PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Experience in the Gas Industry

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Experience in the gas industry

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The transmission and distribution of gas from offshore gas fields to domestic and industrial consumers requires a system of high integrity. This is required not only to provide a safe system but also to ensure that supply commitments to customers are met. Attitudes to defect tolerance assume paramount importance in studies of integrity, and this paper reviews the approaches to the problem in (*a*) polyethylene gas distribution systems and (*b*) steel high-pressure gas transmission pipelines.

A. Polyethylene gas distribution systems

1. *Introduction*

In 1970 a medium-density polyethylene (m.d.p.e.) gas distribution pipe system was initially introduced into the U.K. Since then, it, and other similar systems, have become increasingly used for below-ground applications at pressures up to 2 bar†, and accounted for 75% of all new mains and 80% of domestic services laid during 1978. Most of these systems consist of pipes up to 125 mm outside diameter, which are normally welded together by socket fusion techniques; the larger pipes are jointed by butt fusion and, although only the 180 mm size is used in substantial quantities, 500 mm pipes have been laid by this method.

Polyethylene clearly has certain strength and toughness properties to fit it for engineering use, but, as with all materials, it can be stressed to levels that cause failure. The limits need defining.

Testing at sufficiently high pressures will result in the ductile rupture of all pipelines. For the polyethylene (p.e.) system (s.d.r. 11 grade), bursting will occur within a few hours at pressures of approximately 30 bar, but as the test pressures are reduced, the time to failure will be considerably extended. (S.d.r., standard dimensional ratio, is the ratio of pipe outside diameter to wall thickness.) With sufficient burst data, it is possible to estimate the long-term ductile strength by extrapolation. On this basis the p.e. system could be expected to sustain a pressure of over 16 bar throughout its design life of 50 years.

In service, the p.e. gas distribution system is, in general, only operating at modest pressures up to 2 bar in the temperature range 5–15 °C, and so substantial safety margins exist. In operation, however, the pipe system is also subjected to tension and bending caused by subsidence or ground movement into adjacent excavations. Under these complex stress conditions, defects or other stress raisers in the pipeline network could be potential points for the initiation of stress cracking. This is a failure mechanism that can be demonstrated, within a reasonable timescale, only by testing p.e. pipe and fitting systems at high pressures and elevated temperatures.

Over the past decade, the development of polyethylenes by the addition of other monomers during the polymerization process has greatly improved their resistance to stress cracking.

† 1 bar = 10^5 Pa.

Nevertheless, it is essential to study the p.e. system and determine the operating limits that avoid stress cracking.

The stress cracking resistance of polyethylenes has been measured in the laboratory by using linear elastic fracture mechanics techniques. Also, the stress intensities, K, have been calculated at defects occurring in the p.e. system, under conditions reproducing pressure, end load and bending. Comparison of these two approaches, as outlined below, has enabled the operating conditions and installation codes of practice to be specified, to ensure that stress crack growth from the severest defects will not occur, or will be limited to insignificant growth, during the design life of 50 years.

2. *Pipeline defects*

The most serious field defects, up to 2 mm deep, are produced during the heat fusion jointing process of either socket or butt fusion. Despite careful design of fusion tooling for socket fusion, the action of pushing pipe into the p.e. socket fitting introduces a bead of molten polymer inside the fitting at the end of the pipe. When cool, the bead introduces sharp crack-like defects at a position of existing high stress concentration, caused by the change in material section (see diagram in figure 1). Less obvious are defects introduced externally between pipe and fitting when the molten p.e. bead is flattened against the fitting face by a metal clamp used for re-rounding the pipe end and limiting its penetration into the fitting.

The double bead formed during butt fusion generates sharp notches between the bead and the pipe's surface (see diagram in figure 2), though incorrect welding procedures can also introduce severe defects at the fusion interface. The latter are defects formed by incomplete fusion and would be introduced by too low a fusion temperature. At present there are no non-destructive tests available to detect these defects but quality control can be achieved by controlling the bead width within prescribed limits.

Scoring of the pipe during direct burial has not been found to be significant, as the gouges are not sharp and are normally limited to a depth of less than 1 mm. Potentially more serious longitudinal scoring could occur during the insertion of p.e. pipe through ageing cast-iron pipes, as a means of renewing gas mains economically. The normal procedure is to pull a 6 m test length of p.e. pipe through the old pipeline, so that an examination of the pipe's surface will indicate any cast-iron sections that will cause problems and need to be cut out before the new p.e. main is inserted. By this technique surface defects can be kept to a depth below 15% of the pipe wall thickness and, in normal circumstances, they are well below 10%.

3. *Finite element stress analysis*

(*a*) *Socket fusion*

Laboratory stress crack failures have shown in which direction stress cracks will propagate from the internal and external weld bead defects in socket fusion joints, so that suitable finite element meshes were chosen. The axial symmetry of the joint enabled the internal pressure and end load to be simulated on a computer program from which the strain energy release rate was determined for incremental crack extension. The stress intensity, K, for a given crack length was then calculated from standard formulae by using a long-term creep modulus of 145 MPa and a Poisson ratio of 0.45.

