operating plant or whole set equipment;
10) Lifetime monitoring and assessment of existing plants and components.

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