Reply by Authors to G. Y. Anderson

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ANDERSON's comments and conclusions about the contents of Ref. 1 appear to be based on a misinterpretation or misunderstanding of its content and intent and a displeasure with the integral analysis technique[2-6] used as the standard. The intent of Ref. 1 was and is to show the limitations of assuming a constant-area/constant Mach combustion process for closure of the integral equations of motion in predicting scramjet engine performance compared to the "most widely accepted one...developed by Billig."[7] The content of the Note does just that, using a representative case.

Anderson's attempt to discredit the results presented (using Table 1 in his comment from Fig. 55 of Ref. 8) is a misrepresentation of the facts. First, there are no scramjet performance data given in Ref. 8 for a freestream Mach number of 3.5 at any altitude. Second, the performance numbers at Mach 6 are for a different engine configuration with different values assumed for a number of component efficiencies. Specifically, the performance given in Ref. 8 at Mach 6 is for an aft-mounted engine rather than a nose-mounted configuration with a combustor area ratio of 2.5 rather than 3 and a nozzle exit-to-diffuser inlet area ratio of 2 rather than 1.7. Furthermore, at Mach 6, Ref. 8 assumes an inlet air capture of 0.97 rather than 1.0, an inlet kinetic energy efficiency of 0.975 without including forebody bow shock losses, combustion skin-friction losses that are a factor of 2 to 3 lower than those measured,[4] an exit nozzle efficiency of 0.985 rather than 0.975, and equilibrium thermo-chemistry is the exit nozzle rather than two-thirds frozen.[4] In addition, the integral analysis used in Ref. 8 does not incorporate an oblique precombustion shock model; it permits only no shock or a normal shock. Table 1 of the comment is, therefore, a comparison of "apples-to-oranges," and is, at best, misleading in the context presented. Finally, if the same assumptions, geometries, and efficiencies used in Ref. 8 are used in our integral technique, one obtains identical performance predictions.

These issues aside, the intent of any integral analysis technique is to provide an accurate engineering tool for predicting overall engine performance and parametric or sensitivity studies at minimum cost. No claim is made that it can predict the details of the flow between the initial and final stations assumed. Multidimensional models (see, e.g., Refs. 9 and 10) are required for that. However, even though a number of increasing complex multidimensional models have been developed and solutions obtained using advanced computational fluid dynamic (CFD) techniques, none have been validated, even for inlet diffusors,[11] because of a lack of experimental data. More importantly, no current CFD technique using the full Navier-Stokes equations can solve for the flow in the region of the precombustion shock because it requires an estimated 10^6-10^7 grid points for resolution and 10^4 time steps for convergence, the combination of which is well beyond the capabilities of the most advanced class VI computer. Alternative methods, such as using an integral solution for the initial and boundary conditions downstream of the precombustion shock and then using CFD codes to iteratively solve for the combustor core flow and boundary-layer regions separately,[9] is a much more tractable approach. However, all CFD techniques are expensive to use and, as such, are generally limited to refining a near-optimum design rather than being used as an everyday engineering tool.

The question then is, what is the most physically realistic and accurate approach to take to permit closure of the integral equation of motion? As discussed in the Note,[1] the most accurate and preferred method is that developed by Billig et al.,[2-6] using the Crocco static pressure-area power law relation for closure in the supersonic combustor. *It is the only technique that does not require an a priori knowledge of any of the combustor flow properties,* including the strength of the precombustion shock system, in order to predict combustor or engine performance and compares very favorably with a diverse cross section of experimental data.[2,3,5,12,13]

