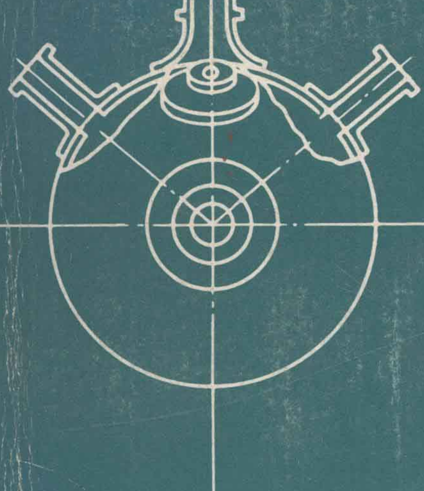

PRESSURE VESSEL TECHNOLOGY

Volume III

LECTURES and DISCUSSIONS

Fifth
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n Francisco, California

Fifth International Conference on

PRESSURE VESSEL TECHNOLOGY

Volume III

LECTURES and DISCUSSIONS

papers presented at the
Fifth International Conference
on Pressure Vessel
Technology

San Francisco, California
September 9-14, 1984

organized by
American Participation Committee of
The American Society of Mechanical Engineers

with the support of
European Participation Committee and
The Institute of Mechanical Engineers (U.K.)

Japanese Participation Committee and
The Japan High Pressure Institute

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

Proceedings of the Fifth International Conference on Pressure Vessel Technology

Volume I – Design and Analysis

Volume II – Materials and Manufacturing

Volume III – Lectures and Discussions

Within the text of each paper, numbers in parentheses indicate equations, and numbers in square brackets denote bibliographical references, which are listed at the end of the paper.

Library of Congress Catalog Card Number 70-99096

FOREWORD

This is Volume III of the *Proceedings of the Fifth International Conference on Pressure Vessel Technology* (ICPVT) held in San Francisco, California, United States, September 9-14, 1984. The first two volumes were published before the Conference and included the majority of the papers that were presented at the Conference. The two volumes were: *Volume I – Design and Analysis* and *Volume II – Materials and Manufacturing.* This volume includes the Lectures which were given at the Conference, several papers which were not printed in Volumes I and II, and discussions and authors' closures of the Conference papers.

In addition to these three volumes, the American Society of Mechanical Engineers printed a special publication, *1984 International Design Criteria of Boilers and Pressure Vessels,* edited by T. J. Capozzi and J. R. Farr, PVP-97, 1984. The publication includes papers presented by the six international panelists in a session of the Conference devoted to discussion of progress in design criteria development.

Those readers who may be interested in the historical background of the ICPVT are referred to the Foreword in the first two volumes.

Included in this volume are papers presented by the invited lecturers for the Conference. One of the papers, "Pressure Vessel Technology – Its Change by Exchange," was the 1984 Robert Wylie Memorial Lecture which was given by Dr. R. W. Nichols, Head of Risley Nuclear Laboratories, United Kingdom Atomic Energy Authority, England. The Lecture was one of the highlights of the ICPVT. The paper reviews some of the recent important international developments in pressure vessel technology and indicates the importance of exchanges between countries and various industrial sectors. It was a very appropriate paper for the ICPVT since one of the main purposes of the ICPVT is to provide a forum for international dialogue on the advancements in pressure vessel technology.

The international pressure vessel technologists are indebted to all of the authors and lecturers for their fine contributions, to the International Council for Pressure Vessel Technology for its continued sponsorship of the ICPVT, to the staff of the American Society of Mechanical Engineers for this ICPVT, and to the Conference Chairman, Dr. Pedro V. Marcal and his staff for the many hours put into organizing the Conference.

Don B. Van Fossen
Technical Program Chairman

DR. BOB WYLIE

"BY THEIR FRUITS
YE SHALL KNOW THEM"

CONTENTS

PRESSURE VESSEL TECHNOLOGY — ITS CHANGE BY EXCHANGE

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ABSTRACT

This paper reviews some developments in pressure vessel technology which have occurred since the last ICPVT Conference, and indicates the importance of exchange between countries and between industrial sectors in producing such developments. Major technical areas covered include materials, fabrication, fatigue, fracture mechanics, environmental effects and nondestructive examination in aid of the assurance of structural integrity.

INTRODUCTION

The preparation and presentation of this lecture is both an honor and a responsibility since both my friendship with and my respect for Bob Wylie make it essential for me to make my best attempt to honor his memory. The theme I have taken is one that I believe would be much to his liking – that it is the exchange of information between technological disciplines and differing applications as well as the exchange between different countries that lead to real development in technology and real benefit to all mankind.

I could quote many examples from Bob Wylie's own career. He joined the South West Research Institute in 1961 with a background experience in pressure vessel technology gained in fabrication experience for a wide range of applications. It was this experience that led to him being called on to make a technical quality assurance audit of the Elk River reactor pressure vessel, and which in turn led to him recommending an ultrasonic examination to be made from the inside of the vessel which was by this time installed in its operational location. The resulting ultrasonic inspection of the nozzle/shell welds made in 1963 from inside the nozzles was as far as I know the first such ultrasonic in-service inspection performed on any reactor pressure vessel. In the 20 years since that inspection, there have been considerable developments in both the techniques and our understanding of the factors controlling effectiveness of ultrasonics, and later in this paper I will review some of these. In this introduction, however, it is worth stressing that many of these developments have occurred because of international exchanges, both those which involve direct collaborative work and those that pass on the chain of existing knowledge to someone who may then forge a new link.

