$Ce_4Si_2O_7N_2$ it seems more likely that nitrogen is distributed statistically among the non-metal sites rather than preferentially occupying the cerium co-ordinated sites, but a complete structure determination would be necessary to confirm this.

A more detailed discussion of the Ce–Si–O–N system will be published separately.

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Fatigue properties of high density polyethylene pipe systems

Plastics pipe-networks are composed of extruded pipe and injection-moulded fittings, and network lifetime assessment concentrates on testing the pipe only, under conditions of static fatigue (i.e. creep). Early work [1] on a high-density polyethylene (HDPE) pipe showed that dynamic, as opposed to static, fatigue did not reduce pipe lifetime, where lifetime is defined by the time under maximum load. However, recent work [2] extended testing to HDPE pipe systems under conditions of dynamic square wave fatigue at a fixed frequency of 4 cycles per minute (cpm) that is $7\frac{1}{2}$ sec on, $7\frac{1}{2}$ sec off; at this fixed frequency pipe system lifetime was significantly reduced in comparison to the creep life of the pipe, and failure was shown to be due, in part, to the incorporation of injection-moulded fittings.

An extensive and systematic study of the performance of a range of mirror-plate butt-welded HDPE pipe systems under burst, creep and fatigue loadings has been undertaken at Brunel University with the aim of identifying more precisely, the lifetime of pipe-networks subject to these various loading profiles. Work centred initially on a HDPE resin, of pipe density $0.954\ g\ cm^{-3}$, fabricated into a 63 mm SDR 11 system, incorporating extruded pipe and injection-moulded flanges, 90° bends and 90° equal tees. This diameter of system was selected for reasons of economy and ease of handling. The pipe systems were assembled to dimensions to conform to the minimum requirements of ASTM standards D2610 and D1598 by mirror-plate butt-welding under optimum conditions of weld temperature and pressure. The details of the test procedures and the geometry and fabrication techniques of the pipe systems will be presented in future publications [3]. So too will be further creep and fatigue data and fractographic studies on this 63 mm system, together with data on other pipe systems. This note serves only to demonstrate that pipe system lifetime can be strongly frequency-dependent over the limited frequency range (up to 10 cpm) of the fatigue loadings studied; in this respect the present work supports the observations of Cowley and Wylde [2], that pipe-network lifetime can depend on the integrity of the injection-moulded fittings or welds between fittings and pipe, as opposed to the strength of the extruded pipe.

Schematic diagrams of the principal 63 mm pipe systems tested are illustrated in Fig. 1. This note reports the results of those tests where the systems were maintained at a temperature of 80° C (353 K), by immersion in a constant temperature (± 1.0 K) water bath, and pressurized to 1.00 MPa

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TABLE I The influence of loading mode and construction of pipe system on actual failure sites for selected 63 mm SDR 11 pipe systems

Loading mode	Pipe system			
	Pipe (A)	Pipe to Pipe (B)	Pipe + 90° equal tee (C)	Pipe + 90° bend (D)
Burst (a)	1	1	1	1
Creep (b)	1	1	1	1
Fatigue (b)	1	1	2 (8)	3 (4, 5)

The body of the table contains the failure site number which can be identified in Fig. 1, along with pipe system configuration. Numbers in brackets refer to sites of failure which appear less frequently.
(a) Tested to ASTM D1599 in the temperature range 293 to 353 K.
(b) Tested at 353 K with 1.00 MPa maximum internal pressure.

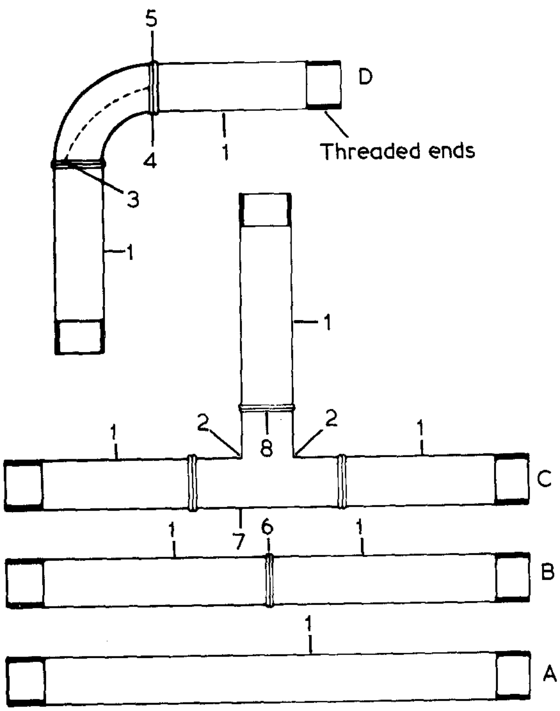

Figure 1 Schematic diagrams of the pipe systems tested: A, pipe only; B, pipe system containing one mirror-plate butt-weld; C, pipe system incorporating a 90° equal tee; D, pipe system incorporating a 90° bend. The diagram also indicates potential sites of failure within these systems (1 to 8) with sites 1 and 2, only, being of interest in the present paper. (A description of remaining failure sites will be given in future publications [3].) Site 1, crack, about 5 mm long, parallel to the pipe extrusion direction. Site 2, crack, about 5 mm long, at the transition between the branch pipes of the tee lying in a plane defined by the tee arms.

