

The Superposition Model and Environmental Crack Propagation in Low-Density Polyethylene

H. A. EL-HAKEEM* and L. E. CULVER, *Imperial College of Science and Technology, Mechanical Engineering Department, London, SW7 2BX England*

Synopsis

A study has been made of dynamic and static fatigue failure phenomena in low-density polyethylene ($\rho = 0.912$) of MFI7 in a methanol environment using SEN specimens. The type of failure, namely, crack propagation, was the same in both conditions and the results were analyzed using fracture mechanics concepts. A previous model for correlating environmental dynamic and static fatigue crack growth in metals was applied to this polymeric material, and good agreement was found between experimental and predicted behavior when the strain-rate sensitivity of the threshold value of the stress intensity factor was taken into account.

INTRODUCTION

An approach based on the linear superposition principle for correlating environmental dynamic and static fatigue crack growth is already available,¹ and it has been shown to be substantially correct for metals. However, the linear superposition of environmental static and inert environment dynamic fatigue contributions as in Wei and Landes' model¹ suggests that the same mechanism of failure due to the aggressive environment is operating in both dynamic and static fatigue, and that the failure behavior is the same in both inert and aggressive environments. These assumptions are not generally easy to justify in the case of polymers, since the role of the aggressive environment may be different in dynamic and static conditions and the type of failure behavior may differ between inert and aggressive environments. For example, PMMA fails in air (inert environment) under both dynamic² and static³ conditions, by crack propagation following some small initial crazing; whereas in alcohol, although failure is by cracking, it is only after significant craze formation and growth under both static and dynamic conditions at low frequencies.^{4,5}

The present work is an attempt to apply the superposition model to dynamic crack growth in a polymeric material in an aggressive environment, in the hope of finding a correlation between dynamic and static loading conditions. Low-density polyethylene (LDPE) was chosen as the test material, since crack growth rate versus fracture toughness, K , data under static loading conditions were available for two grades of this material in two different environments.⁶

Although LDPE is a soft plastic which behaves in a ductile manner in air, a complete transition to environmental brittle stress cracking occurred in alcohols,⁶ and the test results were independent of the specimen thickness, indicating a prevailing plane strain condition. There is thus no difficulty in applying fracture mechanics concepts to such environmental tests.

* Present address: Ministry of Standards, Cairo, Egypt.

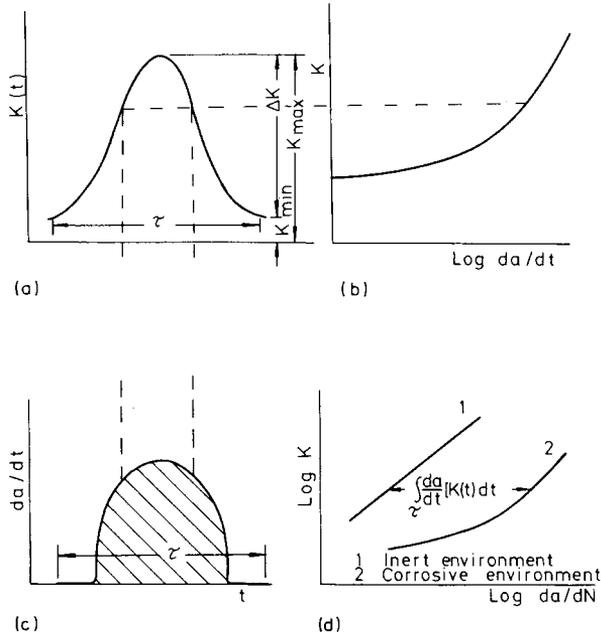


Fig. 1. Schematic diagram illustrating the graphic method of the superposition analysis (after Wei and Landes¹): (a) Stress intensity factor as a function of time in dynamic fatigue. (b) Static fatigue: rate of crack growth under sustained load in an aggressive environment. (c) The area under the curve represents the environmental contribution to crack growth in dynamic fatigue = $\int_{\tau} da/dt [K(t)] dt$. (d) Resulting effect of adding the two contributions on cyclic fatigue crack growth rate.