Bob Wylie was active in both these areas – he initiated the Inter-American Conference on Materials Technology of which the 8th was held in Puerto Rico in July 1984. He had the idea of holding international conferences on pressure vessel technology, of which this present meeting is the fifth, and he arranged discussions with Professor Dirk Latzko from which the first such conference at Delft evolved. But this international collaboration was not limited to conferences – his initiative in developing in-service inspection technology involved him in work with several other countries such as Argentina, Japan and Sweden, and of course it was the crash of a flight connected with such work that led to his tragic and early death.

*Dr. Roy Nichols is Head of Risley Nuclear Laboratories, UKAEA, England and Visiting Professor on Pressure Vessel Technology to Paisley College, Scotland.

Bob Wylie recognized that one of the ways of improving the general level of technology was by codification and as always applied himself actively to help what he belived in. He was one of the principal writers of the Section III (Nuclear) of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, a document which has made a tremendous contribution both within USA and internationally to work, improving the level of Pressure Vessel Technology. However, Bob was not satisfied just to rely on the possibility of other countries adopting the ASME approach but actively worked towards international standardization by his participation in the International Atomic Energy Agency meetings on in-service inspection.

These examples will suffice to show Bob Wylie's foresight and initiative in international exchange and in the technical skills of in-service inspection, and if this were all that he had done his work would still merit this memorial. There is one more aspect of interdisciplinary exchange that has even more importance, his realization that if defects are found there must be methods available to repair them; and since he also recognized that such repairs could be not only difficult and expensive, but also in some cases actually risk leaving the vessel in a worse condition, he recognized that there needed to be a rational basis for assessing the significance of flaws in relation to the continuing integrity of the pressure vessel. It was his cooperation with Bill Cooper on applying fracture mechanics to the crack that had been found in the Hatch 1 RPV nozzle-to-vessel weld which provided one of the earliest examples of assessing the significance of a flaw in such a vessel, and led eventually to the detailed developments of Section XI and its Appendix G, and incidentally to much interesting scientific and experimental work. Similarly, he realized the importance of high quality fabrication, and took the lead in giving good advice in this direction whenever he could. This included advice on post-weld repair techniques to a Swedish vessel which appear to have stood up to repeated and searching tests.

In the remainder of this paper Bob Wylie will not be mentioned, but I hope that the paper will follow in the spirit of his approach so much that his influence will be felt and recognized. It will give a brief review of some of the more evident direction of development of pressure vessel technology that have occurred over the last few years, particularly the four years since ICPVT4. It will then give a number of examples where exchange between different technical disciplines or fields of activity, or between countries, have produced results. Finally, particular attention will be given to developments in the application of NDT and fracture mechanics in the development of the "Fitness-for-Purpose" approach that was so much a personal interest of Bob Wylie.

REVIEW OF RECENT DEVELOPMENT TRENDS

It is always difficult to identify the areas in which industrial technological development is occurring, especially within an industry as wide-ranging and with such ill defined boundaries as the pressure vessels and piping area. This is the case even if we define development in the narrow sense of technical research and development, whilst recognizing that important aspects of industrial development are associated with business, investment and personnel aspects. It is also difficult to separate the effort spent on longer term research and development from the shorter term aspects of technical aid, trouble shooting and quality control applied directly to the manufacturing industry.

This problem was recognized by the UK Committee of Enquiry on Pressure Vessels [1] who used a broad definition in seeking information on directions of pressure vessels R&D, based on a survey made in 1967.

In addition to the directions of work in progress (Fig. 1), the report of this Committee of Enquiry also predicted how it would be divided in what was then the future. It is interesting to compare these predictions with new estimates of the allocation of present day work. These have been made on a different basis from that used in the 1969 Committee of Enquiry report, being based on the publications made in three different sets of international proceedings, information which, by its nature, will relate more to those items of longer term interest and which may exclude aspects where proprietary commercial security prevents publication. The results are summarized in Table 1. A major area of interest indicated in all of these surveys is that of structural analysis; whilst there has been some decrease in elastic stress analysis work, nevertheless, the activity on stress analysis remains at a high level. The interest in getting more information on modes of failure (e.g., Fracture, Creep and Fatigue) appears to have increased over the 1969 expectation. This perhaps arises from the increasing amount of structural integrity assessment done by, for example, the nuclear industry whose purchases of large, thick, high quality vessels for the primary circuits of light water reactors have been of great importance to the high technology sector of the pressure vessel industry. Similar considerations have resulted from the high integrity requirements of the aerospace industry which pioneered much of the fracture mechanics work, and more recently in relation to pipework concerned with offshore plant and natural gas transmission. The widespread application of natural gas has reduced for a while the work on high temperature/high pressure vessels for coal conversion processes, but more recently there have been signs of an increasing interest. This is reflected in the work on materials, which also is notable for its accent on improving by modification and by doing work to allow more efficient use of materials based on well-tried compositions, because of the high cost of demonstrating and proving really novel material for applications related to high-integrity pressure vessels. An area of consistently high effort, which has been an important area for international collaboration, relates to quality control and non-destructive examination, which has progressed alongside developments in manufacturing processes to reduce the risk of these introducing flaws into the pressure vessels and piping, and to lead to more efficient manufacturing processes, for example, as a result of automation which has proved to be an important area of development in all types of vessels ranging from the heaviest nuclear pressure vessel to the small simple vessels used in such large numbers for carrying hydrocarbons.