by compressed air acting on water inside the systems. Loading cycles were ramped square wave in form, with a constant time-off of 6 sec, and time-on varying between 64 and 1 sec (0.86 to 8.57 cpm). The systems were also subjected to burst and creep tests. In none of the tests were the ends constrained, end closures being of the form of (a) in ISO 1167.

From the body of results obtained and presented, two principal observations can be isolated; one, the failure site may depend on mode of testing; two, the lifetimes of certain pipe systems are frequency-dependent for dynamic fatigue loading. Potential sites of failure in the various pipe systems are illustrated in Fig. 1, but the actual (i.e. observed) failure sites are given in Table I below for burst, creep and dynamic fatigue loading.

For all pipe systems burst tested, failure was always in the pipe and always ductile. Under creep, the failure site was again constrained to the pipe but the failure was now brittle, the small cracks lying parallel to the extrusion direction. In dynamic fatigue the failures were all brittle but the site of failure was a function of the type of pipe system under test. Under the three modes of loading the system incorporating pipe only (A), and pipe welded to pipe (B), showed similar lifetimes or strengths and failed at identical sites; in both systems failure occurred in the pipe (site 1). The pipe-to-pipe butt-weld was not, therefore, identified as a source of weakness under creep or fatigue loading. However, if a pipe system included an injection-moulded fitting and the system was tested under fatigue loadings of sufficient frequency ($\geqslant 2$ cpm in this study) positions of failure were observed to change from site 1 to sites 2, 3, 4, 5 or 8. This change in failure site accompanies a substantial reduction in system lifetime under fatigue conditions; Fig. 2 plots the influence of frequency on the lifetime of pipes and pipe systems that include an injection-moulded 90° equal tee.

The results presented in Fig. 2 indicate that pipe lifetime is insensitive to variations in fatigue frequency, but systems incorporating equal tees can fail under conditions of dynamic fatigue loading (at site 2) at lifetimes well below that of the pipe. The importance of loading frequency on equal tee pipe system lifetime (defined, as noted

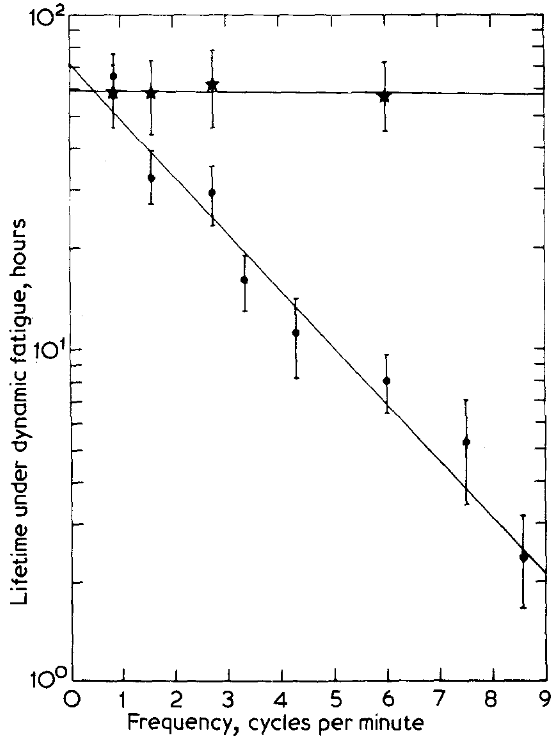

Figure 2 The influence of pulse frequency on the lifetime of pipe systems (★) failing at site 1, and 90° equal tee systems (●), failing at site 2. Lifetime is defined as the time under maximum load. The data in this figure are for a HDPE 63 mm SDR 11 system, tested at 80° C under an internal pressure of 1.00 MPa (i.e. a hoop or comparative stress of 4.93 MPa).