WEI AND LANDES SUPERPOSITION MODEL

Wei and Landes¹ have suggested that the rate of crack growth, da/dN , in a corrosive environment may be considered to be the algebraic sum of the rate of growth in an inert environment and that of an environmental component computed from sustained-load crack growth data obtained in the same aggressive environment and the load profile of the fatigue cycle, viz.,

$$\left(\frac{da}{dN}\right)_{\text{corrosion fatigue}} = \left(\frac{da}{dN}\right)_{\text{environment}} + \left(\frac{da}{dN}\right)_{\text{fatigue in inert environment}} \tag{1}$$

where a is the crack length and N is the number of cycles.

The environmental contribution in the environmental dynamic fatigue process, i.e., $(da/dN)_{\text{environment}}$ in eq. (1), was assumed to be expressed in the form

$$\left(\frac{da}{dN}\right)_{\text{environment}} = \int_{\tau} \frac{da}{dt} dt$$

where τ is the period of one cycle = $1/f$. The crack growth rate in the above integral is a function of the stress intensity factor which is, in turn, a function of time, i.e.,

$$\frac{da}{dt} = \frac{da}{dt} [K(t)]$$

and f is the frequency. Thus,

$$\left(\frac{da}{dN}\right)_{\text{environment}} = \int_{\tau} \frac{da}{dt} [K(t)] dt$$

A schematic diagram which illustrates the graphic method of evaluating $(da/dN)_{\text{corrosion fatigue}}$ as the sum of the two components in eq. (1) is shown in Figure 1.

EXPERIMENTAL

Material, Environment, and Specimen Preparation

The selected material was LDPE ($\rho = 0.912$) of MFI7, and methanol was chosen as the testing environment; these are the same as previously used in static fatigue tests.⁶

Tests were conducted on tensile SEN specimens [Fig. 2(a)] of 150 mm length, 50 mm width, and 3 mm thickness. The specimens were designed to satisfy the requirements of giving accurate values of the stress intensity factor (K) according to the boundary collocation solution of Brown and Srawley,⁷ i.e., the point of load application should be far enough from the plane of the crack ($l'/2w > 0.8$ is satisfactory for $0.1 \leq a/w \leq 0.45$, where l' is the specimen free length and w is the specimen width) [Figs. 2(a) and 3(b)]. Sharp notches were introduced by forcing a razor blade into the specimen body [Fig. 2(b)] to obtain an initial crack length of $0.1w < a < 0.2w$; this was carried out by mounting the razor blade in a jig which was in turn fitted to a Vickers hardness testing machine. Holes were drilled at each end of the specimen for clamping purposes.

Testing Procedure and Testing Program

Perspex minitanks, as shown in Figure 3(a), were used to maintain the methanol surrounding the specimen during the test period. The tanks were sealed to the specimen by a silicon rubber sealer, and each end of the specimen was bolted to a pair of steel plates and pin-loaded in an Instron Universal Testing

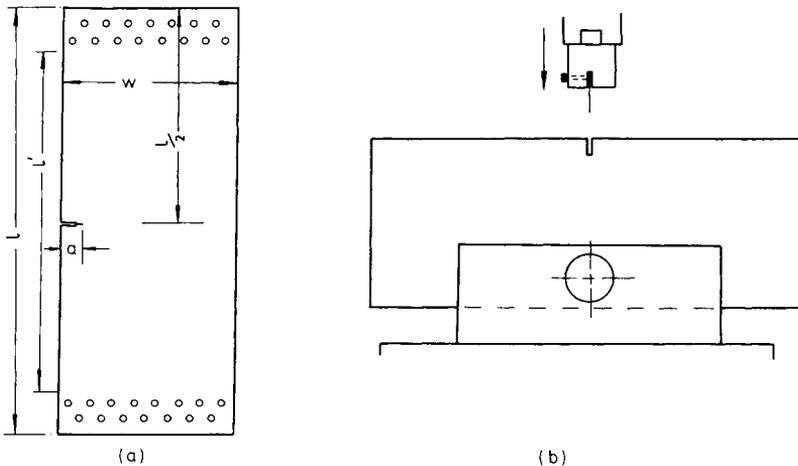


Fig. 2. (a) SEN specimen geometry. (b) Method of notching.

