Summary

As stated in the Introduction to this volume, the papers selected for presentation at this symposium fit neatly into eight technical categories: linear elastic analyses, temperature and environment effects, elastoplastic analyses, elastoplastic experiments, fatigue crack growth, dynamic fracture mechanics, basic considerations, and applications (in this volume the last two categories have been combined). Hence most of the major areas of fracture mechanics were addressed. In common with the preceding fifteen symposia in this series, progress through the presentation of data, discussions of analysis and experimental procedures, and frank exchanges of opinion on the underlying issues was thereby achieved. The following sections summarize, by category, the papers in this volume.

Linear Elastic Analyses

The first group of papers in this volume was focused on expanding the currently available body of results concerning the influence of geometry on the stress intensity factor. Standard specimen geometries and actual structural components were addressed. Because this category treats linear elastic behavior exclusively, a variety of mathematical approaches are applicable. Thus the papers in this category also display an instructive variety of solution techniques.

Civelek obtained solutions for ordered systems of cracks in an infinite strip by representing the cracks as continuous distributions of dislocations. This procedure then required a system of integral equations to be solved. Employing a more conventional procedure, *Kapp et al* obtained algebraic expressions for the crack opening displacements in standard fracture specimens. *Heckel and Rudd* evaluated current stress intensity factor solutions for a corner crack at a hole and, by comparing these with experimental results, they were able to identify which solutions were most accurate. *Oladimeji,* using a numerical stress function technique coupled with the *J*-integral, has provided detailed results for cracks originating from a circular hole under biaxial loads. A weight function approach was developed by *Orange* to obtain the stress intensity factors and crack mouth opening displacements for all crack lengths in a strip with a single edge crack. *Gross et al* used a boundary point collocation method to determine stress intensity factors for through-thickness cracked ring segments subjected to three-point radial loading. Finally, via a boundary collocation analysis procedure, *Mall and Newman* have provided a variety of practically useful relations for a compact specimen using the linear elastic Dugdale model to provide a plastic zone correction.

Temperature and Environmental Effects

The common theme in the second category was the acceleration in cracking rates caused by combinations of high temperatures, environmental influences, and cyclic loading. The treatments, which were empirical and semiempirical, were largely focused on specific materials and therefore do not provide a general theory. Nevertheless, these papers do contain useful background data to support the theoretical analysis that are yet to come.

Esaklul and Gerberich showed that, for fatigue of high-strength, low alloy (HSLA) steel, the presence of internal hydrogen gives rise to higher crack propagation rates and lower threshold stress intensities. In contrast, *Kim et al* found that a hydrogen environment does not significantly influence the crack growth rate; however, they found that it does tend to reduce the crack initiation life. Finally, *Nicholas et al,* using triangular waves shapes with hold times at maximum load, obtained data for Inconel 718 that show that the loading portion of a load cycle is the major contributor to time-dependent fatigue crack growth behavior.

Elastoplastic Analyses

It is possible to obtain estimates of crack-tip plastic zone effects, and thereby extend the applicability of linear elastic analyses, via a Dugdale or a dislocation pile-up model. Ultimately, however, such approaches must be replaced by more rigorous treatments. Approaches that directly incorporate elastoplastic constitute behavior fulfilling this need were provided in this third category of papers. Both closed-form and numerical solutions were presented.

Rhee has proposed a critical load assessment method for analyzing stable crack growth and instability through the use of J versus load relations derived from a flawed structure. His approach eliminates the need to differentiate J for fracture instability estimates. *Aizawa and Yagawa* used a finite element analysis model to deduce the eigenmodes of the HRR singularity, thereby providing estimates of several nonlinear fracture parameters for single-edge-cracked panels and compact tension specimens. Elastoplastic finite element analyses were also conducted by *Wellman et al* on three-point bend specimens as a precursor to a study of flawed pressure vessels. Their results provide useful quantitative conclusions on the use of the CTOD criterion for such purposes. *Macdonald* used finite element analyses to quantify the fracture toughness improvement in two carbon steels due to normalization. *Kikuchi et al,* from three-dimensional elastoplastic finite element analyses for side-grooved compact tension specimens, have provided extensive numerical results for this geometry.

Elastoplastic Experiments

The most widely used procedure for characterizing stable crack growth and fracture instability in elastoplastic conditions is the *J*-integral. Thus experimentation for fracture behavior in this regime is largely based upon the elucidation of this property. At the same time, basic questions still exist as to the uniqueness of *J*-resistance curves and, consequently, the applicability of measurements made on standard test specimens to structural components. The fourth group of papers in this volume focused on these basic issues.