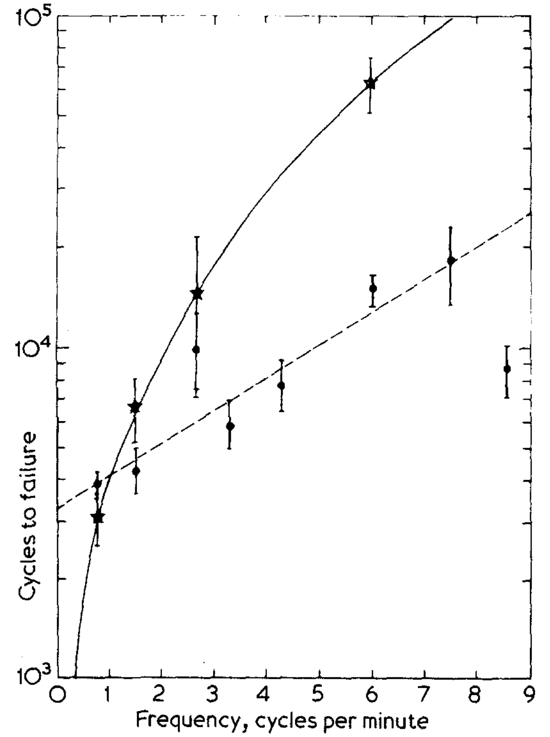

Figure 3 The results presented in Fig. 2 have been replotted to show the variation in the number of cycles to failure of pipe systems (★) failing at site 1, and 90° equal tee systems (●), failing at site 2, as a function of pulse frequency. The data for the point at 8.57 cpm were derived with an increased ramp slope compared to all other data.

earlier as the time under maximum load) is clearly illustrated at frequencies of 6 and 8.57 cpm; at the lower frequency the equal tee fails at approximately 13% of the pipe creep life, while at the higher frequency this is reduced to approximately 3%, both representing a dramatic reduction in system lifetime.

The data in Fig. 2 are replotted in Fig. 3 to highlight the influence of frequency on the number of cycles to failure. For the equal tee, the data in Fig. 2 and fractographic studies of fracture surfaces [3], which revealed fatigue striations, infer failure by a fatigue-type mechanism. However, the data as presented in Fig. 3 indicate that the tee failed by a mechanism which was not pure fatigue, but a mixture of creep and fatigue: when the frequency of loading was decreased, and the time-on for any one cycle increased, the number of cycles required for failure decreased, indicating that lower frequencies allowed crack propagation during load-on times. As noted earlier, the loading profile on the pipe systems was essentially a ramped square wave with a constant ramp slope (except for the 8.6 cpm) so strain-rate strengthening need not be taken into account [4], and the influence of creep is more clearly identified. The increase in the number of cycles to failure with increasing frequency also infers tee failure was not by fatigue thermal melting due to hysteretic energy generated during each loading cycle, but was due to the initiation and propagation of a crack [5]. Scanning electron microscopy of failed tees has clearly identified the site of crack initiation [3].

The limited number of results presented in this note illuminates the importance of both mode ot testing and construction of pipe test specimens on the possible lifetimes of HDPE pipe networks.

Fatigue or cyclical loading is shown to be the most aggressive, and under this type of loading, if premature failure occurs, it is associated (for this 63 mm SDR 11 system) with the injection-moulded 90° equal tees or 90° bends. The failure site is either in the body of the injection-moulded fitting or at the weld between the pipe and the injection-moulded fitting. However, it must be noted that, (a) the pipe supplied clearly met the pipe specification; a creep life of 58 h for a temperature of 353 K and an internal pressure of 1.00 MPa is certainly above specification, (b) the pipe-to-pipe mirror-plate butt-weld does not appear to be a source of weakness if optimum welding conditions are used and the pipes are correctly aligned. This confirms work carried out by Vancromburgge [6] who concluded that this type of butt-weld has a weld quality of 1, i.e. that it fulfills pipe requirements. In addition the authors believe the data as presented do not indicate a weakness that should markedly restrict the use of HDPE for construction of pipe systems.* It is believed, however, that the failures associated with the injection-moulded fittings are a result of one or more of the following factors; firstly, the overall design of the mould used for manufacture of fittings, secondly, the microstructure of the fitting induced during moulding, and thirdly, the notches produced in the fitting to pipe butt-welds which appear as a direct consequence of the fitting microstructure.

Similarly, weld notches are a result of mould design and processing conditions which impose a certain microstructure on the fitting thereby inducing highly anisotropic changes in shape when the surfaces to be joined are heated. Weld notches have been observed to form in areas associated with internal weld lines and mould parting lines on both 90° bends and 90° equal tees.

Design of moulds must, therefore, take account of possible points of high stress concentration, and the gating systems and processing conditions used during fabrication of moulded fittings, must be selected to ensure the development of an appropriate microstructure, which effectively removes sites for crack initiation and also helps in limiting the rate of propagation once a crack has nucleated.

A marked frequency dependence in the lifetimes of both pipes and fittings also occurs when flaws, such as voids or inclusions, are present to act as ready-made crack-nucleation sites. These points of high stress concentration also produce a substantial reduction in creep life.

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*It should also be noted that the reported results do not necessarily apply to other polyethylenes and mouldings.