The use of the finite element programme to calculate stress intensities when the jointed section of pipe is bent to given radii is difficult, because the stress is not axisymmetric. These problems were overcome by simulating the maximum bending moment with an axisymmetric tensile load applied to the pipe end, which reproduced the stresses normal to the crack trajectory in bending.

Different combinations of pressure and bending were found by summation of the separate stress intensity contributions. Stress intensities at other pressures could be calculated as they are directly proportional; however, separate finite element analyses were required for each bend radius, though interpolation is possible.

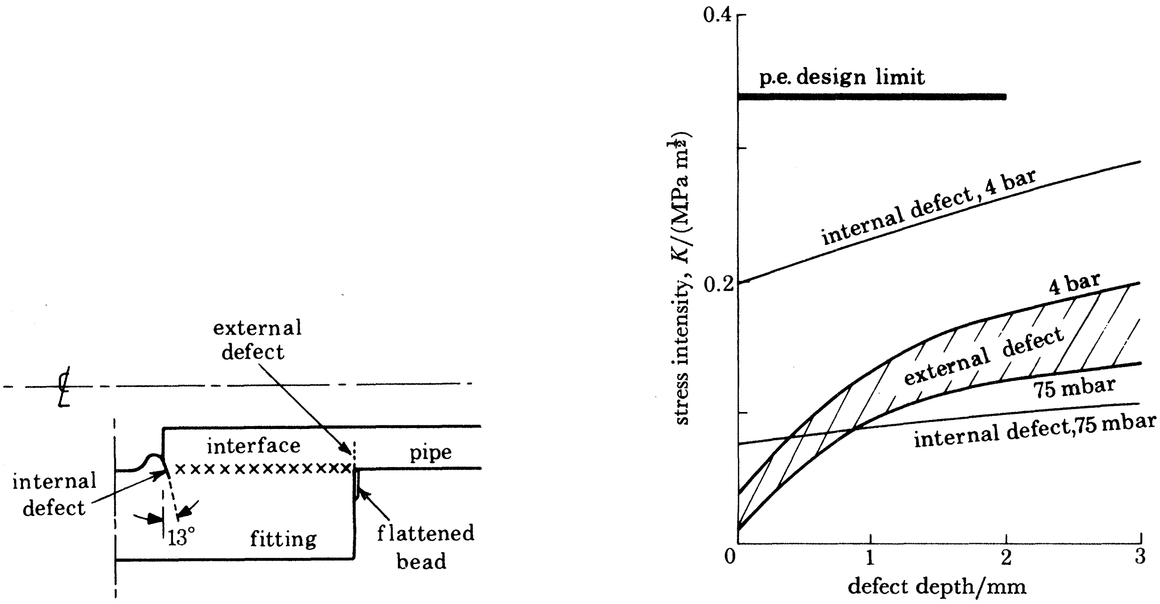

Figure 1. Internal and external 4 in (*ca.* 10 cm) s.d.r. 11 socket fusion defects with bend radius of 25D at 20 °C.

An example of the effect on the stress intensity of increasing defect depth is shown in figure 1 for a 4 in (*ca.* 10 cm) socket fusion joint at pressures of 75 mbar and 4 bar, both subject to a bend radius of 25 pipe diameters (25D). Such a bend radius is normally required during installation to bypass existing buried pipes and cables. At operating pressures above 1 bar, defects at the internal weld bead generate the higher stress intensities, for a given bend radius, than defects at the external weld bead. However, much of the gas distribution network is operating at pressures below 75 mbar and under these circumstances, and with defects above 1 mm, the stress analysis shows that the external weld defect is the more vulnerable.

(*b*) *Butt fusion*

The defect generated by a substandard butt fusion joint is represented by a circumferential crack (figure 2), which has been analysed previously (Harris 1967). By again simulating the stress induced by bending the pipe, with an equivalent end load, the maximum stress intensities were calculated for various crack depths. The results for 180 mm s.d.r. 17 pipe, a common butt fusion size in British Gas, are reproduced in figure 2.

For pipes above 225 mm outside diameter, another design criterion becomes operative to ensure that long sinusoidal brittle fractures down the pipeline at velocities of about 300 m/s cannot occur (Greig 1976).