Another source of information on the most interesting directions of development in pressure vessel technology is the 1984 Long Range Plan of the US Pressure Vessel Research Council [2]. Again, there is work on structural analysis of both pressure vessels and piping, involving studies of elevated temperature design, of dynamic loads and transient occurrences such as water hammer, pipe whip and seismic effects; the effect of tolerances and consideration of thin shell stability; the design of flanges and gaskets and the design of openings, reinforcements and nozzles. Again, the study of fracture mechanics (especially elastoplastic fracture mechanics, dynamic and crack arrest conditions and the "fitness-for-purpose" approach to flaw assessment) is regarded as a priority item, together with work on fatigue and elevated temperature properties. In material, again the accent is on improvement (for example, increasing strength) by modifying existing materials together with such approaches as microalloying and thermal mechanical working. The study of ageing, irradiation and hydrogen effects involve considerable international study. In the field of fabrication the development and assessment of narrow-gap methods is an important trend, whilst further work on operational repair and on the criteria of post-weld heat treatment is envisaged. The PVRC work also envisages considerable effort involving industrial co-operation and international collaboration on the development of effective NDE techniques (for example, for thick section welds) and for the assessment of those round robin tests. Work on personnel certification is also mentioned. The "fitness-for-purpose" approach to flaw assessment demands good characterization of the boundaries and position of any flaw, and this is an important area for further work. The PVRC program includes several other items, but this summary seems to emphasize that it sees similar areas of interest for development.

The rest of this paper will be devoted to giving examples indicative of progress in some of these development areas. Limits of space make it essential for this to be selective rather than comprehensive; because of the very numerous papers in the present conference devoted to the important areas of structural analysis and of the applications of computers to aid pressure vessel and piping structural design, including a plenary paper on the latter topic from Dr. Marcal [3], examples will not be quoted for this area. The examples will all be chosen from areas of personal experience, and thus arise particularly from U.K. work, although in most of the areas close international collaboration and exchange have played an important part in the development. Moreover, it must be emphasized that similar and interlocking developments arise around the world and the importance of these other developments not referred to specifically in this text is recognized.

MATERIAL ASPECTS

It has already been commented that major changes in material for pressurized components occur rarely, and normal progress occurs by evolutionary improvement and optimization of existing materials. Before discussing some of them related specifically to pressure vessels, some important aspects related to the development of iron and steel manufacture will be mentioned. Wilshawe et al. [4] have concluded that the broad aspects of development are little affected by economic depression, wars or even energy crises, but are predominately chosen on the basis of technological superiority. They predict (Fig. 2) that the oxygen processes now so popular for steelmaking will by the year 2000 have passed their prime due to the challenge of the electric arc and electric plasma furnaces – 40 MW plasma furnaces are already operating under commercial conditions. Ward [5] has commented that the inflexibility of operation and large scale of the blast furnaces, together with the high cost of electric energy, could lead to alternative approaches. Figure 3 summarizes the more important new steel making combinations under consideration today, the various initials referring to the names of specific examples of such development being done in many different countries.

Perhaps the biggest development in steelmaking that has occurred over the last few years has been the advent of ladle steelmaking. Such processes involving the injection of reagents, the use of synthetic slags, vacuum treatment, argon stirring and electric arc heating of the ladle have overcome the previously accepted technological limits on lower levels of such elements as sulphur, phosphorus, carbon and the various gases. Over the last 10 years there has been a drop in sulphur content by a factor of 10 (say from 0.03%) to 0.003%, and similarly of carbon content, with significant gains in such properties as fracture toughness and through-thickness ductility. Ladle processing has also made it more practical to obtain microalloyed steels; such steels as the micro alloyed carbon manganese x60 steel with a yield strength of 414 MPa and the more recent x80 steel with a yield strength of 550 MPa have been adopted for pipelines and show good toughness and weldability. Whilst early microalloyed steels relied on niobium and vanadium additions which brought some problems, with vacuum degassing and argon shrouded casting many producers are moving to a low-sulphur, titanium-niobium chemistry. Controlled rolling and the use of water cooling either during or after rolling can also improve properties.

