DISCUSSION

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The authors have produced a valuable contribution to the understanding of the ductile crack propagation process allowing crack speed predictions from first principles. In particular they have followed the approach, adopted in British Gas studies [30, 31],[6] of estimating each component contributing to the energy balance invoking gas dynamics, bulge geometry estimations, toughness evaluation and kinetic energy effects. The gas loadings are so important that British Gas sponsored a detailed study by G. M. Alder at Edinburgh University of the pressure distribution in the fracture zone and the results were incorporated in our analyses. It is gratifying to note that the gas analysis adopted by the authors is similar to that adopted by Alder and that there is close agreement in the results.

It is appropriate to highlight the form of the G (available)—velocity relationship derived by Kanninen and his coworkers. It is precisely this form, showing a maximum G, which an earlier British Gas study [32] required as a prerequisite of a successful description of the ductile fracture propagation process. Kanninen, et al., recognise that the maximum represents a possible route to the prediction of arrest conditions. This approach was, in fact, utilized in the British Gas analyses [30, 31]. Expressions for the maximum available G were derived[7]; these allowed an arrest boundary to be evaluated which correctly classified the majority of full scale test data. Our analysis did, however, require information from full scale tests to obtain values for the unknown constants and we look forward to an extension of the Kanninen analysis to allow direct prediction of fullscale fracture arrest behavior.

Another similarity between the Battelle and British Gas analyses is in the derivation of fracture resistance, Gc from Charpy energy values. Kanninen, et al., used a constant of 3.17 whereas our evaluation [33] based on R curve data yields a value of about 4. These values are not too dissimilar considering the present state of the art and we would agree with the authors' contention that further laboratory studies of toughness evaluation techniques are essential.

It is appropriate to take this opportunity to comment on the authors' "league table" of published analyses (Table 4). It appears that the British Gas analysis has suffered by the omission of two credit stars! Firstly, a major factor in this analysis is the determination of inertia forces and resultant kinetic energy; this factor is the central parameter in providing the characteristic shape of the G–V relationship. Secondly, crack-tip plasticity has in effect been incorporated by the inclusion [2] of the Erdogan-Ratwani relationship for the bulge shape.

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[6]Numbers in brackets designate Additional References at end of discussion.

[7]For the case of a backfilled pipe.

Additional References

30 Poynton, W. A., Shannon, R. W. E., and Fearnehough, G. D., "The Design and Application of Shear Fracture Propagation Studies," Trans. ASME, Vol. 96, 1974, pp. 323–329.

31 Poynton, W. A., "A Theoretical Analysis of Shear Fracture Propagation in Backfilled Gas Pipelines," IGE/British Gas Symposium, Crack Propagation in Pipelines, Newcastle upon Tyne, Mar. 1974.

32 Poynton, W. A., and Fearnehough, G. D., "An Analysis of Shear Fracture Propagation in Gas Pipelines," *Proc. Conf. on Dynamic Crack Propagation*, Lehigh, July 1972.

33 Fearnehough, G. D., "Fracture Propagation Control in Gas Pipelines," IGE/British Gas Symposium, Crack Propagation in Pipelines, Newcastle upon Tyne, Mar. 1974.

Authors' Closure

We would like to thank Dr. Fearnehough for his kind remarks about our work and for pointing out the many similarities between our approach and the British Gas work.

Dr. Fearnehough quite rightly points out that the existence of a maximum crack driving force and its possible use as a crack arrest design parameter was recognized and exploited in the British Gas work. We were remiss in not acknowledging this fact in the paper.

With regard to the evaluation of the various pipeline fracture propagation models given as Table 4 of our paper, we must stand by our original evaluation of the Bristish Gas work, at least as it is represented by reference [21] of our paper. The column designating the consideration of inertia forces in the various analyses referred to the incorporation of inertia forces in the equation of motion of the pipe walls; for example, see equations (5), (6), and (15) of our paper. Granted, kinetic energy effects are included in the British Gas model, but this is not at all the same thing. Similarly, in the crack tip plasticity column, we intended to designate models that directly incorporate this effect into the governing equations. This, again, is not done in reference [21] where, in any event, the Erdogan-Ratwani relation mentioned by Dr. Fearnehough is not used.

As a final comment, we would like to re-emphasize that our intention in presenting Table 4 was not to initiate a Michlin Guide for pipeline fracture analyses by awarding or withholding "credit stars." Instead, we simply wanted to help both ourselves and other investigators to become more cognizant of all the critical elements in the problem. Accordingly, we will happily apologize to any or all of the investigators cited if we have misunderstood their work. Nevertheless, we feel that we will have succeeded in our purpose if they have thereby re-examined their work in connection with Table 4.