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A brief review of corrosion-fatigue phenomena in simulated pressurized water-reactor environments

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SYNOPSIS

A short review is given of the effects of corrosion fatigue on the materials used in pressurized water-reactor vessels. Selected topics such as testing procedures, test data, and mechanisms in simulated environments are discussed. The main fact that emerges is that most of the data on the growth of fatigue cracks reside below the ASME X1 1980 High-*R* 'Wet' design-code lines, i.e. they fall within that specification.

Finally, some recent advances in the understanding of the corrosion-fatigue behaviour of such materials in pressurized water reactors are highlighted.

SAMEVATTING

Daar word 'n kort oorsig gegee oor die uitwerking van korrosievermoeidheid op die materiale wat in drukwaterreaktorhouers gebruik word. Uitgesoekte onderwerpe soos toetsprosedures, toetsdata en meganismes in gesimuleerde omgewings word bespreek. Die vernaamste feit wat na vore kom, is dat die meeste data oor die groei van vermoeidheidskrake onder die ontwerpkodelyne van ASME X1 1980 High-*R* 'Wet' val, m.a.w. hulle voldoen aan daardie spesifikasie.

Ten slotte word die jongste vordering met die begrip van die korrosievermoeidheidsgedrag van sodanige materiale in drukwater-reaktors uitgelig.

Introduction

The realization that certain environments can significantly reduce the fatigue strength or fatigue resistance of metals was initially due to the early work of McAdam[1] some six decades ago. In essence, McAdam demonstrated that the usual fatigue limit or endurance limit of steels in air was no longer evident, and that the number of stress cycles to failure is markedly reduced, when steels are subjected to a corrosive environment, e.g. water.

Considerable engineering and scientific studies have been devoted, especially during the past two decades, to the evaluation of corrosion-fatigue response and the elucidation of the mechanisms involved in the corrosion-fatigue process. Despite this intensive research effort, however, the failure of a wide range of engineering components as a direct result of corrosion or environmental fatigue still remains an immense and costly problem. There are a number of reasons for this unsatisfactory situation:

(1) the uncertainty surrounding the selection of relevant laboratory tests,
(2) the application of the data to a valid design criterion,
(3) the difficulty in determining the exact alloy-environment situation in certain regions of industrial plant, which can be subject to a wide range of operating conditions, and
(4) the lack of a cogent mechanistic rationale to explain the environmentally assisted cracking process.

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In the present short review, various aspects of the corrosion-fatigue characteristics of the materials used for reactor pressure vessels (RPV) in a simulated pressurized water reactor (PWR) are highlighted.

Environment and Material

The environment relevant to a PWR is essentially a demineralized, deoxygenated water that contains controlled additions of boron and lithium and is operated with a hydrogen overpressure. The specifications for the chemistry of PWR water are given in Table I. Present PWR systems involve the use of a steel RPV to enclose the aqueous primary system. In service, the pressure vessel is subjected to simultaneously acting alternate stresses and aqueous environments, typical operating conditions for a PWR being a pressure of 180 bars and a temperature of 300°C.

The PWR is cylindrical and can have a wall thickness of up to 300 mm and a diameter of up to some 6000 mm. It is fabricated from two RPV materials: A533B and A508 Cl III low-alloy steels. The bulk chemical composition and the tensile requirements of these steels are listed in Table II.

Test Procedures

As evident from Table I, a sophisticated water-conditioning plant is required for certain tests in a simulated PWR environment. The water-treatment plant generally consists of a series of ion-exchange columns that clean and demineralize raw tap-water, which is subjected to a deoxygenation treatment and then dosed with carefully controlled amounts of boric acid, lithium hydroxide, and hydrogen. This PWR water is then inserted into a high-

TABLE I

SPECIFICATIONS FOR THE CHEMISTRY OF PWR WATER

Conductivity, μs	1-40
Oxygen content, p.p.m.	≤0,10
Chlorides, p.p.m.	≤0,150
Fluorides, p.p.m.	≤0,150
LiOH, p.p.m.	0,6-6,2
H_3BO_3, p.p.m.	0-13 000
pH (at 25°C)	4-10,5
Hydrogen content, ml/kg (s.t.p.)	0-50

TABLE II

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF A533B AND A508 CL III STEELS

Carbon, %	0,25 (max.)	0,27 (max.)
Manganese, %	1,10-1,55	0,50-1,00
Silicon, %	0,13-0,32	0,15-0,40
Molybdenum, %	0,41-0,64	0,55-0,70
Nickel, %	0,37-0,73	0,50-1,00
Phosphorus, %	0,035 (max.)	0,025 (max.)
Sulphur, %	0,040 (max.)	0,025 (max.)
Chromium, %	-	0,25-0,45
Vanadium, %	-	0,05 (max.)
Tensile strength, MPa	552-689	550-725
Yield strength, MPa	≥344	≥345
Elongation in 50 mm, %	≥18	≥18
Reduction in area, %	-	≥38

pressure, high-temperature circulating loop to attain the correct PWR operating conditions, i.e. water at 300°C under a pressure of about 180 bars.

The high-temperature pressurized PWR water flows into and through a small pressure vessel or autoclave that is compatible with the circulating loop. The fatigue tests are conducted inside the autoclave, which is usually fabricated from stainless steel, a closed-loop servo hydraulic system being used for the tests. Details of the autoclave and the linkage of the test specimens to the fatigue-testing system are shown in Fig. 1.

By the very nature of the test, the monitoring of crack extensions is remote. Several techniques can be used for this, including those employing an internal linear differential transducer (LDT), an LDT-external LDT, an internal clip gauge, a d.c. potential-drop probe, and an eddy-current probe. The first three techniques monitor crack length by measuring the compliance of the specimen, and an example of this is illustrated in Fig. 2.

During testing, the water chemistry is monitored constantly to ensure that it conforms to the PWR specifications.

Test Results

In 1972, Kondo *et al.*[2] pointed out that the 'air' design line of the American Society of Mechanical Engineers (ASME) was not an upper bound and that the extension of fatigue cracks in an aqueous environment is strongly dependent on frequency. Two years later, cracks were found in feedwater nozzles in several U.S. light-water reactor (LWR) plants[3].

In 1978, a group known as the International Cyclic Crack Growth Rate (ICCGR) was formed, its brief being