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(*c*) *Longitudinal scoring*

In the field the most serious longitudinal pipe scoring can be represented by a longitudinal sharp defect whose stress intensity can be calculated for a given internal pressure (Emery & Segedin 1972). The additional circumferential stresses caused by bending the pipe to a given radius can be determined from the maximum tensile strains induced by the resulting elliptical section of the pipe. Measurements were taken of these elliptical shapes for different bend radii. Combining these approaches generated curves of stress intensities for various crack depths and bend radii (figure 3). As expected, the effect of even severe bending near the limit of buckling,

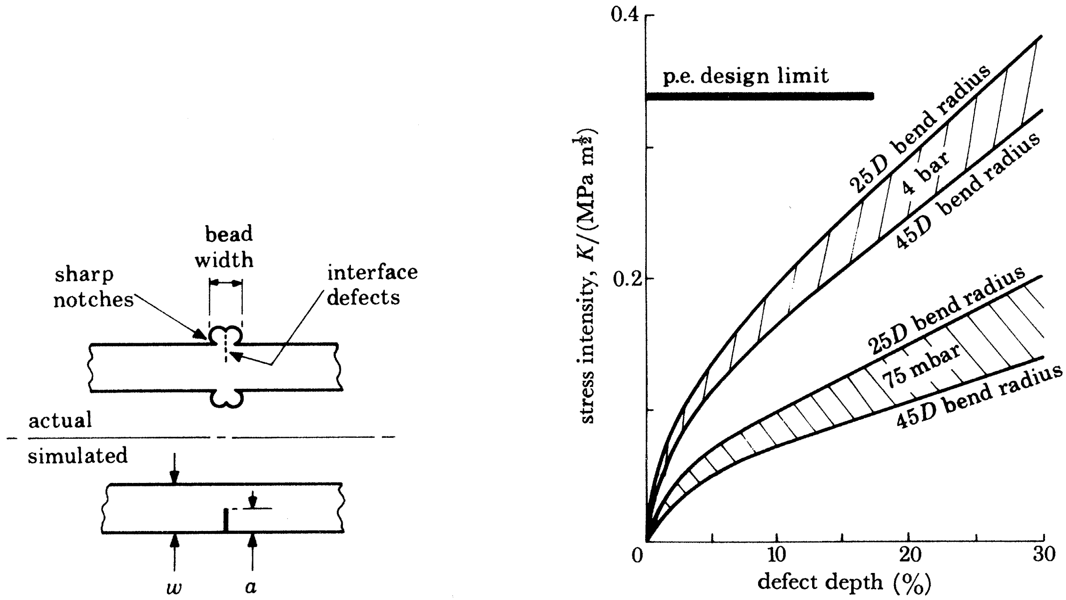

FIGURE 2. Simulated defects in 180 mm s.d.r. 17 butt fusion joint at 20 °C. Defect depth = a/w.

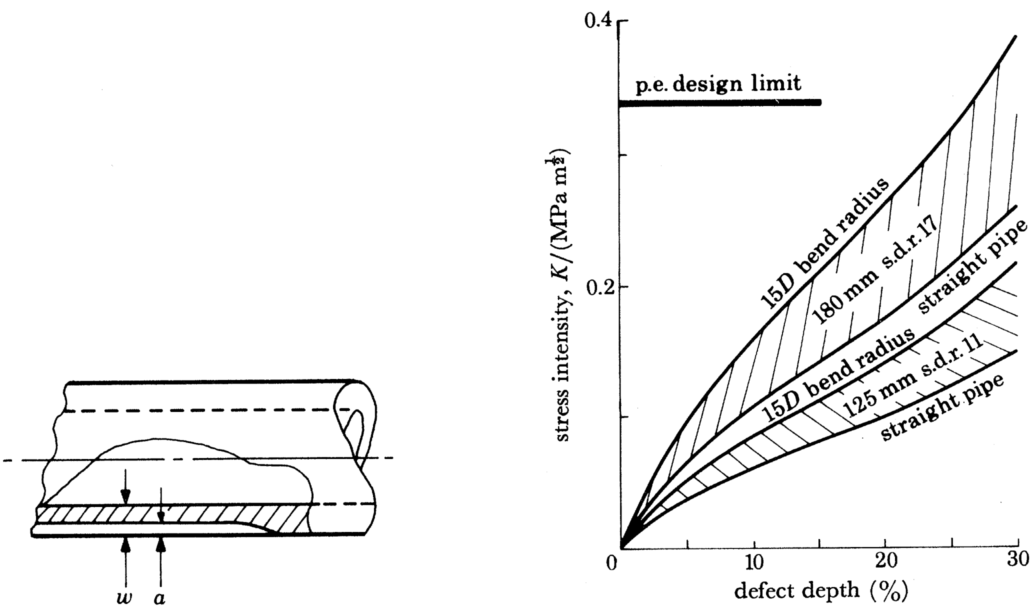

FIGURE 3. Longitudinal defect in pipes at a pressure of 2 bar, at 20 °C. Defect depth = a/w.

i.e. $15D$, does not alter the stress intensities remarkably from that of straight pipe, provided defect depths can be maintained below 20 % of the pipe wall thickness.

4. *Stress crack resistance*

The material property that characterises p.e. resistance to stress cracking is the critical stress intensity, K_c. Values of K_c, which depend on crack speed, have been measured in the laboratory by loading, in tension, centre-notched p.e. plaques in a thermostatically controlled water bath and monitoring crack growth over a period of time. The Srawley–Brown formula (Brown & Srawley 1966) was used to calculate the K_c from the crack growth data.