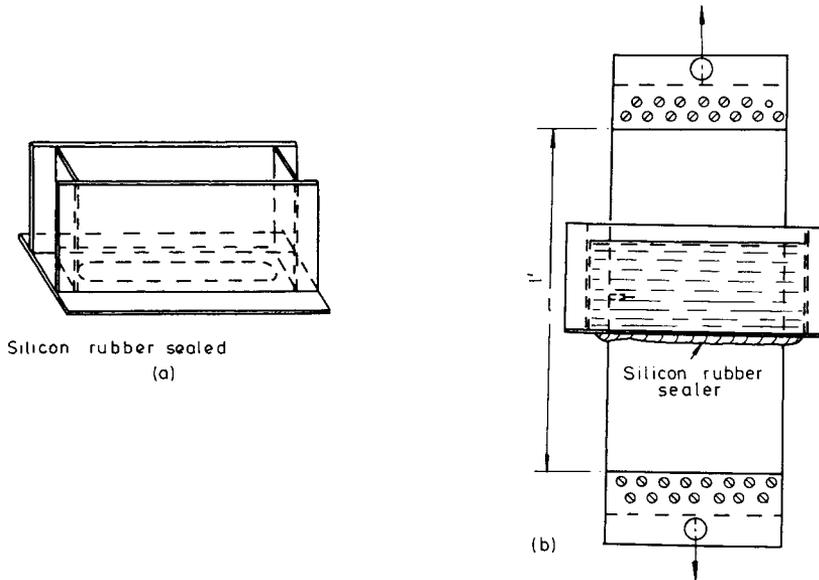


Fig. 3. (a) The minitank. (b) Specimen in minitank and bolted to two pairs of steel plates.

Machine [Fig. 3(b)]. Crack propagation was monitored by a traveling microscope.

Tests were conducted in tension at a frequency of approximately 0.125 Hz and a cross-head speed of 5 mm/min, the load varying from zero to maximum, then to zero (i.e., the stress ratio $R = 0$) in a cyclic ramp form. Fracture mechanics concepts were used in analyzing the crack propagation data obtained, as in the case of the earlier static fatigue tests.⁶ The stress intensity factor K for the SEN specimen was calculated using the Brown and Srawley solution⁷ given as

$$K = \sigma Y a^{1/2} \quad (2)$$

where σ is the gross stress, a is the crack length, and Y is the finite effects correction factor:

$$Y = 1.99 - 0.41 \left(\frac{a}{w}\right) + 18.70 \left(\frac{a}{w}\right)^2 - 38.48 \left(\frac{a}{w}\right)^3 + 53.85 \left(\frac{a}{w}\right)^4$$

Crack growth measurements were only considered in the range of $0.1 \leq a/w \leq 0.4$.

It should be mentioned that there was no discernible temperature rise during the tests, also that the fracture surfaces produced by crack growth in cyclic loading were completely flat, with no sign of ductility or shear lips.

RESULTS AND DISCUSSION

In all tests, the relation between crack length a and the number of cycles N was typically as shown in Figure 4. From these crack growth data, plots of ΔK versus cyclic crack growth rate \dot{a}_N were made for each specimen, where \dot{a}_N represents the slope of the $a-N$ curve at any particular crack length and ΔK , corresponding to this particular crack length, was determined by substituting the value of the maximum applied stress and the instantaneous crack length in eq.

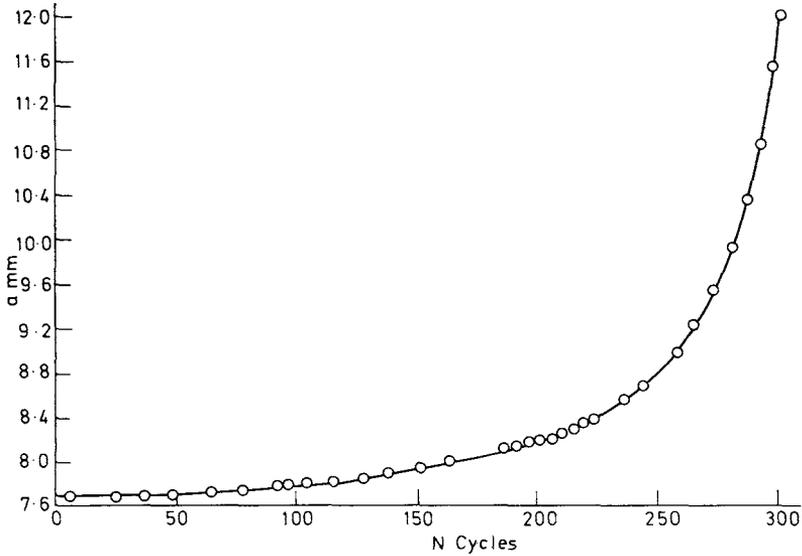


Fig. 4. Crack length vs number of cycles. LDPE tested in methanol at $f = 0.125$ Hz and $R = 0$.