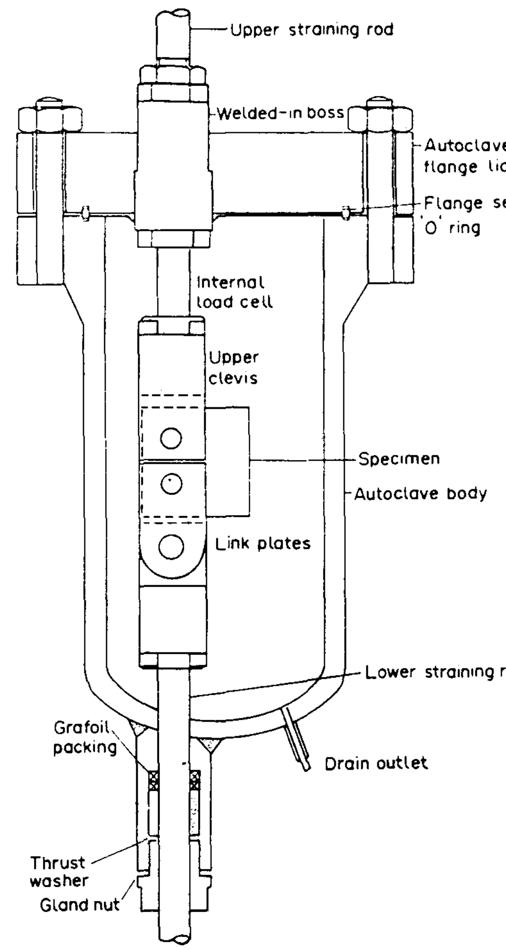


Fig. 1—Section through an autoclave showing the loading arrangement

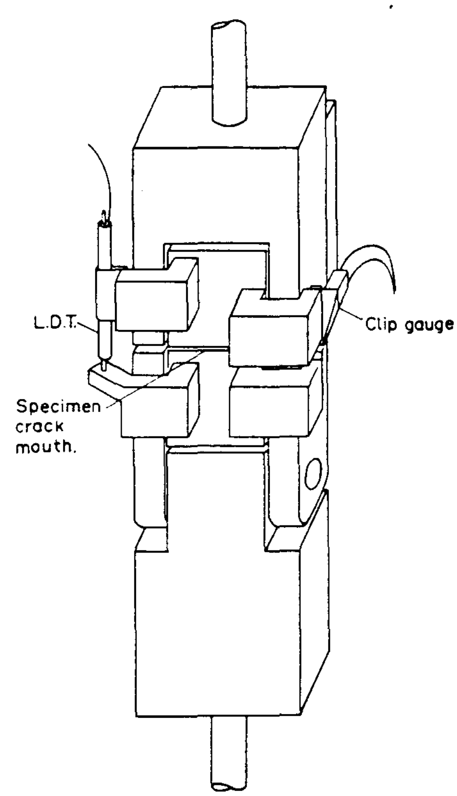


Fig. 2—Crack-monitoring equipment attached to a test specimen

to conduct a programme of fatigue testing on RPV materials subjected to LWR environments. This group consisted of three task sections dealing with test methods, mechanisms, and data collection and evaluation. As a result of a data compiliation by Bamford[4] (Fig. 3), the ASME XI design-code lines were revised in 1980. The new reference curves for fatigue-crack growth for carbon and low-alloy ferritic steels are illustrated in Fig. 4. These curves incorporate the effect of *R*-ratio ($R = K_{min}/K_{max}$), where *K* is the applied stress-intensity factor, and are based mainly on data taken from tests conducted at a frequency of 0,0167 Hz.

In 1981, the results from the ICCGR low *R*-ratio 'Round Robin' test programme became available[5] (Fig. 5), and possible sources of interlaboratory scatter were identified, i.e. waveforms, control modes (constant *K* or load), oxygen contents of the PWR water, and the flowrate of the water through the testing autoclave (static to highly turbulent). Subsequent work has shown

(i) that the waveform affects the growth rates of fatigue cracks[6],
(ii) that the oxygen content of the water can significantly affect the growth rates of fatigue cracks, and
(iii) that there are conflicting effects on the flow of fluid through an autoclave.

From the available data, it is evident that tests at high *R*-ratios, 0,7 to 0,9, result in the fastest growth of fatigue cracks, and hence the greatest growth of environmentally assisted cracks (EAC)[4]. Temperature is also important, and it has been shown[7,8] that growth rates exhibit minima in PWR water at about 200°C; above that temperature, the growth rates increase with increasing temperature. Also, it was shown recently that the irradiation of specimens before they are tested has no apparent effect on the growth rates of fatigue cracks.

The most important variable appears to be the distribution of non-metallic sulphide inclusions, i.e. segregation effects are important. Bulloch[9] has shown that the bulk level of sulphur exerts little influence on the growth of EAC (Fig. 6). The specific water chemistry adopted for corrosion control appears to be unimportant, but at least one study[10] has shown that the level of sulphates can affect the growth of EAC.

Another factor affecting the growth of EAC in tests is the flowrate of fluid through the test autoclave; data generated when the flowrate is low or the fluid test facilities are static generally exhibit faster fatigue-crack growth than those under conditions of high flowrate[11]. The combined effects of flowrate, bulk sulphur level, and sulphate level on the susceptibility of RPV steels to the growth of EAC has recently been reported by Atkinson *et al.*[10], and are shown in Fig. 7.

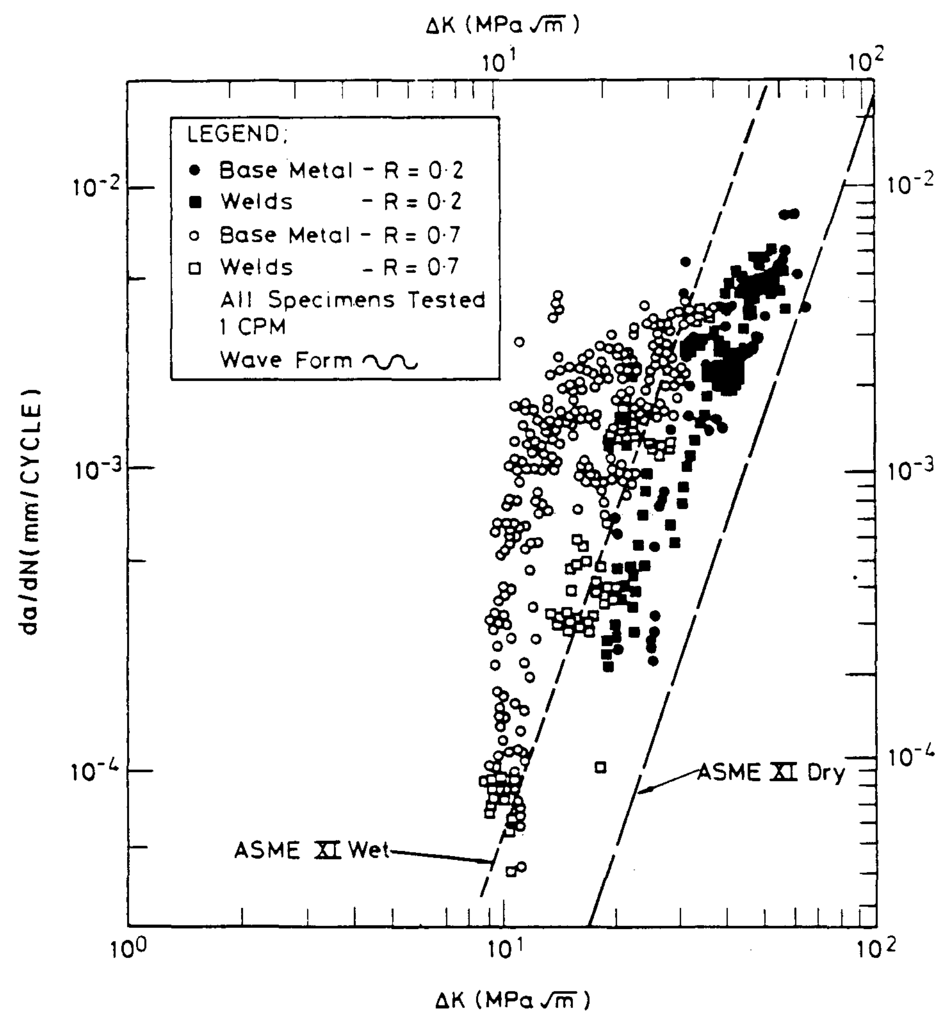


Fig. 3—Corrosion-fatigue data for A533B and A508 base materials and weldments in primary PWR water (after Bamford[4])