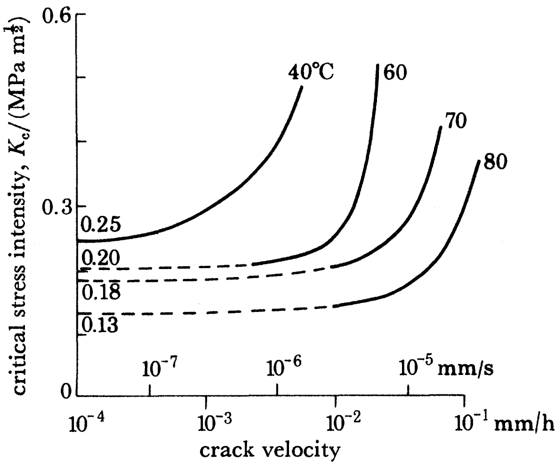

FIGURE 4. Stress cracking characteristics for a medium-density polyethylene (m.d.p.e.).

At any test temperature, the K_c – crack speed characteristic attains an asymptotic threshold value at very low crack velocities (approx. 10^{-4}mm/h) (figure 4). This threshold represents a limiting value of the critical stress intensity, K_L, below which cracking would be inhibited or limited to some insignificant value. Data collected during the incubation period for stress cracking initiation are discarded as this period depends upon the notching technique, especially the sharpness of the artificial cracks made in the test plaque. Data are only used while the stress crack is growing naturally so that extrapolation of the characteristic can be made accurately to low crack speeds. Characteristics of a p.e. material have been obtained at temperatures ranging from 80 °C to the longer-term tests at 40 °C. It is useful to be able to obtain characteristics at elevated temperatures, where stress cracking occurs in a relatively short time, so that estimates of the test conditions, e.g. stress and crack length, can be made to produce satisfactory data at lower temperatures. Extrapolation of these K_L values to 20 °C gives a limiting value of 0.33 MPa $m^{\frac{1}{2}}$.

Recently, a slightly different approach has been made by Epstein and coworkers at Battelle's Columbus Laboratories (Epstein 1979), whereby stress cracking was obtained in square section, notched bars, machined from pipe or fittings and loaded in bending. After a small amount of crack growth had occurred, the specimen was fractured to measure crack length and thus the average stress intensity and average crack speed calculated. Published data at 20 °C of a material similar to that tested by ourselves indicated a limiting value, K_L, almost identical to that predicted by our own test results.

The newer m.d.p.es required by the British Gas specifications, are so resistant to stress cracking that it is difficult to obtain data at temperatures below 60 °C. However, a tentative estimation of K_L for the newer p.e. grades at 20 °C has been made by taking the 0.33 MPa $m^{\frac{1}{2}}$ value and multiplying it by the ratio of the two m.d.p.e. materials' K_L performance at 80 °C. This calculation results in a K_L value of 0.51 MPa $m^{\frac{1}{2}}$ for the newer m.d.p.es at 20 °C. However, a safety factor of 1.5 is applied to take into consideration possible errors in (i) K_L measurements; (ii) stress intensity calculations from finite element analyses; (iii) material variability from batch to batch; (iv) processing variability, especially frozen-in stress in thick sections.

Thus, until further direct test data are obtained, a design stress intensity of 0.34 MPa $m^{\frac{1}{2}}$ (i.e. 0.51 MPa $m^{\frac{1}{2}} \div 1.5$) will be used for materials currently purchased against the British Gas specifications.

5. *Discussion and conclusions*

The design critical stress intensity limit of 0.34 MPa $m^{\frac{1}{2}}$ is indicated on figures 2, 3 and 4 to enable a comparison to be made with the stress intensities generated at defects in the p.e. system when subject to pressure, end load and bending. Socket and butt fusion joints at pressures of up to 4 bar would appear to be safe from stress cracking from defects up to 2 mm deep, i.e. a depth considered to be the maximum that could be produced during normal installation practices.

Longitudinal sharp defects in pipes do not create conditions likely to cause stress cracking, provided the installation procedures of using a test length of pipe first are maintained so that defects do not exceed about 15% of the pipe wall thickness.

On the basis of the approach outlined here, specifications and codes of practice for p.e. systems have been devised that ensure that defects introduced during system construction will not be a cause of failure during the minimum design life of 50 years.

B. Steel high-pressure gas transmission mains

1. *Introduction*

Studies of fracture mechanics over recent decades have arisen owing to the recognition that defects do exist in structures and that there is a need to 'live with them'. This need is even more apparent as more sophisticated and searching inspection techniques become available; increasing numbers of defects are being revealed by these procedures, and realistic means of evaluating their influence on performance are necessary if repair schemes involving uneconomic plant shutdowns are to be avoided. It is easy to imagine, for instance, the economic cost of making incorrect judgements of defect significance in the British Gas high-pressure gas transmission system of over 15000 km length. Most of this length includes a longitudinal seam weld and a circumferential girth weld every 10 m or so. It is just not possible to adopt the view that such an engineering undertaking can be achieved without fabrication defects or that it can be operated without defects occurring in service. However, account can be taken of these defects, and a combination of carefully monitored policies of system design, material selection, quality assurance and maintenance and revalidation practices will ensure that a gas transmission system will operate with a high level of safety. The result is a philosophy in which defect inspection, sentencing and repair are treated on a realistic fitness for purpose basis. In this way repairs to insignificant defects can be avoided.