Similar changes in steelmaking technology has led to cleaner pressure vessel steels of the high fracture toughness required for Pressurized Water Reactor (PWR) pressure vessels. Figure 4 shows the results of fracture toughness tests using large scale specimens (each of thickness over 240 mm) and it will be seen how temperature at which the K value reaches 200 MPa has progressively reduced, being at about 20°C in 1966 and -35°C in 1980. Expressed in terms of the Nil Ductility Transition Reference Temperature (RT_{NDT}), a mean value of -45°C is achievable [6] (Fig. 5). The same processes produce also a reduction in the segregation in the steel produced, and an increased cleanliness which is invaluable in improving the Flaw Signal/Noise ratio when doing ultrasonic examination of weld areas, thus allowing the use of high sensitivity techniques. Such processes, together with the careful control of scrap have allowed the consistent reduction in copper and phosphorus contents of reactor pressure vessel steels to achieve commercially and repeatedly values of around 0.03% Cu and 0.0056% P, which results in a steel that shows very little irradiation embrittlement, as shown in Fig. 6.

Another important materials development has been the increase in forging size now available. This use of forged rings to avoid longitudinal welds has been European practice for some time, but increased forging sizes have allowed the cylindrical welds to be put well away from the core region, and even to allow consideration of integral top ring/flange/nozzle forgings (Fig. 7). A similar approach has been made to manufacture in one piece the reactor bottom head dome. Taking advantage of these approaches can lead to a halving of the overall length of weld seams in a reactor pressure vessel [7]. Similar approaches have been used in the manufacture of other components in the reactor pressure circuit. For thinner wall vessels used in process plant a useful savings in length of weld scan can often be achieved still using a plate-welded design but increasing the plate size. A more recent development in forging, for which the results of making a 220T ingot and 1300 MWe PWR shell ring have been described [8], is that using a hollow ingot. It is considered that not only will this process have economic advantages, but it will also show reduced segregation (Fig. 8), reduced porosity and more uniform mechanical properties; the process is being adopted in Europe as well as Japan. Like all of the other examples in this section, such procedures are applicable not only to nuclear plant but to a wide range of pressure vessels and piping application, not only promising improved quality, but also offering reductions in cost and in manufacturing time.

FABRICATION AND WELDING

This emphasis on improvements in quality and on reduction in overall cost has also applied to developments in the processes for shaping and welding the various materials into a finished component. An example is the use of computer controlled presses for plate bending. One of the first computer controlled vertical press was supplied in 1977 to Westinghouse, Florida, USA and since then such plant has been considerably developed by ASEA (Sweden), another example of international collaboration [9]. Similar principals have been adopted for computer control of large Portal presses (Fig. 9), whic can give controlled press depths within 0.1 mm of pre-set values. By using the computer to store in its memory the operator's experience on forming the first plate or by using it to set feed and press depths which have been calculated to allow for spring back, such computer adaptive control can be used for cold forming operations to produce cylindrical shells and pipes. Robot carriages and associated lifting arms can also be computer controlled making use of position sensors. One method that can extend the range of products for lower press force capacities is to use step-wise forming with short tools and multiple press points (Fig. 10).

The concept of reducing the volume of weldment, from consideration both of avoidance of flaws and of giving economies of energy, of consumables and of workshop time has encouraged the development in several countries of narrow gap (or narrow groove) welding. Whilst the concept of using a narrow, almost parallel-sided joint preparation for butt welding of heavy section material originated some 20 years ago and has been worked on in several countries, one of the first practical prototypes was a narrow gap Metal Inert Gas (MIG) system produced in the USA [10]. Developments around the world to improve quality and reduce spatter include filling of the narrow gap such as by using weld beads produced from two electrodes, or by using arc rotation or oscillation (e.g., by using two wires twisted together, by rocking the electrode, by rotating an eccentric guide tube or by deforming the feed wire) (Fig. 11). Application of one version of the narrow gap gas-metal arc (GMA) system to a 1100 MW BWR pressure vessel has shown excellent dynamic fracture toughness throughout the narrow weldment (Fig. 12) [12]. Narrow gap orbital techniques have been used in the UK for some years for thick wall, low alloy steam piping (Fig. 13) and have made [13] feasible TIG welding for material thicknesses previously thought to be uneconomic. A version using the TIG narrow gap process using hot wire feed has been used for horizontal and vertical positional welding of 50 mm thick austentic steel vessels [14].

Narrow gap submerged arc welding equipment is in widespread use in Europe and Japan. The two-bead per layer technique is now well established and it can be achieved by using a hinged contact jaw with a joint tracking mechanism (Fig. 14) [15]. Such a technique has been incorporated in a large, fully automatic welding machine for thick shells up to 7.5 m dia for which it produced weldments with almost parallel sides 18 mm wide and up to 350 mm thick. The welding is done continuously from root to last bead without risking interruptions, and the concave shape of the bead is claimed to give exact fusion to the joint wall and to reduce the risk of slag inclusions. This is one of the factors which, with careful design of preheat equipment, has produced a marked reduction between 1977 and 1982 in the number of unacceptable indications given by high sensitivity ultrasonic tests. (Figs. 15a, 15b, and 16). Similar techniques have been used for numerous heat exchangers made in A336F22 forged steels and for AP15LXX52 off shore pipes [17].