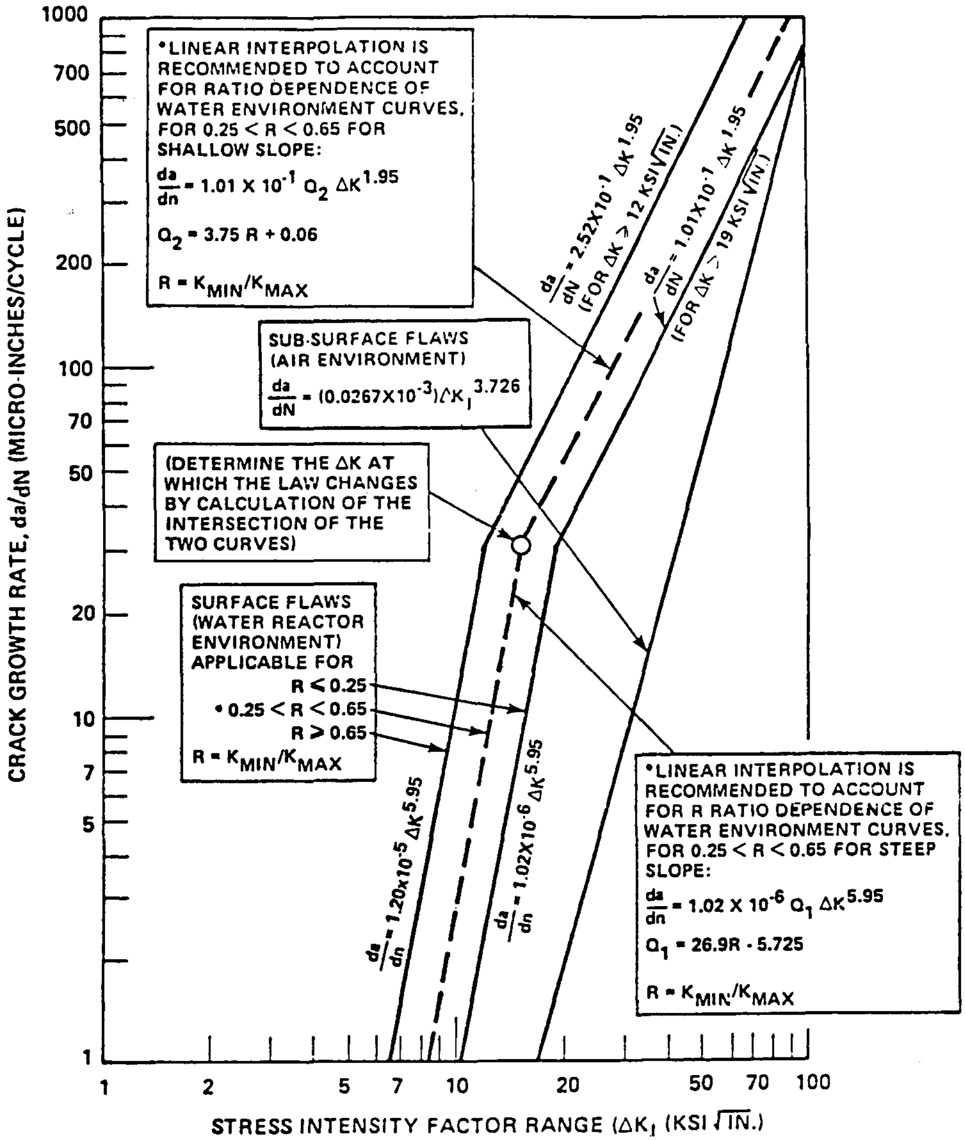


Fig. 4—Reference curves of fatigue-crack growth for carbon and low-alloy ferritic steels, ASME Code, Section XI, 1980 (after Bamford[4])

Extensive fractographic studies[6,9,12,13] on the surfaces of fatigue fractures have shown that fan-shaped 'cleavage-like' features, associated with inclusions of non-metallic sulphides, are evident when the growth of EAC is recorded.

One important fact has emerged from the extensive data on fatigue-crack growth that have been amassed over the past few years, viz most growth-rate data reside below the ASME XI 1980 High-R 'Wet' design-code lines, i.e. they are within the specification.

Mechanisms of Cracking

Essentially, two mechanisms—dissolution-controlled and hydrogen-induced cracking—have been suggested to account for the occurrence of EAC in the waters of simulated LWR. In the former process, the growth of fatigue cracks is controlled by the anodic dissolution of fresh metal at the tip of the crack (produced by slip emergence) whereas, in the latter process, physical separation of the material at the tip of the crack is assisted by hydrogen embrittlement.

Both mechanisms depend on the same rate-controlling step, i.e. oxide rupture at the tip of the crack, and it is thus difficult to differentiate experimentally between them[14]. A dissolution-controlled mechanism was proposed by Scott and Truswell[15], who portrayed the plateau velocities of EAC growth as a function of the average strain rate ($\dot{\epsilon}_{Av}$):

$$\dot{\epsilon}_{Av} = \frac{-1}{T} \ln[1 - \tfrac{1}{2}(1-R)^2],$$

where T is the tensile portion of the fatigue cycle in seconds and R is the R-ratio. Similarly, the test results on fatigue cracks generated in a simulated PWR environment by other establishments are portrayed as a function of $\dot{\epsilon}_{Av}$ and are shown in Fig. 8. This diagram illustrates the effect of flowrate on the sensitivity of EAC growth as a function of average crack-tip strain rate ($\dot{\epsilon}_{Av}$), viz the data obtained at high flowrates are greatly influenced by $\dot{\epsilon}_{Av}$, $(da/dt)\dot{\epsilon}_{Av}$, and show an apparent 'threshold' for EAC growth at $\dot{\epsilon}_{Av} \cdot 10^{-3}$s, while the data obtained at low flowrates are almost insensitive to changes in $\dot{\epsilon}_{Av}$. Essentially, Fig. 8 shows that the growth of EAC under a low-flowrate regime does not show such a dependence.

The second basic mechanism[16,17] that has been proposed to explain the growth of EAC in simulated PWR

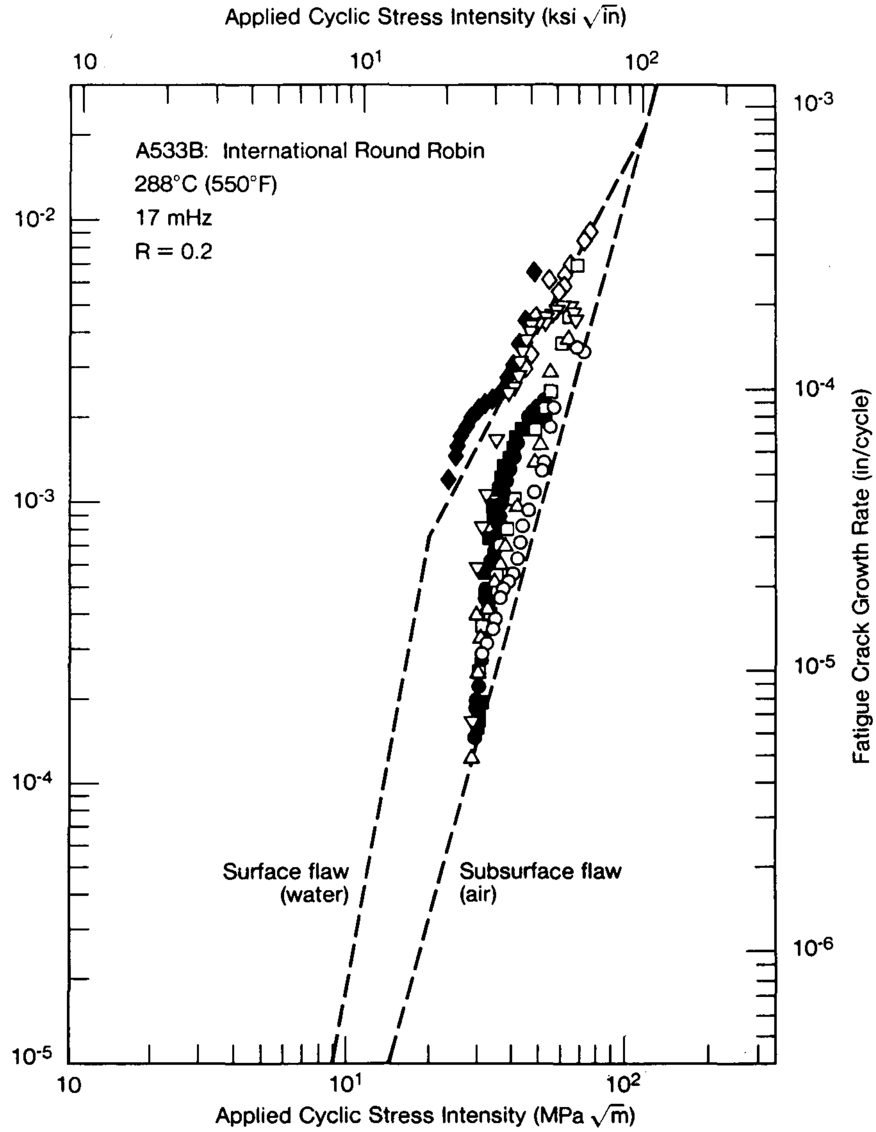


Fig. 5—Data generated from the ICCGR low *R*-ratio Round Robin test (after Slama and Jones[5])

water involves hydrogen-induced cracking and is based on extensive fractographic studies of specimens subjected to corrosion fatigue, hydrogen embrittlement, and stress-corrosion cracking. These specimens exhibited similar features such as fan-shaped cleavage-like facets, which could generally be linked to the existence of inclusions of non-metallic manganese sulphide. In one study of fatigue-crack growth, extensive fractography[13] showed that the incidence and distribution of manganese sulphides strongly influence behaviour during EAC growth. Indeed, incidences of transient localized EAC growth in isolated regions suggest that the critical factors to trigger the onset of EAC growth are the attainment of the 'right' local crack-tip chemistry and mechanical conditions. It was demonstrated recently that manganese sulphides readily dissolve in a PWR environment, forming a source of soluble sulphide species (H_2S, HS^-, S^{2-})[18], which act as powerful catalysts in electrochemical reactions. Such reactions can cause the corrosion potential to become more negative, promoting a hydrogen-embrittlement mechanism, which strongly affects behaviour during EAC growth[19]. This localized effect on crack-tip water chemistry can explain the various EAC growth transients that were observed in the fractographic study mentioned earlier[13].