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It is important to define realistic standards for the repair of defects. One wishes to avoid the costly detailed examination schemes that, for instance, were adopted on sections of the Aleyaska pipeline involving defect repair, the necessity of which has been questioned by several workers. We must also remember that repairs themselves may present a potential hazard, a fact clearly demonstrated by the failure of the Fawley oil tanks after repair of a cut-out made solely for the purposes of routine weld examinations. Equally, we must recognize that a gas transmission system represents, by its length, a formidable statistical problem in the evaluation of defects; thus while the measures outlined above ensure that the probability of failure from defects is almost negligible, strategies that would account for the effects of any unforeseen failure are adopted. These involve considerations of the type of failure in relation to defect type and material properties so that design stresses can be selected to minimize the risk from such incidents.

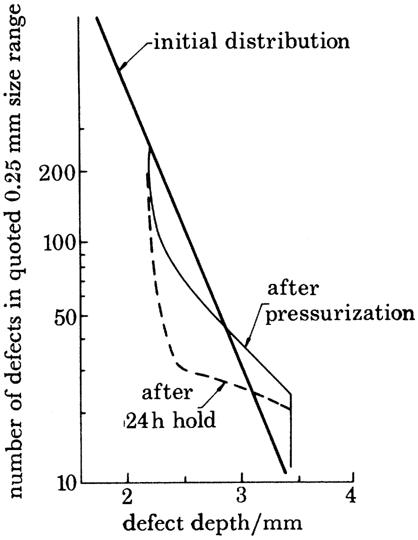

FIGURE 5. Defect size distribution and effect of pressure testing.

The results of the policies outlined above, which have been developed for many years both in the U.S.A. and Europe, is a U.K. gas transmission system which has accumulated 150000 km years of service and has suffered only one significant incident: a failure during commissioning, due to external interference. Some of the background considerations which form the basis of design and operational policies for 'living with defects' will be discussed in this section.

2. *Defect population*

(*a*) *Defect size distribution*

The starting point in developing attitudes to defects in such an extensive system as a gas transmission system is a knowledge of the actual defect population. An estimate of this has been made (Fearnehough & Jones 1978) from statistics of failures during pre-service proof pressure testing. In the gas industry, pipelines are hydrostatically tested to levels that may exceed the specified minimum yield stress (SMYS). (Yielding is, in fact, limited to small amounts because the average yield stress always considerably exceeds the minimum specified.) Failures have occurred in some early pipe supplies owing to manufacturing or constructional defects either during pressurization or during the subsequent 24 h hold period. The failure pressure of those defects that fail during pressurization may be used to calculate the initial defect size. In this way it is possible to build up a distribution of defect sizes, as shown in figure 5. (This figure also includes the results of a study of defects in seamless pipe. These defects were sized by measurements taken during their removal by grinding.)

(*b*) *Modification by hydrostatic proof testing*

The defect distribution of an installed pipeline is modified as a result of hydrostatic testing. First, all defects that are larger than the critical size fail during the hydrostatic test. The limiting size defined by the maximum test pressure is indicated by the vertical line in figure 5. No defects larger than this size can remain in the pipeline. Secondly, all defects that are smaller than this critical size grow during pressurizing and during the hold period. The extent of the growth is estimated from the number of failures that have occurred in each stage (65 during pressurizing, 100 during the hold period). The net defect distribution is indicated by the line in figure 5. It will be observed that the hydrostatic test decreases the number of subcritical defects within a certain size range (it was assumed that only those of size larger than a certain size actually grow during testing), whereas the population of defects that are just subcritical is increased by the pressure test. This population is again influenced as a result of the hold period (Fearnehough & Jones 1978), which causes a further reduction in the number of subcritical defects.

There is considerable evidence to show that the hydrostatic test carried out to a high level renders a pipeline immune to subsequent failure from surviving defects. Operating experience of a Texas Eastern pipeline has been quoted by Duffy *et al.* (1968) in support of this thesis. The 1200 km line suffered seven breaks and seven leaks in service before revalidation in 1950 by pressure testing for 20 min to 90–100% SMYS (264 failures occurred during testing). In the subsequent 7 years of service six leaks but no breaks occurred. A repeat hydrostatic test was then carried out for 24 h and in a further 7 years of service only one leak occurred. British Gas experience of hydrostatic testing to yield is similar in that there have been no failures resulting from any defect that has survived such a test.

It is important to recognize that hydrostatic testing to high levels not only defines the maximum size of defect in the installed pipeline but is also a quality control procedure which, together with n.d.t. inspection at the mill, has constrained manufacturers to improve pipe products. Mercer (1979) shows clearly how product quality has improved since the introduction of high-level testing so that such failures are rare; indeed, the defect distribution of figure 5 could only be determined from the relatively high failure rates of pipe produced before 1970. The failure rates and hence defect population of subsequent pipe productions are one or two orders of magnitude lower than previous levels.