(2). Figure 5 shows the $\log \dot{a}_N$ - $\log \Delta K$ relationship for different specimens. The results obtained demonstrate that, within the limits, there is a unique relationship between ΔK and the cyclic crack speed (the scatter in results is of the order of $\pm 5\%$, which is acceptable for this type of test). The results seem reasonably representable by a straight line for $\dot{a}_N > 8.1 \times 10^{-3}$ mm/cycle; below this value, a tendency toward a limiting ΔK value has been observed.

An additional test was performed in air under the same test frequency and stress ratio R as used in the methanol tests; the observed cyclic crack growth rate

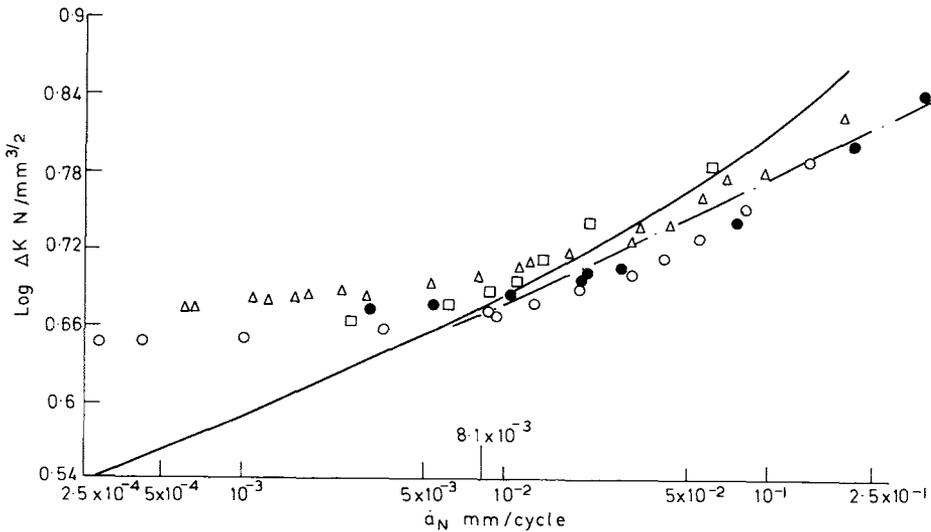


Fig. 5. The $\log \dot{a}_N$ - $\log \Delta K$ relationship of LDPE tested in methanol at $f = 0.125$ Hz and $R = 0$: (Δ), (\bullet), (\circ), (\square) results of individual specimens; (—) predicted curve using the superposition method.

was much lower. Moreover, up to $\Delta K = 12 \text{ N/mm}^{3/2}$, there was no sign of crack propagation after 20,000 cycles, indicating that this is less than the threshold value in air. Since the highest ΔK applied in the methanol tests was $7 \text{ N/mm}^{3/2}$, which corresponded to the highest observed $\dot{a}_N (= 3.7 \times 10^{-1} \text{ mm/cycle})$, it is reasonable to assume that the cyclic crack growth up to the highest ΔK in methanol tests is only due to the environmental effect of methanol at the crack tip without any contribution from growth in an inert environment such as air. It should be mentioned that methanol is a precipitant for polyethylene; thus, under the test conditions, it is not likely to be significantly absorbed by the bulk material and will have little effect on the overall mechanical properties. Its effect is thus confined to the highly stressed crack tip zone.

Considering the above, and noting that the type of failure in this material is the same in both dynamic and static fatigue (in both cases failure was by crack propagation), it was decided to examine the applicability of the linear superposition model by Weir and Landes¹ to the present results.

THE APPLICABILITY OF THE SUPERPOSITION MODEL TO LDPE RESULTS

Static fatigue results of LDPE of MFI7 in a methanol environment were previously obtained.⁶ Figure 6 shows the relationship between K and $\log (da/dt)$. To check any discrepancy in the behavior due to changes in the material properties (e.g., changes due to an ageing effect), a static fatigue test was performed, and the results obtained are superimposed on Figure 6. The results are within the scatter band previously determined by Marshall et al.,⁶ but tend to fall within its lower half.

