Authors' Closure

The authors would like to thank Professor Cumpsty for his interest in, and thought provoking comments on, our paper.

We agree with the first point made by Professor Cumpsty regarding the need to include the additional losses in blade rows downstream of the one that has the tip clearance (e.g., in the stator for the usual case of a rotor tip clearance) when estimating the loss of stage efficiency from rotor loss coefficients determined from a fundamental rather than empirical viewpoint. A distinction of the origin of the loss coefficient is necessary because the empirical approach is self-correcting in that loss coefficient changes consistent with many observed stage efficiency changes are correlated. By contrast the work of Storer and Cumpsty seeks to compute tip clearance losses from consideration of the fundamental fluid mechanics of tip clearance flow with no reference to measured stage efficiency changes. In this case additional losses arising downstream will need to be included. It would be most interesting to evaluate a three-dimensional Navier–Stokes calculation in this way, initially as a rotor-alone case and then as a stage calculation.

Professor Cumpsty's second point addresses the issue of deduction of rotor losses from stationary frame traverses with pneumatic probes. We remain to be convinced that there is a fundamental error due to use of a probe in the stationary frame on the basis that the main issue requiring ingenuity is the appropriate way of analyzing the measurements. Given an ideal probe that resolves absolute stagnation pressure and angle through time our approach would be to transform the absolute frame data to the relative frame through the rotor exit velocity triangle and then to average.

Because no such ideal probe exists we have adopted a more pragmatic approach, which, due to space limitations, is only outlined in the paper. In Appendix B of the paper the importance of the rotor exit absolute swirl angle measurement is highlighted. Given the severe temporal fluctuation in absolute swirl angle the pneumatic results are remarkably good. Used with no adjustment these absolute swirl angles can be used to compute the work input distribution across the span. When combined with stator exit pressure measurements a central region of constant stage efficiency is often revealed. From the stator exit traverses similar wakes are usually observed at the different radial heights within this region, suggesting constant stator losses in this central region of the annulus (between 40 and 65 percent of height based on Fig. 7). Clearly within this region constant rotor loss with span should also result from the analysis. Our approach does give this (Fig. 7) but since adjustments were found necessary the data presented in the paper are more reliable for obtaining radial distributions than absolute levels of loss. Our view is that the agreement in deduced radial distributions of blade performance from alternative types of pneumatic probe (wedge versus cobra) shown in Fig. 7 is significant and offers considerable justification of our approach.

The theme of our paper is a study of endwall effects where reliable radial distributions allow many valuable conclusions to be drawn. If it was important to determine both rotor and stator midspan losses accurately the best approach would be to arrange for traversing in the rotating reference frame, which is considered practical for low-speed rigs only. Such a capability has now been designed and manufactured for the Cranfield four-stage rig and will be tested before the summer of 1995.

Faced with the difficulty of stationary frame traversing, as is the case for high-speed research, there are two alternatives:

1 a high-response instrument (work on this has commenced, Cook, 1989)
2 phase-locked laser anemometry

Professor Cumpsty is correct to point out the importance of the shape of the velocity triangle on the signal to be expected from such a probe, but it is not clear to us why it should be valid to compare his Eqs. (1) and (2), which are for relative and absolute pressure differences, respectively. Our view is that losses to be deduced from the measurements must be in the relative frame for the rotor.

References

Cook, S. C., 1989, "Development and Use of a High Response Aerodynamic Wedge Probe and Its Use on a High Speed Research Compressor," *Proc. of the Ninth International Symposium on Air Breathing Engines*, Athens, Vol. 1, pp. 1113–1125.