Törronen *et al.*[20] recently demonstrated that the size and distribution of the manganese sulphide inclusions, rather than the sulphur level *per se*, have the strongest influence on the magnitude of EAC growth in RPV steels in a PWR environment. Basically, they showed that EAC growth occurs if the mean distance between inclusions of manganous sulphide in the fracture plane is less than the monotonic plastic-zone size $R_{max} = 0{,}036\ (K_{max}/\sigma y)^2$, where K_{max} is the maximum stress intensity and σy is the yield strength. These observations were for a low-*R* test ($R = 0{,}2$), in which the monotonic plastic-zone size was of the order of the inclusion spacing (in this case 300 μm). However, in the high-*R* tests, where R_{max} was 2 to 3 mm and greatly in excess of interinclusion distances, the application of the same philosophy means that sustained EAC growth should always occur; however, this statement is not borne out by certain experimental data. Indeed, one fractographic study[13] indicated that there was no clear relationship between either the monotonic or the reversed plastic zones and EAC growth, and generally showed that EAC growth initiated from segregated

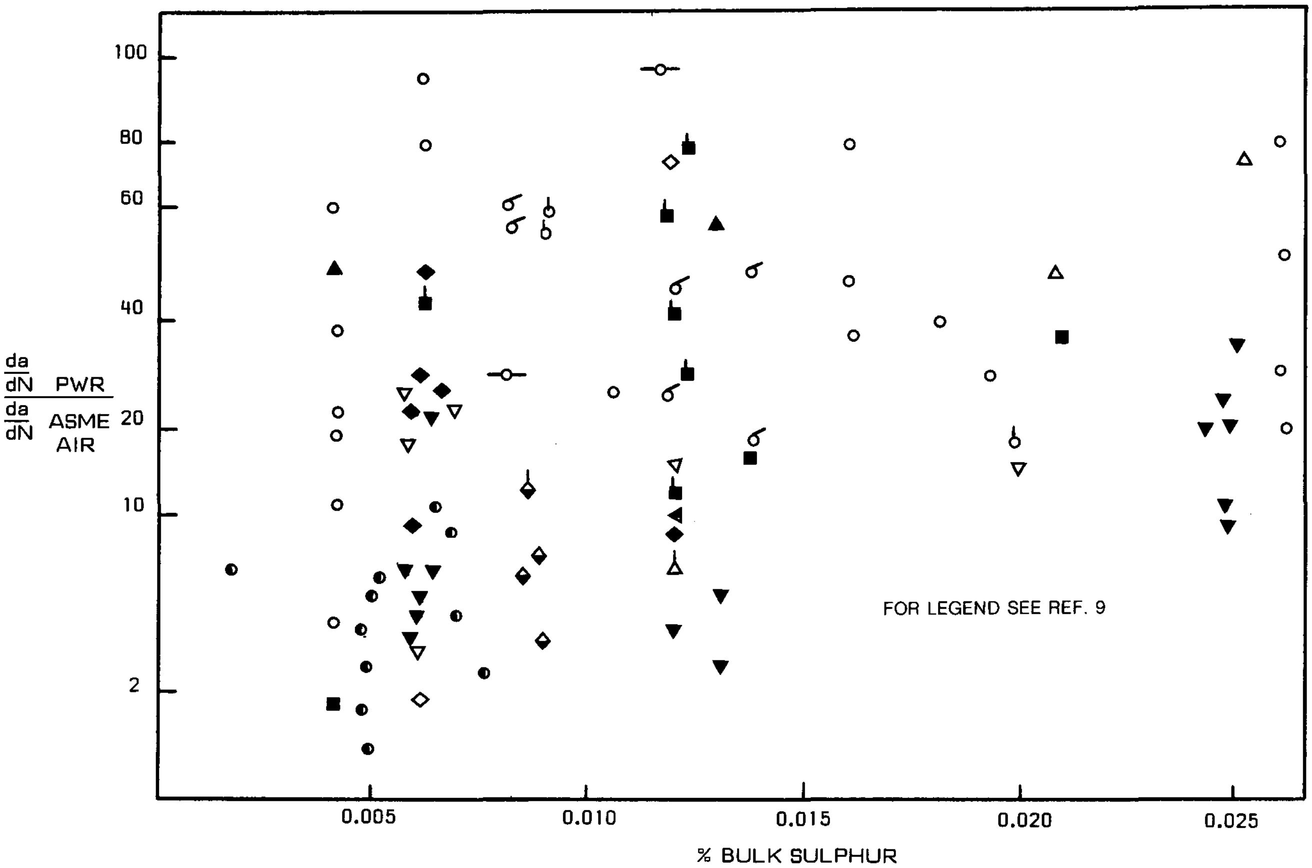


Fig. 6—Literature values of the effect of bulk sulphur on the growth of EAC in RPV materials (after Bulloch[9])

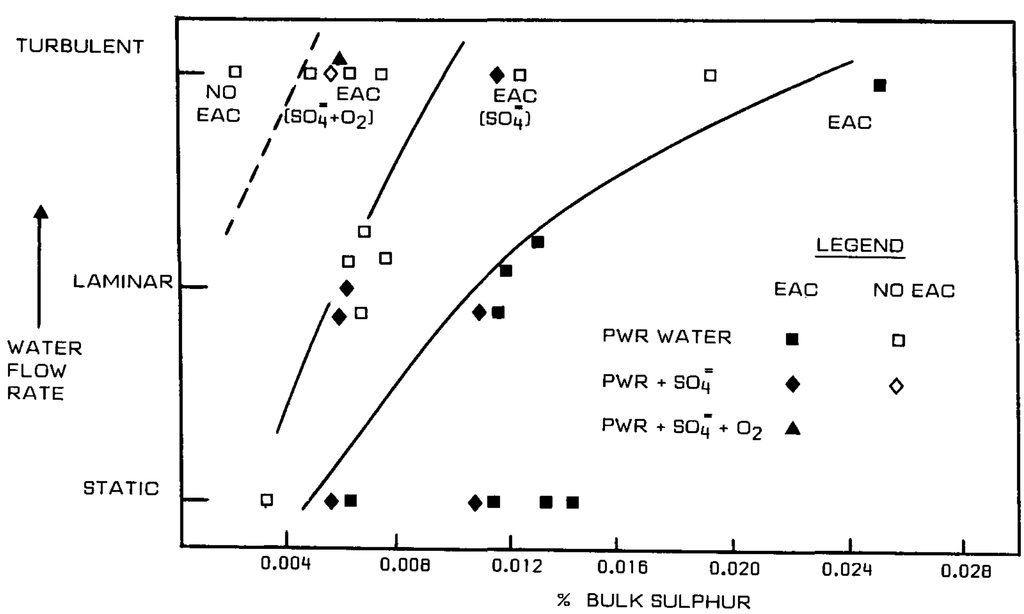


Fig. 7—Susceptibility of RPV steels to EAC (after Atkinson *et al.*[10])