The graphic method schematically shown in Figure 1 was applied, considering

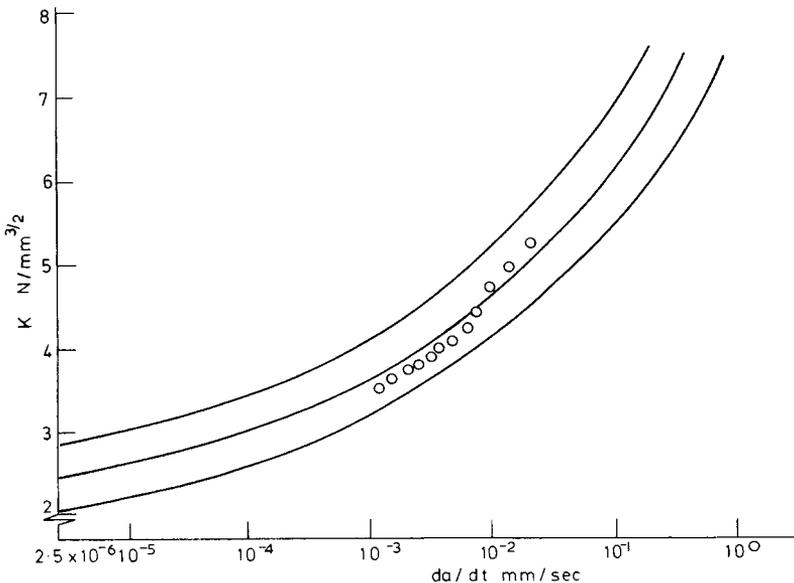


Fig. 6. Fracture toughness vs crack speed for LDPE in methanol; constant load test. After Marshall et al.⁶; (O) results of the present test.

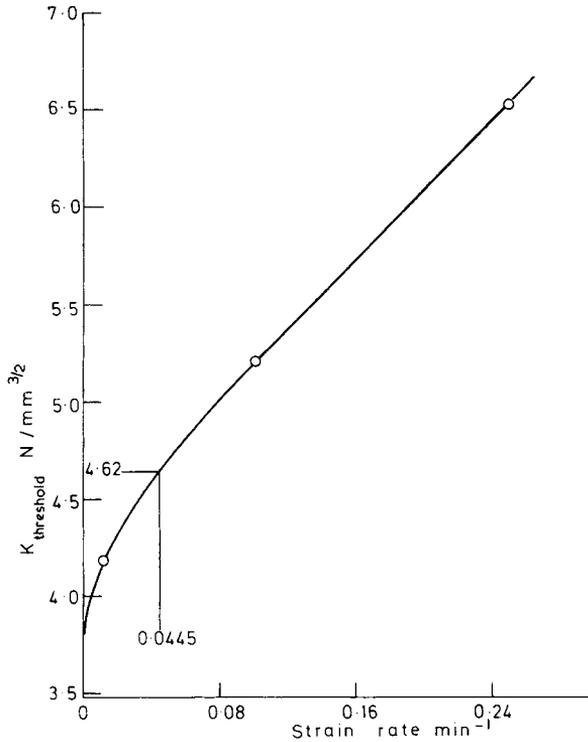


Fig. 7. Effect of strain rate on the threshold value of K ; LDPE in methanol.

the middle curve in Figure 6. However, in the present case, the contribution of dynamic fatigue in an inert environment may be considered as equal to zero, and eq. (1) is reduced to

$$\left(\frac{da}{dN}\right)_{\text{corrosion fatigue}} = \left(\frac{da}{dN}\right)_{\text{environment}} \tag{3}$$

The resulting curve, according to eq. (3), is shown in Figure 5, the first glance at which suggests that the linear superposition model is not applicable to LDPE. However, this might not be the case if the rate dependence of K at which the crack starts to propagate is considered.

It has been shown in reference 6 that in monotonic constant strain rate tests on notched specimens of LDPE of MFI7 in a methanol environment, the value of K at which the crack starts to propagate is strain rate dependent, and the higher the strain rate the higher will be the value of $K_{\text{threshold}}$. The relation between $K_{\text{threshold}}$ and the strain rate can be deduced from the results in reference 6 and is indicated in Figure 7.