(*c*) *Fatigue*

Freedom from failure in operation is, of course, a direct result of the safety margin defined by the proof test. Defects that survive the proof test can only lead to failure as a result of time-dependent growth processes such as fatigue and corrosion. Fatigue is an important consideration in U.K. pipelines since some are used for storing gas, in addition to transmission, by pressure cycling according to the gas supply–demand profile. Studies have been made (Fearnehough & Jones 1978) of the cyclic life guaranteed by the proof test. These studies involved tests on 760 mm diameter, 15.9 mm wall pipe containing defects of a size that would just survive the proof test. The results showed, first, that there was a significant beneficial effect on the fatigue life as a result of the proof testing (the well known effect of induced residual compressive stresses). Secondly, a significant safe life is obtained so that transmission pipelines can be used for gas storage. A direct demonstration of the validity of this conclusion was obtained from a fatigue test on a pipe section containing a manufacturing defect approximately 1 mm deep, at the toe of the longitudinal seam weld. The pipe was subjected to a testing scheme in which proof tests were carried out at approximately 5000–10000 cycle intervals. The cumulative life at a cyclic stress range of 240 MPa was 68000 cycles and the life subsequent to the last proof test was 5100 cycles. Since the defect would have been just subcritical at the last proof test (confirmed by the fact that the fractured surfaces showed its maximum depth to be 5.6 mm, approximately the critical depth at the proof test level), this life represents the life implicitly defined by pre-service testing procedures. Studies of this type have led to the definition of an acceptable cyclic stress range of 124 MPa for pipes for a 40 year life involving 1 cycle per day, incorporating a factor of safety of 10.

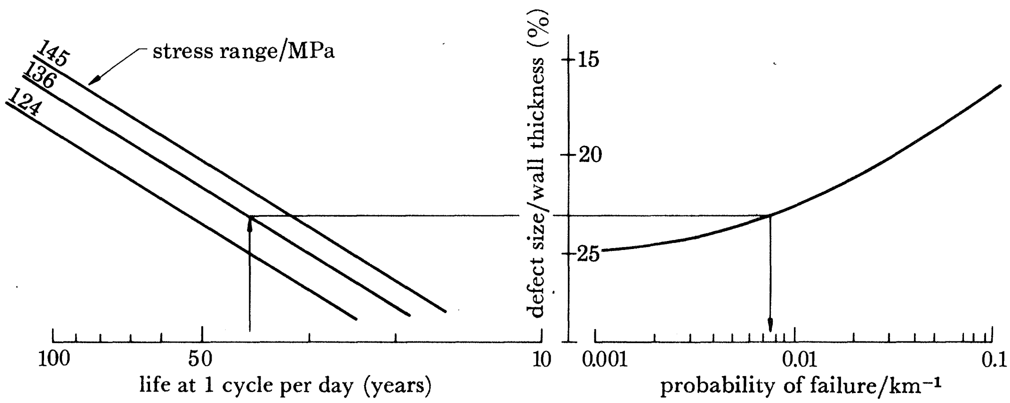

FIGURE 6. Determination of failure probability from fatigue data (left) and defect size distribution (right).

It is possible to quantify the consequences of exceeding the above stress range by considering the effect of fatigue on the defect population in figure 5. Figure 6, taken from Fearnehough & Jones (1978), shows the stress range–life lines derived from the fatigue tests described above. The defect sizes corresponding to the indicated lives are then linked to the defect size distribution in figure 5 to give the failure probability locus in figure 6. Note that the diagram indicates zero failure probability for a 40 year life at a stress range of 124 MPa, in agreement with the philosophy defined above. A 40 year life at 136 MPa, for example, would give a failure probability of 0.0076/km, even incorporating a safety factor of 10 on the fatigue data.

This section has shown that the defect population as determined by the proof test can be used to define stress ranges so that defects can be tolerated in pipeline systems.

(*d*) *Environmental growth processes*

Defects may be introduced and grow owing to environmental effects by either corrosion or stress corrosion cracking.

Corrosion is resisted by coating the pipeline externally. Reinforced coal tar coatings have been extensively used, but these are being superseded by tougher epoxy coatings. Since coating faults do occur, cathodic protection is applied, coupled with c.p. monitoring, and its efficiency monitored by pipe–soil potential surveys; any coating defects are detected by regular Pearson surveys. Nevertheless, corrosion is still an important defect source and it is necessary to know the kinetics of the process to define safe operation and maintenance schemes.

Stress corrosion cracking (s.c.c.) has been a problem, particularly in the U.S.A., where elevated temperatures downstream of compressor stations have aggravated s.c.c. and resulted in hydrostatic test and operational failures. The kinetics of the s.c.c. process have been determined and it has been demonstrated that temperature, stress and stress variations are particularly important parameters in addition to electrochemical factors. Problems from s.c.c. can, however, be eliminated by installing after-coolers at compressor stations to reduce pipeline temperatures to below about 35 °C.