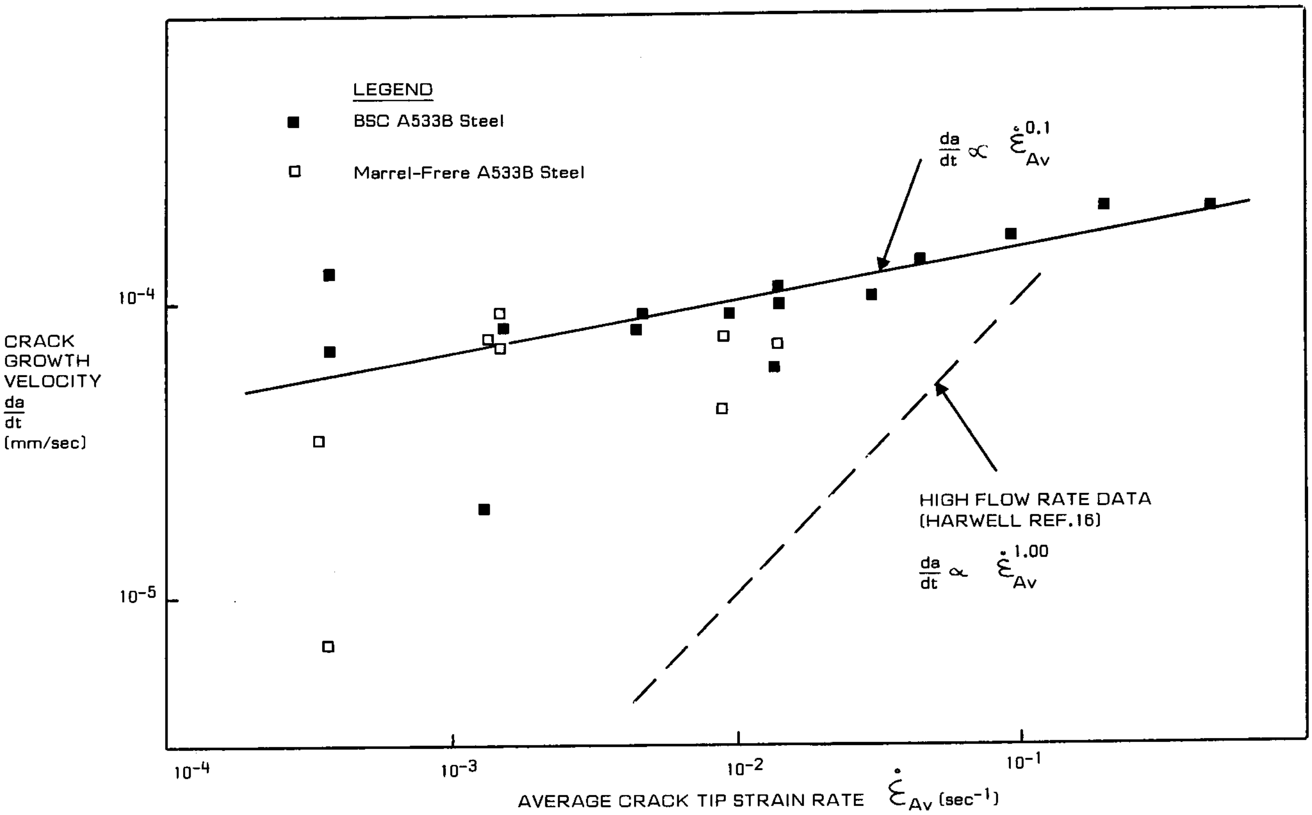


Fig. 8—Velocity of crack growth in A533B steels in PWR water at low and high flowrates as a function of average crack-tip strain rate (after Bulloch[9])

regions (clusters of inclusions), where the local volume fraction of manganous sulphide was about 1000 times greater than that for an ideal isolated distribution.

Recent Advances

From Fig. 8 it is evident that the crack-growth characteristics of an RPV steel in a PWR environment are insensitive to changes in the average crack-tip strain rate ($\dot{\epsilon}_{Av}$). It has been suggested that the time-based growth rate of fatigue cracks in air is representative of the crack-tip strain rate irrespective of the loading condition. Such a parameter, [da/dt] air, is easy to measure, or can be calculated from a knowledge of ΔK, the R-ratio, and the frequency. The parameter should reflect some measure of the new surface-creation rate at the crack tip that is pertinent to EAC processes. A schematic illustration of material exhibiting EAC growth is given in Fig. 9. Atkinson *et al.*[21] portrayed various data on fatigue-crack growth in terms of crack velocity, ($\dot{a}$), and determined a sharp transition from non-EAC growth to fast EAC growth at a critical crack velocity, ($\dot{a}$ crit), independent of R-ratio. This critical crack velocity, which signals the onset of EAC growth (Fig. 10), appears to depend on the material, i.e. $\dot{a}$ crit $\approx 5 \times 10^{-7}$ mm/s for BSC A533B steel, and $\dot{a}$ crit $\approx 2 \times 10^{-6}$ mm/s for Marrel–Frere A533B steel. This method appears to be a promising way of portraying the EAC-growth behaviour of RPV materials in a PWR environment.

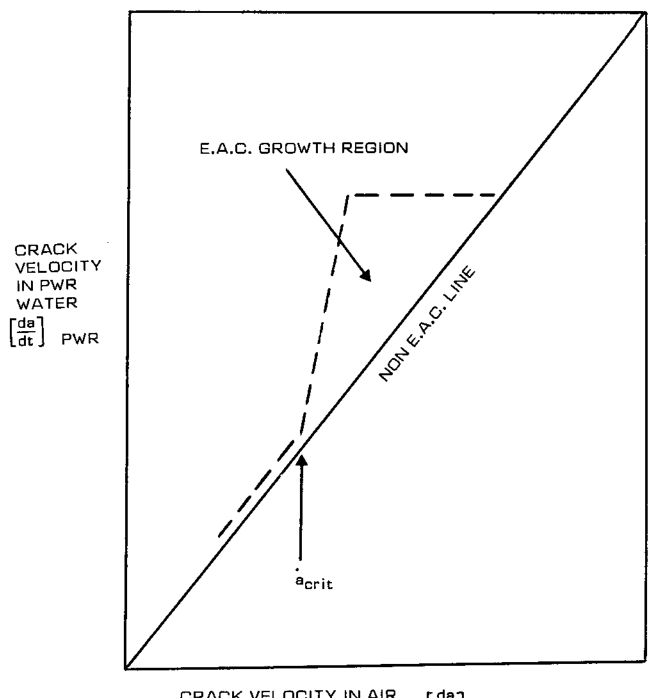


Fig. 9—Crack velocity during the growth of EAC

Jones[22] recently proposed a new mechanism to account for both stress–corrosion cracking and corrosion-fatigue phenomena. The keystone of this mechanism is that anodic dissolution or the corrosion process relieves strain hardening at the crack tip in metallic materials. Relief of strain hardening at the surface of the crack tip reduces the fracture stress, and facilitates the nucleation of brittle cracks through divacancy formation. However,

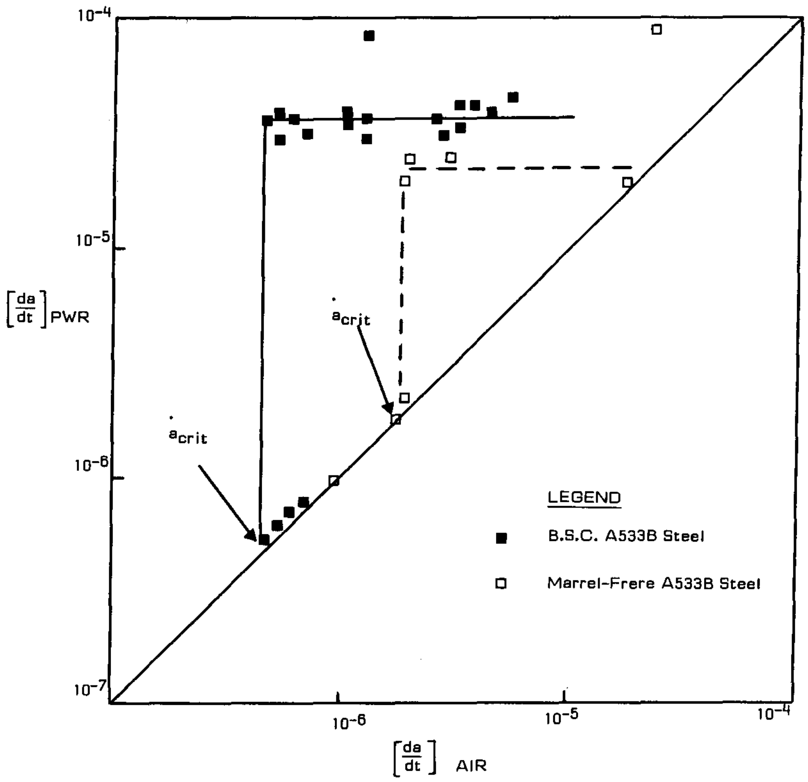


Fig. 10—Velocity of fatigue-crack growth showing the critical crack velocity for two A533B steels (after Atkinson *et al.*[21])

while this mechanism may explain the cleavage or brittle nature of EAC, it cannot account for the fact that the growth of brittle or fan-shaped EAC almost always occurs at sites of non-metallic inclusions.