Kapp determined *J*-resistance curves for several different materials using three different measurement techniques and found that the results obtained with each technique gave remarkably similar results. *Balladon et al* examined the influence of cyclic and monotonic strain hardening in 316L stainless steel and found that the initiation fracture toughness is decreased by each although the *J*-resistance curve is affected somewhat differently. The problem of measuring the resistance curves for thin pressure tube material was addressed by *Davies and Stearns.* Finally, *Salzbrenner et al* determined the fracture toughness of ferritic, spheroidal graphite, ductile cast iron using a *J*-based approach.

Fatigue Crack Growth

The basic problem areas in fatigue are those involving very short cracks, ductile material behavior, and/or nonuniform load spectra. The complicating feature in each such instance is the invalidity of the similitude criterion that ordinarily enables fatigue crack growth data generated in the laboratory to be used in structural applications. Among the analysis procedures that have been introduced to cope with the absence of similitude are the crack closure concept and the *J*-integral as a crack tip characterizing parameter. This fifth group of papers focused on the use of such approaches.

As an alternative to the stress intensity factor, *Broek* has proposed the crack tip plastic strain range as a similitude crack growth parameter. *Sehitoglu* presented a systematic experimental study of crack closure in 1070 steel. He found that crack closure occurs during a significant portion of a fatigue cycle and that his analytical predictions of the opening level were in good agreement with experimental results. *Jolles* used a cyclic *J* to characterize fatigue crack growth in A533B steel and, by accounting for crack closure, was able to achieve good agreement for fatigue crack growth rates in a wide range of loading conditions. Finally, *Yoder et al* reported on a study of fatigue crack growth in Ti-6Al-4V alloy that showed that single-notched compact specimen testing can provide very efficient determination of the resistance to both fatigue crack initiation and propagation.

Dynamic Fracture Mechanics

Current research in dynamic fracture mechanics centers on the effects of elastoplastic material behavior for crack growth initiation under high loading rates and for rapid (dynamic) crack propagation and arrest. The basic issue is the identification of the proper crack tip characterizing parameter for these conditions. Hence the work reported in this sixth category involves elastoplastic-dynamic and viscoplastic-dynamic analyses coupled with experimentation.

Hoff et al presented a new analytical technique to enable the HRR singularity solutions to be used to characterize the crack tip deformation fields for a dynamically loaded, strain rate sensitive, material. The effects of crack tip plasticity in rapid crack propagation were treated through the use of a Dugdale model, modified by dynamic photoelasticity results, by *Lee and Kobayashi.* A combination of blast-loaded experiments and elastic-thermoplastic finite element analyses on welded specimens was performed by *Barnes et al* that indicates the necessity to take direct account of the weld-induced deformation. Finally, *Lin and Hoagland* reported a series of crack arrest tests on a high-strength aluminum alloy which, owing to the small rate sensitivity and the absence of unbroken ligaments in this material, showed that the elastic fracture mechanics parameters behave differently than do those of medium-strength steel.

Basic Considerations and Applications

The remaining papers addressed an individual outstanding issue or a particular problem area. *Sato et al,* in a study of the fracture mechanisms in short fiber reinforced thermoplastic composites, identified the sequence of events leading to fracture in those materials. In addition to reviewing the restrictions of the method, *Smith and Epstein* provided the results of an experimental optical study of the three-dimensional aspects of subcritical flaw growth. A line-spring model was described by *Miyoshi et al* for determining the stress intensity factors for arbitrarily shaped surface cracks in plates and shells. *Solecki and Swedlow* presented a three-dimensional finite element analysis of a center-cracked plate. *Underwood and Scavullo* described the failure of a long rod penetrator and concluded that the failure of both uranium and tungsten penetrators is controlled by the plane strain fracture toughness. *Knorovsky,* after gathering data showing the inadequacy of a linear relation for the effect of strain rate on the ductile/brittle transition as a function of yield strength for bridge steels, proposed an alternative analysis in terms of fracture mechanics testing. The burst pressures of internally pressurized vessels, manufactured from steels with varying yield strengths, were successfully predicted by *Sciammarella* using a *J*-resistance curve approach. *Aurich et al* performed elastic-plastic three-dimensional finite element computations on surface cracks in pressure vessels. Finally, *Willoughby and Garwood* assessed the general applicability of the CTOD design curve method and the R6 and other elastoplastic predictive procedures by experimentation on a pipeline steel. Various degrees of conservatism were found for each procedure.

M. F. Kanninen
Southwest Research Institute, San Antonio, Texas; symposium chairman and editor

A. T. Hopper
Battelle's Columbus Laboratories, Columbus, Ohio; symposium chairman and editor