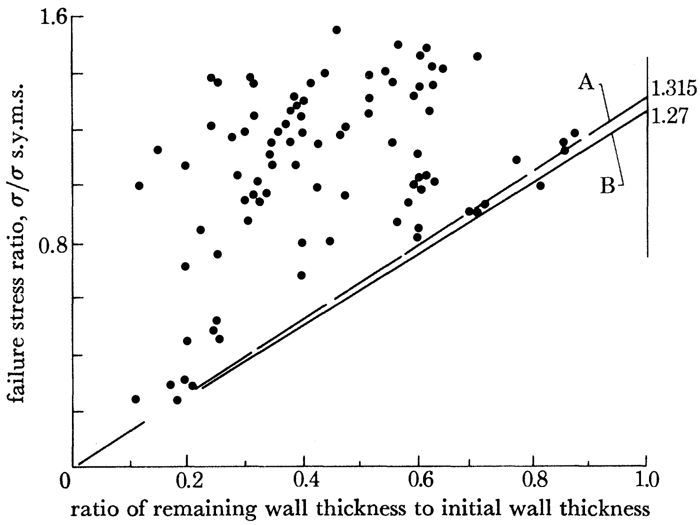

FIGURE 7. Analysis of failure stress of pipe defects: (A) 95% lower confidence limit; (B) allowance of 5% for time dependence.

3. *Defect instability*

A knowledge of the conditions under which defects fail is a prerequisite of all defect acceptance standards. Failure criteria may be generally defined by linear elastic or elastic–plastic fracture mechanics, or by plastic collapse conditions. Failure in pipelines is generally controlled by plastic collapse criteria as, for instance, shown in the statistical study by Fearnehough & Jones (1978) of a large number of tests on defective pipes. The study showed that the probability of optimistic (i.e. high) estimates of failure stress of part-wall and through-wall defects, from plastic collapse formulae, is very small.

A simple approach to the problem of part-wall defect behaviour is to make the pessimistic assumption that they are of infinite length and to assess their behaviour on the basis of the remaining ligament. Data from actual failures and experimental burst tests have been collated in this way in figure 7 according to failure stress/SMYS ratio and remaining ligament/wall thickness ratio, r. A statistical analysis gives a 95% lower confidence limit as shown in figure 7 and an allowance of 5% on stress made to account for the effect of time on failure. Such analyses are useful for defining defect tolerance in pipelines and they show that at an operating stress of 72% SMYS, a defect does not fail until its depth exceeds 40% of the wall thickness.

The validity of the plastic collapse assumptions has also been demonstrated by laboratory and full-scale tests on defective girth welds (Fearnehough & Jones 1978). These tests show that defects in the weld toe of 20% wall thickness depth do not fail until nominal stresses of yield point magnitude are exceeded. Considerations of this nature have led (Lumb & Fearnehough 1975) to relaxations in attitude to girth weld defects, particularly with regard to the unnecessary sentencing of slag type defects and lack of fusion of limited length.

4. *Revalidation*

Pipelines can deteriorate during service and it may be necessary to revalidate their structural integrity. This is carried out to ensure that the safety margin before defects can fail is maintained. One obvious way of doing this is to repeat the hydrostatic proof test at intervals. This procedure has been adopted, particularly in the U.S.A. and Canada, and has been successful in reducing the failure rate in service. As shown earlier, it is possible to define the safe service life which such testing confers. There are, however, practical difficulties with revalidation by hydrostatic testing because (*a*) the pipeline has to be removed from service, (*b*) the line has to be cut into sections of suitable length for testing and (*c*) being a destructive test, precautions are necessary during testing and the expense of repairing burst pipe results.

Alternative revalidation procedures are being developed by British Gas, which involve inspection from the inside of the pipeline while it is still in service. This on-line inspection (o.l.i.) system uses a 'pig' driven along the pipeline by flowing gas and containing defect detection and electronic data processing and recording systems (Clerehugh 1979). Defects in which there is a loss of metal in the pipe wall are detected by magnetic flux perturbations. Crack-like defects are detected by modifications to oscillating elastic stress waves generated in the pipe wall.

The inspection programme involves establishing a priority rating for all pipelines according to (*a*) the pipe's age, stress level and probability of external interference and (*b*) the consequences arising from proximity considerations of a hypothetical failure. Pipelines with a high priority rating, determined from a statistical analysis of the above factors, will be inspected more frequently than those with a low rating.

On-line inspection is clearly a more convenient and economic means of revalidation than hydrostatic testing. A comparison of the technical merits is interesting. Hydrostatic revalidation has the advantage of generating residual compressive stresses around defects which have a beneficial effect, for instance, in retarding fatigue. On the other hand, by inducing growth of some subcritical defects, it has a deleterious effect on the population of subcritical defects. Nevertheless, there is an unambiguous definition of maximum remaining defect size and consequently a guaranteed safety margin. No non-destructive testing scheme is 100% reliable and any potential disadvantage in this respect that may relate to on-line inspection can be more than offset by the ability to carry out more frequent inspections; it is unlikely that any significant subcritical defect will escape detection on several consecutive runs. Additionally, on-line inspection has the facility to monitor the condition, i.e. the stability, of subcritical defects which would not even fail during, and consequently remain undetected by, hydrostatic revalidation. This condition monitoring is a valuable tool which, by statistical techniques, will allow the defect population of a pipeline to be quantified and remedial action taken with those defects that might become hazardous.