Congleton[23] developed a tentative model for EAC growth during fatigue loading that is consistent with both the phenomenological (crack-growth data) and the fractographic observations. The model implies that

(i) if there is a growth-rate plateau in the corrosion-fatigue curve (Fig. 11), which is generally indicative of EAC growth, then the percentage of fan-shaped facets on the surface of the fatigue fracture should decrease with increasing ΔK, and
(ii) if the percentage EAC growth remains constant, the growth rate should increase with ΔK level.

A comparison of the predicted correlation arising from Congleton's model between the extent of EAC growth and the percentage fan-shaped EAC-growth mode and the experimental data of Törronen *et al.*[12] and Bulloch *et al.*[13] is shown in Fig. 12. There is reasonable agreement between the model and the experimental data at levels of EAC growth below a factor of about 20. Also, a recent detailed fractographic study[24] showed that another prediction from Congleton's model, viz that the percentage EAC fan-shaped growth should decrease along the growth-rate plateau, is indeed correct. This study also showed that the relationship between the degree of EAC growth, $\left[\frac{(da/dN)\ PWR}{(da/dN)_{air}\ \text{ASME}}\right]$, the percentage fan-shaped EAC growth, and the ΔK level can be conveniently portrayed in a three-dimensional diagram as shown in Fig. 13. This diagram illustrates that the maximum enhancement in EAC growth rate occurs at the maximum percentage of fan-shaped growth, and also

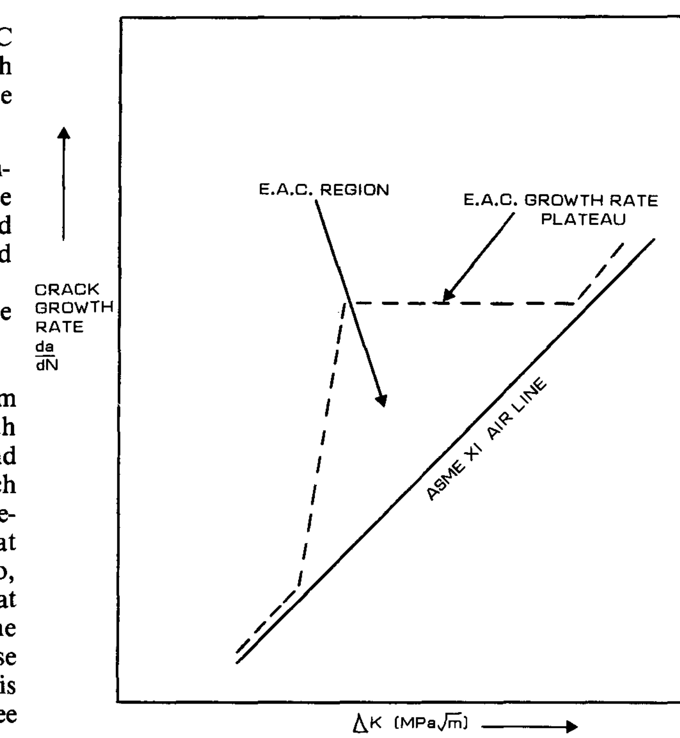
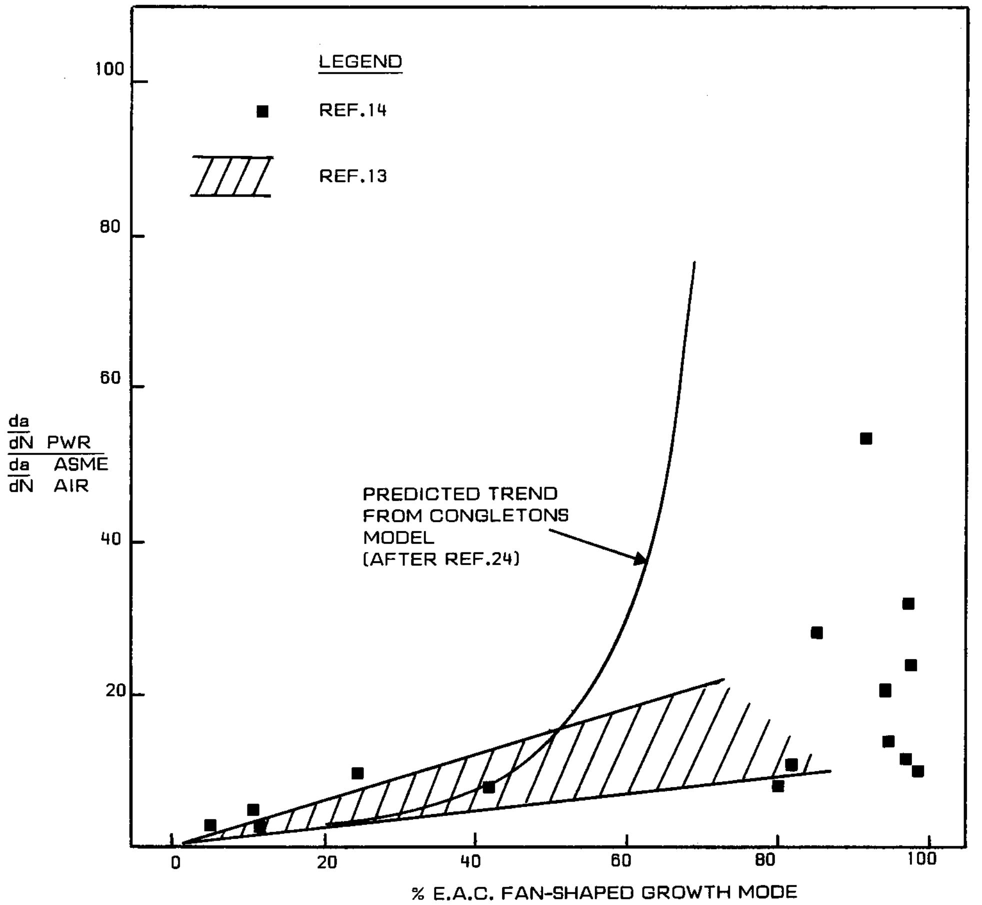