Another welding process that leads to narrow, parallel sides weld joints but which can be welded in a single pass with low distortion and high quality is the Electron Beam technique. Conventional electron beam welding is done in a vacuum chamber and large vacuum chambers have been constructed such as that at the Welding Institute, U.K. (Fig. 16) [18]. Electron beam welds can also be made by using a localized vacuum and techniques have been demonstrated involving inflatable and sliding seals for both longitudinal and circumferential welds (Fig. 17). These methods have been applied to a model of the ultra high strength pressure hulls for deep submergence vessels [19] and more recently to a large vacuum vessel (outside diameter 3.5 m, inside diameter 1.7 m) and to demonstration lengths of HT60 pipe [20]. Screening of the operators from X-rays must be considered carefully. An important feature of this approach is a feedback system for controlling the welding conditions making use of a groove gap detector based on a photoelectric sensor.

The concept of feedback control and other forms of computerized control of welding is now well-established as a means of improving the quality, reducing the probability of flaws and making the welding process more economic. Similar reasons have led to the growing replacement of manual welding by automated techniques. Clevers [21] considered that by the year 2000 about 63% of the total deposited weld metal would be by mechanized processes (Fig. 18), a significant factor being the increased use of flux-cored wire to replace stick electrodes. The extension of such automated welding to the use of a robot welding system to interface with a computerized control unit for setting weld parameters is an active area of development, such robots now being applied in some applications. Indeed it can be expected that there will be growing use of computers and microprocessors for all aspects of fabrication, welding and shaping of pressure parts, from computer numerically controlled (CNC) equipment for tube and pipe bending, computer controlled welding processes and finally CNC machining, particularly applicable to preparation of such features as a nozzle/shell joint. Such CNC machining can make it more economic to machine from the solid complex items like tube sheets and even items now made by casting giving increased freedom of choice to the designer [22].

There is another aspect of welding development which is of more relevance to continued plant operation than to its initial manufacture, namely that of repair welding. An example of such a development is one which was done in order to fix internal sleeves to bridge over cracks in the tube/tubesheet welds of the UK Prototype Fast Breeder Reactor secondary heat exchangers [23]. This sleeve was brazed into the leaking tube some 100 mm below the suspect weld and explosively welded at its other end to the top of the tubesheet. In-situ machining was used to open out to a depth of 145 mm the tubesheet bore to receive the explosive weld, and to bore out 100 mm of the 2¼ CrMo tubes to provide a clean surface and truly circular hole suitable for brazing. Careful control of surface finish (e.g., to 0.4 m CLA for the explosive weld and about 1 m CLA for the brazing) is essential, the brazing process being done one tube at a time by RF induction heating using coils developed to fit inside the 16 mm bore of the tube, to heat it uniformly to 1150-1210°C. A high nickel brazing alloy (Nicrobraze 135) was used in an atmosphere of argon. Somewhat different environmental problems were faced by the designers of a subsea repair and welding system [24], which involved putting on the sea bed hydraulically operated pipe handling frames each side the pipe joint position, which itself was surrounded by a lightweight habitat and alignment unit (max. individual lift 50 tonnes). The whole system has considerable versatility and can be worked from a diving support vessel rather than from a construction barge. The importance of accurate pipeline alignment was also recognized in the automatic welding of the Riyadk 246 mile long pipeline for desalinated water, a

Saudi Arabian project in which companies from France, Holland, USA and West Germany collaborated to make 36,000 welds between the 60 in diameter x52 and x60 steel pipes achieving up to 104 joints in one 10 h day (Fig. 19) [25].

THE EFFECTS OF SERVICE CONDITIONS – FATIGUE AND CORROSION

The growing use of fracture mechanics to assess structural integrity of a wide range of pressure vessels and pipelines has directed attention to the assessment of the rate of growth of crack like flaws under the cyclic loading conditions that may arise in service. A state-of-the-art review of various aspects of this topic has recently been prepared for the Fracture committee of the Royal Society [26]. In this report, the design philosophies relating to pressure vessels, boilers and pipelines are reviewed, as is the application of fracture mechanics to sub-critical crack growth. Whilst the method described in ASME Boiler and Pressure Vessel Code Section XI (ASME XI) for the Linear Elastic Fracture Mechanics (LEFM) assessment of sub-critical crack growth by fatigue is endorsed for many applications, problems may arise in particular cases such as those involving predictions related to short cracks, the effects of residual stress and for a wide range of crack sizes and crack morphologies. Recommendations were made in relation to areas requiring work on standard specifications (mainly for test procedures) and for further research (methods of crack sizing NDT for in-service examination; compilation of lists of stress intensity factor solutions, study of crack growth from short cracks and in different environments).

Turning to the effect of environment on sub-critical crack growth, this area of work has proved to be an excellent example of active international collaboration involving work-sharing and result exchanges between many laboratories across the world. An interesting feature of the collaboration known as the International Cyclic Crack Growth Rate Group (ICCGR) [27] is that it has worked with the minimum of formality and is not part of any formal international exchange agreement. The group has provided an extensive data base for relating to crack growth of A533 and A508 steels and weldments in PWR water and related environments and has done much to identify causes of interlaboratory variations and reduce these. More recently the group has diversified into stress corrosion studies on the basis that the mechanisms for corrosion fatigue and for stress corrosion mechanisms could be related. The present section of this paper reviews briefly some of the results generated for this program by UKAEA Laboratories and demonstrate how experiment and theory are being linked to study a problem which is very subject to materials variability. In Fig. 20 some corrosion fatigue data obtained at AERE Harwell on a range of weld metals and heat-affected zone materials are compared with the ASME Boiler and Pressure Vessel Code, Section XI High R wet curve and the ASME Boiler and Pressure Vessel Code, Section XI dry curve. It will be noted that although some increase in crack growth rate is observed, the overall rates still remain substantially below the high R wet ASME Boiler and Pressure Vessel Code, Section XI curve. This latter curve was generated using ferritic plate materials and more importantly, a low flow of water in the experimental loop. This picture of much reduced crack growth rates in water at high flow rates is now being confirmed by a systematic collaborative study including other important variables (such as steel sulphur content and water chemistry), and it may well lead to the use of less conservative assessment curves in the future.