5. *Design*

The above sections have concentrated on measures to prevent defects failing. However, it has been recognized that there are situations over which a pipeline operator does not have complete control. This situation occurs with mechanical interference by third parties, the result of which is a very low but finite risk of failure. Where pipelines pass close to populated areas this risk must be reduced so that it is possible to 'live with defects' which may be introduced by mechanical interference. This reduction in risk is achieved either by increasing the wall thickness or by reducing the pressure so that the design stress is below 30% SMYS. This solution to the problem arose because (*a*) it was realized that long defects (figure 8) are necessary for a burst to be possible at these low stress levels (Shannon 1974), and (*b*) a statistical evaluation of actual defects in pipelines showed that the probability of such long defects being present is extremely low. This leak–break philosophy is even more powerful for corrosion defects, where a rupture is not possible below stress levels of 45% SMYS. These concepts are the background to the '30% rule' adopted in the U.K. for transmission pipelines in certain areas; this rule gives a low probability of failure and ensures that any failure that did occur would be a leak, detectable before it reaches a serious magnitude.

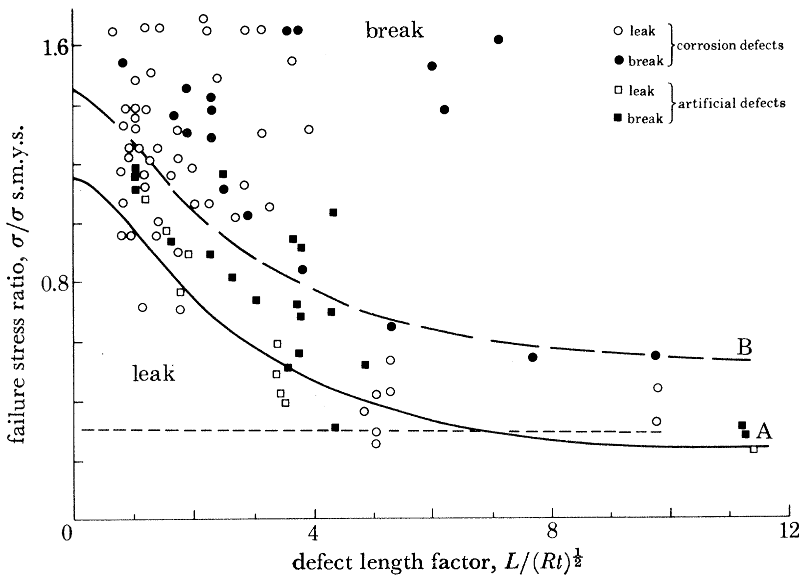

Figure 8. Leak–break behaviour of pipeline defects. Curve A is leak–break boundary for artificial defects; curve B is leak–break boundary for corrosion defects. L is defect length, R is pipe radius, t is wall thickness.

6. *Repair*

A non-destructive inspection scheme must be accompanied by a policy of repair. Defect removal by cut-out is an unnecessarily expensive approach, particularly with the detection sensitivity of on-line inspection. Repair policies are being drafted which incorporate several techniques according to the severity of the defect. Superficial defects may be dressed by grinding and recoating. More severe defects demand reinforcement by either repair welding, wrap-round sleeves or epoxy-grouted sleeves. The wrap-round sleeves, circumferentially welded to the pipe, have several functions: they prevent access of aggressive environments, restrict extensive bulging, which favours failure by leakage, and provide containment for leaking gas. Epoxy fills with minimum shrinkage characteristics are being developed for unwelded sleeves. The function of this type of sleeve is to prevent any bulging of the defect during service so imparting stability. This latter effect becomes more pronounced if the repair is carried out at low pressure.

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Decisions on the type of repair, the precautions during repair and also on the standards for sensitivity of on-line inspection are related to the defect size and the safety margin before failure would occur. One approach is to require that on-line inspection should have the same discrimination in detecting defects as hydrostatic testing and that defects should not remain in a pipeline if their size is such that they would fail during a hydrostatic proof test. Such standards can be derived from the information given in figure 7, which shows that at yield stress levels, defects have an increasing chance of being critical when their depth exceeds 20% of wall thickness. Thus, as a general principle, defects shallower than this may be repaired by surface dressing and recoating; deeper defects require repair by a sleeving technique which either reinforces the defect or which prevents bulging and consequent bursting.

7. *Concluding remarks*

The above sections have shown how it is possible to operate a pipeline system safely, by a combination of defect control measures, by pre-installation testing, in-service revalidation and design. In this way, we can see why a 'perfect' structure, however desirable, is not necessary and one can 'live with defects' provided that there is a rational basis for their evaluation and repair.

References (Fearnehough & Greig)

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