In the present study, tests were conducted at a machine cross-head speed of 5 mm/min and the effective length l' of the specimen between the clamps [Fig. 3(b)] was equal to 112 mm. The strain rate in the cyclic loading was thus equal to 0.0445 min⁻¹, which corresponds to a $K_{\text{threshold}}$ of 4.62 N/mm^{3/2} from Figure 7. Therefore, it would be expected in the present cyclic fatigue tests that the crack would not start to propagate unless the value of K exceeds $K_{\text{threshold}} = 4.62$ N/mm^{3/2}. The graphic method schematically shown in Figure 1 was therefore

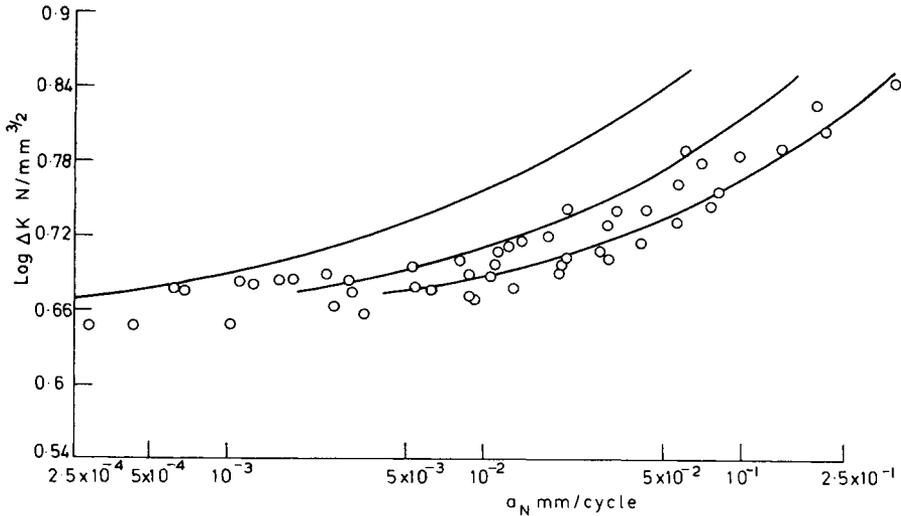


Fig. 8. Comparison of experimental and predicted results by the superposition method considering the rate sensitivity of K_{th} ; LDPE in methanol at $f = 0.125$ Hz and $R = 0$; (—) predicted; (O) experimental.

applied to the upper, middle, and lower curves in Figure 6 assuming there was no crack growth below $K = 4.62$ N/mm^{3/2}. The resulting three curves and the points representing the experimental results are shown in Figure 8. Most of the experimental points fall within the lower half of the scatter band. Considering that this tendency had been observed in the static fatigue results in Figure 6, it suggests that the superposition model is, in fact, applicable in the present case.

CONCLUSIONS

1. The linear superposition model previously suggested for metals may be applied in the case of polymeric materials when the rate sensitivity of the stress intensity factor is taken into account. The applicability of the model is restricted to the cases where the type of failure is the same in both inert and aggressive environments and the role of the environment is the same in both dynamic and static conditions.

2. The LDPE/methanol system may be considered as a special case, since the contribution of dynamic pure fatigue (inert environmental dynamic fatigue) in environmental fatigue crack growth was found to be negligible.

References

1. R. P. Wei and J. D. Landes, *Mat. Res. Standards*, ASTM, July 9, 1969.
2. S. Arad, J. C. Radon, and L. E. Culver, *J. Mech. Eng. Sci.*, **13**, 75 (1971).
3. G. P. Marshall, L. E. Culver, and J. G. Williams, *Plast. Polym.*, **37**, 75 (1969).

4. G. P. Marshall, L. E. Culver, and J. Williams, *Proc. R. Soc. (London)*, **A 319**, (1970).
5. G. P. Marshall and J. G. Willims, *J. Appl. Polym. Sci.*, **17**, 987 (1973).
6. G. P. Marshall, L. E. Culver, and J. G. Williams, Proceedings of the International Conference on Research on Engineering Properties of Plastics, Cranfield, January 6-8, 1969, p. 95.
7. H. F. Brown and J. E. Srawley, ASTM, STP, 1966, p. 410.

Received April 8, 1976

Revised July 1, 1976