Fig. 11—Growth of EAC associated with the formation of a growth-rate plateau

Fig. 12—Relationship between the growth of EAC and the area of fan-shaped facets



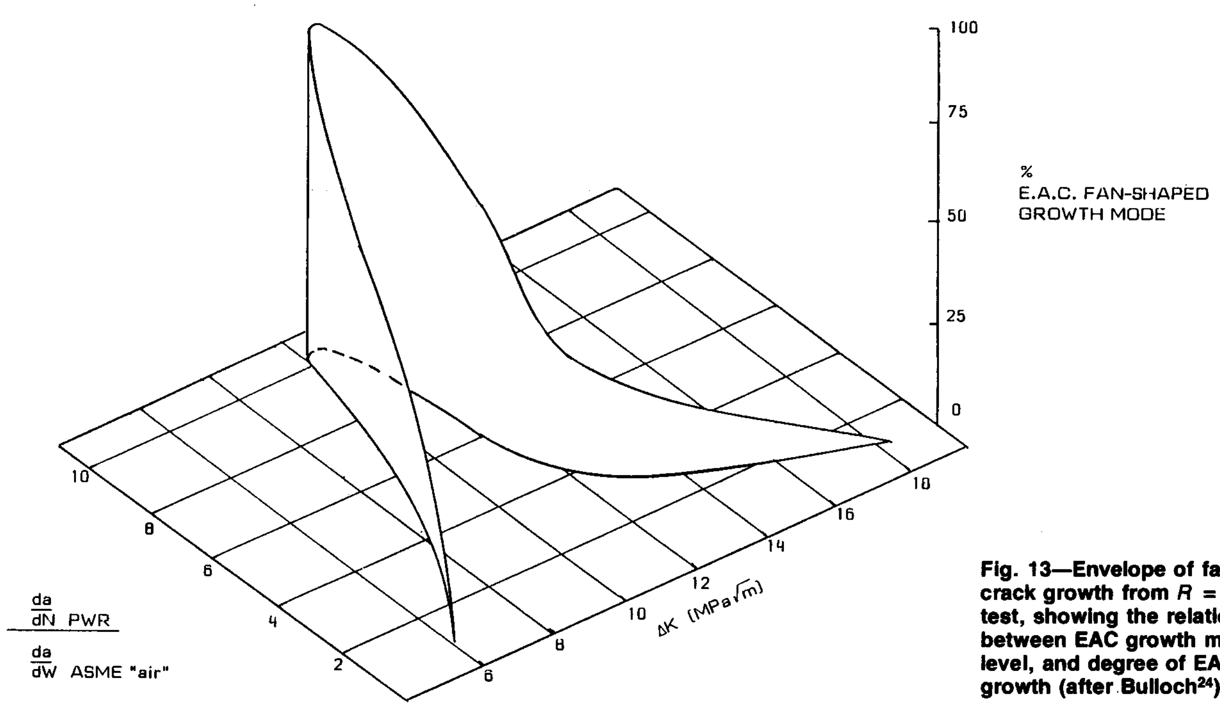


Fig. 13—Envelope of fatigue-crack growth from R = 0,8 test, showing the relationship between EAC growth mode, ΔK level, and degree of EAC growth (after Bulloch[24])

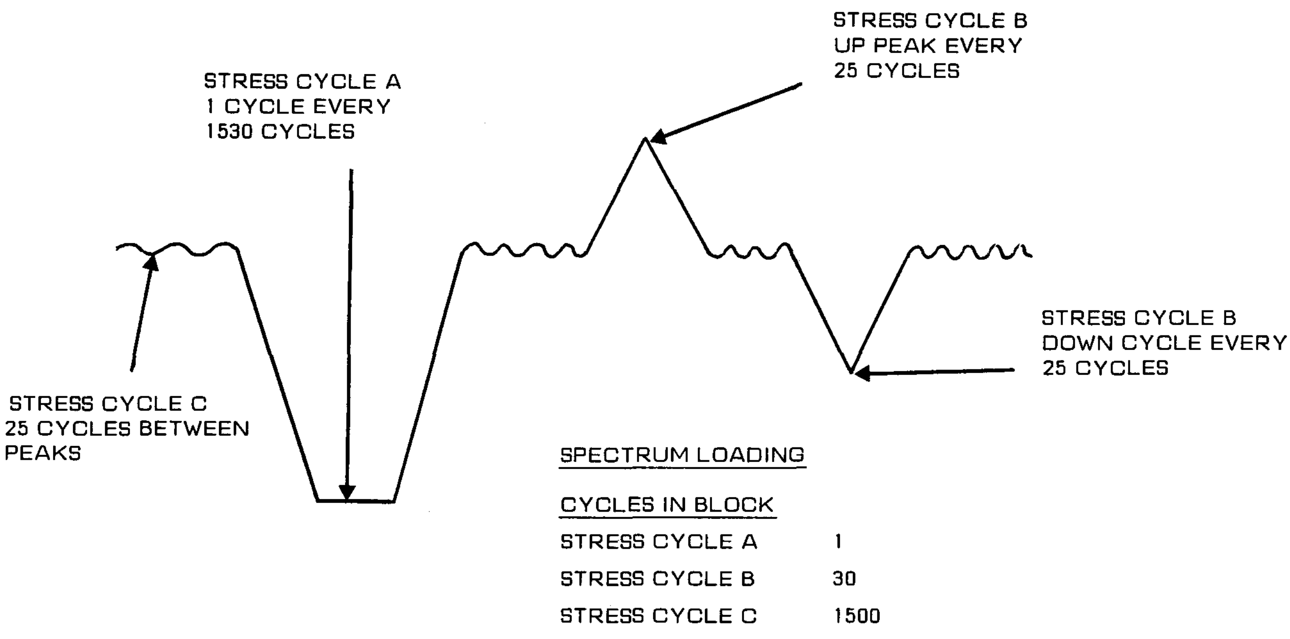


Fig. 14—Conditions of spectrum loading relevant to a working PWR (after Bamford[4])

that, along the growth-rate plateau region, as ΔK increases, the percentage of fan-shaped growth decreases.

All the data on the growth rate of fatigue cracks already discussed have applied to a situation in which the fatigue is of constant amplitude. However, it has been widely recognized that the loading conditions relevant to a working PWR facility are fairly varied. A sequence of variable or spectrum-loading cycles (Fig. 14) has been proposed by Scott[25] for a series of corrosion-fatigue experiments in PWR primary coolant water. This spectrum sequence was based on a simplified sequence of three separate types of stress cycle—A, B, and C with R-ratios of 0,2, 0,7, and 0,9 respectively. Such transients are along the lines given by Bamford[4] and are approximately equivalent to a heat up–cool down cycle (A), a load–unload cycle (B), and a high R-ratio cycle such as steady-state fluctuations during a normal working situation (C). Very few data on spectrum-loading fatigue-crack growth are available at present; however, a recent study reported by Achilles and Bulloch[26] showed that, when the test data on the three transient cycles in an argon environment were added together, they agreed well with those generated by the spectrum-loading test. In the case of the PWR water tests, the spectrum-loading test exhibited a greater amount of crack extension than the sum total of the three transient-cycle tests. This difference was explained in terms of crack length and availability of clusters of non-metallic inclusions. A significant frequency effect was also observed during spectrum-loading tests in a PWR water environment.

Finally, it is envisaged that much of the future work in the field of corrosion fatigue in PWR environments will concentrate on spectrum-loading conditions. The results of such tests would then be assessed in terms of the ASME XI 1980 design-code lines.

References

1. McAdam, D. *Proc. ASIM,* vol. 26, no. 11. 1926. p. 224.
2. Kondo, T., Kikuyama, H., Shind, M., and Nagasaki, R. Corrosion fatigue of ASTM A302B steel in high temperature water. *Corrosion fatigue* (NACE-2). 1972. p. 539.
3. Jones, R.L. Introduction and background. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.
4. Bamford, W.H. *Trans. A.S.M.E., J. Pressure Vessel Technol.,* vol. 102. 1980. p. 433.
5. Slama, G., and Jones, R.L. Structural integrity of light water reactor components. *Appl. Sci.,* 1982. p. 261.
6. Bulloch, J.H., and Buchanan, L.W. *Corr. Sci.,* vol. 24, no. 8. 1984. p. 661.
7. Cullen, W.H. Effects of introduction and temperature on fatigue crack growth rates of pressure vessel steels in PWR environments. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.
8. Bulloch, J.H., and Buchanan, L.W. The influence of environment and temperature on the fatigue crack growth behaviour of a pressure vessel steel. To be published in *Res Mechanica.*
9. Bulloch, J.H. Environmental fatigue crack growth studies: The effects of non-metallic inclusions. To be published in *Res Mechanica.*
10. Atkinson, J.D., Scott, P.M., and Tice, D.R. A review of the U.K. research programme on corrosion fatigue crack propagation in pressure vessel steels exposed to PWR environments. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.
11. Ford, F.P. Presented at ICCGR Group Meeting, Schenectady, Oct. 1983.
12. Törronen, K., Kemppainen, M., and Hanninen, H. Fractographic evaluation of specimens of A533B pressure vessel steel NP-3483. EPRI Research Project 1325-7, May 1984.
13. Bulloch, J.H., Atkinson, J.D., and Forrest, J.E. A fractographic study of fatigue cracks produced in A533B pressure vessel steel exposed to simulated PWR primary water environments. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.
14. Ford, F.P. *Proceedings 3rd International Conference on Mechanical Behaviour of Materials.* Miller, K.J., and Smith, R.F. (eds.). Oxford, Pergamon Press, 1980. vol. 2. p. 431.
15. Scott, P.M., and Truswell, A.E. *Proceedings of I.A.E.A. Specialists' Meetings on Subcritical Crack Growth.* Freiburg, 1981. p. 109.
16. Cullen, W.H., Provenzano, V., Törronen, K.J., Watson, H.E., and Loss, F.J. Fatigue crack growth of A508 steel in high temperature, pressurised reactor grade water. NUREG/CR-0969.