In an attempt to understand the mechanistic base of environmentally-assisted cracking in ferritic-steel-water systems more generally, quantitative modelling has been developed to rationalize both corrosion fatigue data and stress corrosion data. The operative mechanism in the combination of PWR steel with high temperature water combination is believed to be a localized breakdown of passivity; the rate of environmental crack extension is seen as depending on a balance between rate of dynamic straining at the crack tip (which servés to rupture the protective metal oxide) and the rate of repassivation. Using this type of analysis, it has been possible to plot both corrosion fatigue data (converted to a time base) and slow strain rate test crack propagation data on the same graphical space. The trends with important environmental variables is clearly shown in Fig. 21. A difference in slope is noted, the corrosion fatigue data partitioning broadly according to flow rate and the slow strain rate data according to oxygen level. If this type of approach can be further developed, it offers a potential method for evaluating behavior at strain rates likely to be experienced in plant transients.

Stress corrosion data of the type used in Fig. 22 have been generated during slow strain rate potentiostatic experiments in PWR water. The particular results shown in Fig. 22 arise from a range of materials in good quality water and it is seen that, although for all materials a positive shift from the free corrosion potential of 600 mV is required to cause cracking, the amount of shift depends acutely on the material and the orientation of the test specimen. This emphasizes the great variability of behavior which besets this particular corrosion problem. Turning from low alloy pressure vessel steels to types 304 and 316 austenitic piping, intergranular stress corrosion cracking recently has been a pressing problem on BWR plant. In addition to ASME Code Case N-335, an extensive investigation and evaluation of this has been conducted by the U.S. Nuclear Regulatory Commission, again involving important aspects of international exchange and collaboration. Suggestions for improvement include the non-destructive examination of operational plant control of water chemistry by hydrogen addition and by reduction of the level of ionic species, additional structural integrity studies, and improved procedures to detect "leak-before break" situations. Another important aspect is the reduction of residual stress by induction heating stress improvement (regarded by some experts as the most effective) or by heat sink or heat-pass heat sink welding (even in situ at existing plants).

Turning away from the nuclear industry, stress corrosion cracking is an important issue in relation to vessels for the storage and transportation of anhydrous ammonia. Whilst some of the earliest cases were reported from the U.S.A., similar problems have occurred around the world; the results of a recent world wide survey was reported [27] in Los Angeles in Nov 1982 in which careful inspection of 72 storage spheres revealed that 37 of these contained stress corrosion cracks. Towers [29] summarizes the present U.K. situation as follows:

"The risk of SCC in welded ferritic steel storage vessels appears to be minimized if the vessel is fabricated from relatively low strength steels (say a specified minimum yield stress of 350 N/mn^2) and is thermally stress relieved before operation, or is operated at approximately atmospheric pressure at a temperature of approximately -33°C. In view of this, it would be prudent not to build any new non-stress relieved vessels for storage of ammonia under pressure until methods are found for avoiding SCC. Vessels should either be post weld heat treated or operate a -33°C besides being made of appropriate low strength steels. Current UK codes of practice for storage of anhydrous ammonia at a low temperature (-33°C) and at ambient temperature under pressure in bullets and for transport in bulk by road or rail, adopt one of the two measures for minimizing the risk of SCC referred to above. For storage spheres operating at ambient temperature, however, stress relief is not a mandatory requirement and may indeed be inconvenient. Under these circumstances spheres may be susceptible to SCC. An indication of the maximum allowable depth of stress corrosion cracks in existing vessels may be obtained by use of fracture mechanics, though the problem is complicated by the absence of fracture toughness data on the actual materials used, difficulties in sizing the crack depths and the diffuse nature of the cracking."

This topic is one of several pressure vessel topics on which there are recommendations from the European standardization body CEOC (Colloque European des Organismes de Controle). Recommendations R43/CEOC/CP82 dEf relates to pressure vessels containing anhydrous ammonia above -20°C, and recommends the lower yield strength of the steel should not exceed 450 n/mm^2, that the vessels shall be fully stress relieved if possible, otherwise locally stress relieved, that they should be inspected at intervals not longer than 4 years with increased frequency for vessels which have not received a full stress relief, and that they should be so operated as to remove oxygen from the system as quickly as possible (especially in the absence of moisture). Vessels that are left empty of ammonia for a long period being filled with inert gas.