Anderson, however, contends that Refs. 7 and 14-17 show otherwise. Reference 7 claims that the Crocco assumption cannot physically represent the precombustion shock structure, the local combustion efficiency, and the accumulated wall shear and heat losses; nor is the assumption used to minimize the combustor entropy rise, i. e., that the slope of the Crocco power law relationship at the combustor exit be the same as the slope of the isentrope at the combustor exit conditions, physically realistic. On the contrary, the integral technique accurately predicts the strength of the precombustion shock and, physically, the slope of the Crocco power relationship must match the slope of the isentrope at the combustor exit conditions if the laws of fluid mechanics are valid in the limiting case of zero heat addition. True, the technique used does not predict the distribution of the precombustion shock static pressure rise. No integral analysis technique can, since they are independent of the process path between the initial and final stations. Although the Crocco power law is in good agreement with a large data base of measured combustor static pressure distributions, ultimately the distribution does not matter as long as the $\int P dA$ is correct. Other techniques, based on an extensive data base, are incorporated in the cycle analysis to account for wall shear and heat-transfer losses,[4-6] as well as the distribution of the precombustion wall static pressure rise,[2,3,5,6] which are physically accurate and all that is required globally.

Reference 7, on the other hand, rather than permitting the $\int P dA$ to be evaluated without an a priori knowledge of at least one combustor flow property, assumes that the precombustion static pressure rise must be known as a function of the magnitude and distribution of heat release within the combustor in order to evaluate the $\int P dA$ and then minimizes the combustor entropy rise, just as the current analysis does, to obtain a solution. This would appear to be a step backward in the evolution of a useful, accurate integral technique since it will yield the same solution, but only if two combustors properties (other than wall shear and heat transfer) are known a priori. This approach also raises the questions: 1) how does one know what the pressure rise is as a function of heat release, and heat release as a function of distance for a particular combustor configuration unless extensive experimental data are already in hand over a wide range of test conditions? and 2) how does one determine the axial heat release from the experimental measurements and distinguish it from the precombustion shock effects?

Anderson also cites Cookson's work[14] as further evidence of the inappropriateness of using the Crocco pressure-area relationship for closure. However, the conclusions given in Ref. 14 do not include the effects of a precombustion shock, require an a priori knowledge of the heat release schedule and are based on a definition of a critical (choking) Mach number [Eq. (30) of Ref. 15] that has no physical basis except, fortuitously, for the case of constant-area heat addition. If one uses the Crocco exponent of $\epsilon/(\epsilon-1)$ in Eq. 35 of Ref. 15, one finds that the critical Mach number is unity (rather than nonunity as claimed by Cookson) when $\epsilon=1$, i. e., for the

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constant-area heat addition case (see, e. g., Ref. 6). In addition, Cookson uses only partial arguments found in Shapiro[18] to show that the Mach number after combustion in an initially supersonic diverging area combustor cannot be less than unity. If one continues reading on the same and next pages (pp. 256-260), one finds that Shapiro discusses the possibility and potential for the post combustion Mach number to be less than unity.

Reference 15 (Anderson's Ref. 6) is an old report that indeed uses an assumed heat release schedule for closure of the integral conservation equations in the supersonic combustor. It, too, neglects the precombustion shock system, but was developed at a time (late 1960s) when our understanding of the supersonic combustion process was just beginning to emerge into adolescence.

Reference 16 (Anderson's Ref. 7) also uses the heat release schedule for closure but, rather than assuming one, attempts to relate it to mixing predictions, limiting its potential utility to diffusion-controlled combustion processes. However, the veracity of diffusion-controlled combustion models in supersonic flows with heat addition has yet to be established. Because of this limitation and the exclusion of the precombustion shock pressure rise in the analysis, its utility for engine cycle calculations is questionable.

Reference 17 (Anderson's Ref. 9) also requires an a priori model of the heat release distribution in the supersonic combustor and includes only the no-shock and normal precombustion shock cases. In addition, it does not include a realistic wall shear model nor noncalorically perfect gas thermochemistry and its veracity is unknown.

Summarizing Refs. 7 and 14-17, one observes that *all of these integral techniques require an a priori knowledge of at least one combustor flow property (generally heat release) for closure* and only one accounts for the presence of an oblique precombustion shock (which encompasses most cases of interest in typical scramjets other than when a normal shock is present); as such, their utility and veracity for performing engine cycle performance estimates is suspect. On the other hand, the integral analysis[2,4-6] used in Ref. 1 *does not require an a priori knowledge of any combustor flow property* and incorporates realistic wall property and precombustion shock models; its veracity is well established. Consequently, it is the preferred integral model for scramjet engines.

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