N.R.L. Memorandum Report 4063, Washington D.C., 1979.
17. TÖRRONEN, K.J., HANNINEN, H., and CULLEN, W.H. *PROCEEDINGS I.A.E.A. SPECIALISTS' MEETING ON SUBCRITICAL CRACK GROWTH*. Frieburg, 1981. p. 313.
18. WRANGLEN, G. *PROCEEDINGS INTERNATIONAL SYMPOSIUM ON SULPHIDE INCLUSIONS IN STEELS*. New York, 1974. p. 361.
19. BAMFORD, W.H., MOON, D.M., and CESHINI, L.J. Environmentally assisted crack growth in L.W.R. materials. Westinghouse Electric Corpn, *Annual Technical Progress Report*, 1981.
20. TÖRRONEN, K., SAARIO, T., HANNINEN, H., KEMPPAINEN, M., and SALONEN, S. *PROCEEDINGS 4TH EUROPEAN CONFERENCE ON FRACTURE*. Leoben (Austria), Sep. 1982. vol. 2, p. 539.
21. ATKINSON, J.D., FORREST, J.E., and TICE, D.R. The use of time-based crack growth data in corrosion fatigue assessments. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth (Japan), May 1985. To be published.
22. JONES, D.A. *Metall. Trans.*, vol. 16a. 1985. p. 1133.
23. CONGLETON, J. Predicting environment assisted cracking in RPV steels in high temperature water. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.
24. BULLOCH, J.H. Quantitative fractographic details of the fatigue crack growth of A533B steel in a simulated PWR environment. Submitted to *Theoretical and Applied Fracture Mechanics*.
25. SCOTT, P.M. Proposed high frequency spectrum loading experiment. I.C.C.G.R. Group Meeting, Schenectady (U.S.A.), Oct. 1983.
26. ACHILLES, R.D., and BULLOCH, J.H. Subcritical crack growth behaviour under spectrum loading in argon and PWR environments. I.A.E.A. Specialists' Meeting on Subcritical Crack Growth, Sendai (Japan), May 1985. To be published.

Geophysical and geochemical exploration

The Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater—Exploration 87—will be held in Toronto, Canada, from 27th September to 1st October, 1987.

Building on the success of conferences held in Niagara Falls and Ottawa in 1967 and 1977, which were attended by delegates from many countries, the Canadian exploration community is pleased to invite their colleagues to participate in Exploration 87.

The theme of the Conference is centred on geophysical and geochemical methods and their roles in modern exploration for mineral, groundwater, and geothermal resources; recent advances in methodology, instrumentation, field procedures, data processing, and interpretation; and trends for the future. Emphasis will be placed on the presentation of case histories and on the application of these sciences in developing countries.

This theme will be elaborated through lectures, seminars, an exhibition, poster sessions, and in field schools. Post-conference visits to instrument manufacturers, geoscience laboratories, and service companies will be provided for those interested.

The activities of Exploration 87 will be of interest and value to a wide variety of earth scientists, including geophysicists, geochemists, and geologists, as well as managers, academics, and civil servants involved in mineral, groundwater, and geothermal exploration.

The objective of the two-week Field Schools, which will be held prior to the Conference, is to demonstrate how modern geophysical and geochemical techniques should be applied in the field. Correct survey procedures, proper use of instrumentation, selection of appropriate parameters, in-field processing of data, and preliminary interpretation of results will be taught by experts. Three Field Schools, each dedicated to one of the following topics, will be held: Mineral Exploration Geophysics, Exploration Geochemistry for Base and Precious Metals, and Engineering and Groundwater Geophysics.

Leading international authorities will be invited to deliver keynote addresses in their areas of specialization. Other contributed papers, emphasizing current geophysical and geochemical applications, will serve to round out the treatment of the following topics:

- The Economic, Technical, and Geopolitical Factors in Exploration
- Exploration in the Next Decade
- Recent Advances in Exploration Geophysics
- Recent Advances in Exploration Geochemistry
- Applications of Geophysical Methods for Ore Exploration
- Applications of Geochemistry in Weathered and Residual Terrains
- Applications of Geochemistry in Transported Non-glacial and Glacial Terrains
- Geophysics in Regional Mineral Assessment and Indirect Exploration
- Integrated Geophysics and Geochemistry for Indirect Ore Exploration
- The Role of Geophysics and Geochemistry in Groundwater Exploration
- Geophysical and Geochemical Methods for Geothermal Exploration
- Case Histories of Integrated Prospecting Techniques
- Trends in Education, Business, Government, and International Development.

Enquiries should be addressed to
Exploration 87
c/o 222 Snidercroft Road
Concord, Ontario
Canada L4K 1B5.
Telephone: (416) 669-2280
Telex: 06-964570
Fax: (416) 669-5132.

IMM awards

Given below are details of the trust funds, etc., to which applications are invited for grants, etc., made by the Institution of Mining and Metallurgical Engineers that are payable in 1987. Application forms, which must be returned to the Secretary before 16th March, 1987, are available on request. Applicants should note that, in general, preference will be given to members of the Institution.

Bosworth Smith Trust Fund

Approximately £3500 will be available in 1987 for grants from the Bosworth Smith Trust Fund for the assistance of post-graduate research in metal mining, non-ferrous extraction metallurgy, or mineral dressing. Applications will be considered for grants towards working expenses, the cost of visits to mines and plants in connection with such research, and the purchase of apparatus.

Stanley Elmore Fellowships

Applications are invited for Stanley Elmore Fellowships, which are awarded by the Institution and tenable at United Kingdom universities, for research into all branches of extractive metallurgy and mineral processing. Fellowships of between £1500 and £6000 per annum will be available from October 1987.

Atlas Copco Bursaries

Two Atlas Copco travel bursaries for study tours of Swedish mines may be awarded annually to younger mining graduates. One bursary is open to engineers in any country who have at least 3 years of practical mining experience; the second bursary will be awarded to an engineer who is studying at a British university and has a minimum of one year's practical mining experience. The awards, which were established by the Atlas Copco organization in collaboration with the Swedish Mining Association, will comprise a 3- to 4-week tour of Swedish mining operations in September 1987. Travel expenses from any country will be paid for the first bursar and from London for the second; accommodation expenses will be met for both. The Council of the Institution of Mining and Metallurgy is responsible for the selection of the bursars, who will be required to present a written report to the Institution on any aspect of Swedish mining practice, methods, or organization that they found particularly interesting before 1st December, 1987.

G. Vernon Hobson Bequest

Applications are invited for awards from the income of the G. Vernon Hobson Bequest, established for the 'advancement of teaching and practice of geology as applied to mining'. It is expected that approximately £1500 will be available in 1987. One or more awards may be made for travel, research, or other objects in accordance with the terms of the Bequest.

Applications

Applicants for IMM awards must ensure that the particular fund from which support is being sought is relevant to their field(s) of interest. Applications that do not meet the terms and conditions of any field(s) and those which are received by the secretary *after* 16th March, 1987, will not be considered by the Awards and Grants Committee. Equally, applications for which the appropriate letters of support have not been received by 16th March, 1987, will not be submitted to the Committee.

Application forms for the Institution awards can be obtained from

The Secretary
The Institution of Mining and Metallurgy
44 Portland Place
London W1N 4BR
England.

Telephone: 01 580 3802. Telex: 261410.

Asian Mining 88

Asian Mining 88, the third conference in the series devoted to topics that cover the minerals industry—geology, mining, mineral processing, and metallurgy—will be organized by The Institution of Mining and Metallurgy, in association with other international bodies, and held in Kuala Lumpur, Malaysia, from 8th to 11th March, 1988.

As in the earlier conferences (held in Singapore in 1981 and Manila, Philippines, in February 1985), specific attention will be paid to topics that are of particular relevance to the Asian region, and technical tours and an associated international exhibition of equipment, products, services, etc., for the minerals industry will be arranged.

Requests for further information and copies of conference circulars should be made to

The Conference Office
The Institution of Mining and Metallurgy
44 Portland Place
London W1N 4BR
England.