STRUCTURAL INTEGRITY ASSESSMENT

The last technical area to be discussed in this paper is the one which is perhaps the best example in the pressure vessel field of low exchange between different countries and between different industrial sectors has encouraged development. The assurance of integrity of pressure vessel and piping systems, recognizing the possibility of the occurrence of some manufacturing flaws, rests on the detailed appraisal of what flaw sizes are tolerable under the most stringent conditions envisaged for the operational structure and on the development of procedures to ensure that no such flaws exist in such structures when they are pressurized.

Interest in this topic has been most keen in industrial sectors where it is desirable to assure a failure rate lower than that which has been historically observed in several surveys. Smith and Warwick [30], for example, in a survey reported in 198 covering more than 3×10^5 vessel years service accumulated by some 20,000 vessels concluded that the "failure" rate was about 4×10^{-5} per vessel year. Most of these failures were detected by in-service examinations or by leakage, only 6% of them leading to actual failures in service (Table IIIa). Of the 229 failures observed, 216 involved cracks, of which (Table IIIb) 29% were from flaws which existed before the vessel was put into service emphasizing the importance of applying effective NDE. The considerable and widespread interest in structural integrity aspects arises for example from discussions of "fitness-for-purpose" flaw acceptance standards for oil and gas transmission pipeline; from the need to prevent failure in chemical and petrochemical plant; from the stringent requirements of the aerospace industry; from such nuclear reactor considerations as the BWR piping and the PWR pressure vessel materials toughness issue [31]. In addition to person-to-person exchanges and other informal arrangements, various international committees have been involved such as: the International Institute of Welding Commission X; the International Congress on Fracture; the International Atomic Energy Agency Committee on Reliability of Primary Circuits; the Nuclear Energy Agency Principal Working Group 3 (Pressure Circuit Integrity); and the International and national standardization bodies. Many of these organizations have arranged collaborative and interacting research programs as well as meetings and information exchange.

It is impossible in the remaining space to do justice to recent world-wide work in these areas; comments will be restricted to a few highlights of recent U.K. work on fracture mechanics and nondestructive examination mainly related to the nuclear field; it must be remembered that much similar and related work is in progress in many other countries and in other industrial sectors. Of recent years, such assessments of tolerable flaw sizes have taken note of the relatively high fracture toughness that can be obtained in modern materials, and have included examination of both the possibility of crack extension by fast fracture following some local or even general plasticity (e.g., Elasto-plastic fracture mechanics) or by plastic collapse of the reduced section near to a flaw. In the U.K., after a comprehensive study of available techniques, the Marshall committee [32] concluded that the CEGB R6 method was the preferred assessment route for its study. This method, which is now well known [33] involves: the estimation of all relevant system transients and their effect on pressure vessel temperatures and stresses; detailed stress analysis relevant to all points of the vessel (usually done at a number of selected points considered to be the most important or the most critical); calculation of local stress intensities in the neighborhood of a number of postulated flaws of assumed size, shape and position; determination of the ratios of these calculated stress intensities to the critical stress intensity for fracture (K_R) or for plastic failure (S_R); plotting of the locus of the various results on a failure analysis diagram to give the limiting flaw size. The method as usually applied is based on pessimistic estimates of end-of-life properties taking account of such features as thermal and strain ageing and irradiation damage, taking account of thermal and residual stresses; sensitivity studies are made to assess the effects of variation in all of these features.

Having determined the limiting size of flaw which at the end of life could lead to failure, it is necessary to deduce what size of flaw left in the structure before commissioning could grow to this limiting flaw size. This involves considerationof the various loading cycles which may be imposed on the vessel by service transients, and what crack growth these cycles will produce. The effect of the service environment on rate of crack growth must be considered. Finally, having thus determined the flaw size which is "tolerable" at start of life (taking account of any safety factor which it is decided then to apply since the method itself whilst making conservative assumptions does not inherently include any arbitrary safety factors), it is necessary to demonstrate that such flaws cannot and do not exist in the subject structure. The first part of this aspect can involve the choice of fracture tough material and low stress designs such that the tolerable flaw sizes calculated are much larger than any that engineering experience would lead one to expect in structures fabricated to the highly-developed, proven and controlled procedures of present practice. The choice of designs to reduce the amount of weldments and the choice of materials which are tolerant of variations in manufacturing parameters will also contribute to taking out the occurrence of flaws more severe than the tolerable size. Nevertheless, the demonstration that such unlikely flaws do not in fact exist, depends on the inspection and testing of the structure. The hydraulic pressure test does this to some extent, but rigorous demonstration involves the use of effective methods of volumetric non-destructive examination, for example, ultrasonic scanning. Details and results of such assessments have been described elsewhere [34]. Whilst the present situation is one where the approach is considered well validated, considerable work is in progress in the U.K. as part of a collaborative program aimed at identifying and assessing margins.

SOME FRACTURE MECHANICS DEVELOPMENTS

The 2nd report of the Marshall Study Group [32] emphasized the desirability that a PWR vessel should be kept at upper shelf temperatures during all potential transients. Upper shelf toughness data available at that time were evaluated to provide reference initiation toughness temperature relationships and lower bound resistance to crack growth data for modern ($S < 0.0110$ wt %) pressure vessel materials. Results from recent tests are compared with the Study Group Assessment in Fig. 23. Methods of interpreting upper shelf toughness data are being actively discussed by the technical community, since there is a widespread opinion that the present ASTM E815 procedure does not provide an accurate measurement of the toughness at the outset of ductile crack growth, particularly for high toughness materials. Because of the difficulties in obtaining a precise definition of "initiation" toughness and also the relevance of "true initiation" to structural integrity, initiation as the toughness corresponding to a fixed small increment of initiation as the toughness corresponding to a fixed small increment of ductile crack growth, Δa = 0.2 mm. Comparison of linear and nonlinear J_R analyses for A533B-1 indicate that nonlinear analyses provide a closer representation of resistance to crack growth. Our preferred method of interpretation is therefore to define upper shelf toughness data using power law J_R analyses. Values of "initiation" toughness which have been derived from multiple specimen tests on proportional compact specimens of material Pl with thicknesses ranging from 10 mm to 100 mm are shown in Fig. 24. The toughness at 0.2 mm crack growth ($J_{0.2}$) corresponds reasonably well with the reference toughness values defined by the Study Group whereas toughness at 0.5 mm crack growth correspond more closely with ASTM E813 J_K values.

Increasing use is being made of the unloading compliance technique to provide single specimen J_R data. A formal method has been developed at RNL to examine such data to ensure that the results are not being influenced unduly by effects which may be caused by the testing system, such as apparent negative crack growth at early stages of the test. Work has been done on both unirradiated and irradiated samples. Figure 25 shows that there is only a very small effect of irradiation on the initiation toughness and resistance to crack growth for a modern A508-3 forging even after irradiation to a fluence of 1×10^{19} n/mm^2 (E 1 MeV).

Two areas of great interest involve the assessment of the effects of the engineering structure such as those associated with the nature of the applied stress, stored energy and compliance. The first of these areas involves the study of the effects on flaw instability of a severe thermal shock. The second considers such aspects as the conditions under which the instability strain will be increased by warm pre-stressing effects, the degree to which structural effects on the instability point limit the use of the J_R curve, and the conditions for crack arrest. Work is going on in several countries, and that in the U.K. includes studies on large spinning cylinders using an equipment in construction at RNL [35].

THE ROLE OF NDE

Having estimated the tolerable flaw sizes it is necessary to ensure that such flaws do not exist in the structure when it goes into service. A recent study [36] of the role of the pre-service and in-service pressure tests concluded that it is not practical to give a rigorous quantitative demonstration of integrity by the overpressure test alone, a conclusion which again emphasizes the importance of making non-destructive examination (NDE) so chosen that they are highly effective in preventing the commissioning of any structures containing flaws above the tolerable level of severity.

The effectiveness of the then current manual ultrasonic techniques was seriously questioned by the results from the first European round-robin trials (PISC I) and those from other round-robin trails and the reasons for these and the directions which will give improvement have been reviewed [37]. Subsequently the U.K. Defect Detection Trial [38] gave clear evidence that the overall probability of detection exceeded 95% with a confidence of 99.99%. Excellent results were also obtained in the characterization of the detected flaws, such that there was close correspondence between the NDT estimates of the flaw position and size and those obtained from destructive examination. Even with the best techniques there is a possible range of uncertainty in size measurement and in any practical case involving the sentencing of a real flaw indication, an addition should be made to the 'best estimate' result to cover this uncertainty. Assuming this uncertainty to be 4 mm in height measurement, Fig. 26 shows for the UK NDT results the fractional frequency ('probability') of misclassification by height against flaw height for all of the four DDT plates. In this figure the results are compared with the B(a) curve of the Marshall report [32], since the NDT effectives shown in the Marshall B(a) curve was sufficient to give very high vessel integrity results in the probablistic fracture mechanics calculations. In the U.K. Defect Detection Trial, for most of the flaw sizes, and especially for flaw heights under 25 mm, the misclassification was zero, and the results lay very near to or below the Marshall B(a) curve when results from both clad and unclad side inspections were taken into account. There was little variations in misclassification with flaw heights accept near to the "limiting" values for surface and buried defects respectively at which values further analyses would be required. Taking the combined data, the flaws were correctly classified in 99 out of 100 trials indicating a probability of correct classification in excess of 95% with a confidence of 96%. However, no flaw was misclassified by more than one team. Thus, if the result from any two of the UK teams were combined, as could be the case when multiple inspections with diverse techniques was used in practice, and if nonacceptance (i.e., flaws which would be referred for further analysis) was taken as the classification if either one of the teams called for nonacceptance, then all flaws would be correctly classified.

Over the last two years, two plate and two nozzle assemblies each containing deliberate flaws have been circulating around Europe, U.S.A. and Japan as part of the PISC II program initiated by the Committee for the Safety of Nuclear Installations [39]. The round robin inspection of this program have now been completed and the test assemblies have been returned to ISPRA in Italy for identification of the actual embedded flaws by detailed NDT and destructive examination. Data analysis of the inspection reports is now in hand and it is intended to report the first stages of this analysis to the post-SMiRT conference to be held in ISPRA in August 1985. A particularly interesting test assembly is the reaslistic set-in