

**THE ARS - AFOSR INTERNATIONAL HYPERSONICS  
CONFERENCE: SUMMARY AND COMMENTS**

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In this section a short summary of the papers given at the International Hypersonics Conference and of the ensuing discussion is presented.<sup>2</sup> The summary is factual in nature, and no attempt has been made to present a critical analysis.

This specialist Conference was concerned solely with problems of hypersonic gasdynamics. Most of the papers represented work either just completed or still underway, with the result that the current state of the art was clearly indicated.

The meeting was divided into five technical sessions, concerning both theoretical and experimental problems, including inviscid analyses, low Reynolds number and chemical kinetic effects, and experimental facility development.

The opening session dealt with theoretical work on low Reynolds number hypersonic flows. Lester Lees served as chairman and contributed several interesting and pertinent observations.

In the first paper, by H. Oguchi, titled "Density Behavior Along the Stagnation Line of a Blunt Body in Hyperthermal Flow," an analytic solution, based on a Boltzmann representation of the gas, was found along the stagnation streamline. A plot of density variation along this streamline showed a decrease in density with increasing distance from the stagnation point, and gave no indication of any shock structure. This is, of course, not surprising since, as pointed out by Lees, the approach followed by Oguchi is valid only for very small Reynolds numbers, for which no shock would be expected. D. R. Willis mentioned that Oguchi's analysis was similar to the first iteration of a technique followed by himself for the problem of a piston being

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pushed into still air, where he had found that for Reynolds numbers at which a shock would be expected, the shock structure did not begin to appear until later iterations involving higher-order approximations.

The second paper, "Second-Order Boundary-Layer Theory for Blunt Bodies in Hypersonic Flow," by M. Van Dyke, was a very informative presentation which did much to clarify the present uncertainty with regard to the effect of external vorticity upon the boundary layer. In particular a systematic expansion scheme, which also contains the conventional boundary-layer results, is presented for the determination of viscous hypersonic continuum flow near the nose of a blunt body. Inasmuch as many of the other effects which are neglected in conventional boundary-layer flow are equally important as vorticity, seven second-order effects are considered: Longitudinal and transverse curvature, slip and temperature jump, entropy and total enthalpy gradients, and displacement effects. Unfortunately, while it was shown to be feasible to calculate each of these effects, the only actual numerical results to be presented were for the combined influence of slip and temperature jump. This was shown to be of the order of 20% of the vorticity effect and of opposite sign, and hence certainly not negligible. It was further stated that the remaining second-order effects would also be of opposite sign to the vorticity effect, with the result that the total of all these effects would tend to be very small.

### Other Opinions on the Subject

A rather lively discussion followed the presentation, and included a prepared comment by M. Lenard on similar work he has done on the problem. Lees cautioned that while such a systematic expansion procedure is formally correct and leads mathematically to just one answer, the analysis is not always relevant. In particular, as was mentioned by Lees and re-emphasized by R. Probstein, some significant factors involve nonlinear effects which cannot be taken into account in such a procedure.

The third paper of the session, "Rarefied Hypersonic Flow Over a Sphere" by E. S. Levinsky and H. Yoshihara, presented a direct numerical integration technique for the Navier-Stokes equations appropriately simplified for the stagnation region. The simplification involves approximating the equations as a parabolic system, giving rise to a locally similar solution. Results, including flow-field profiles from the body to the free stream, were presented for both adiabatic and cold-wall cases over a range of Reynolds numbers extending from boundary-layer to merged layer regimes. A major part of the discussion following the paper involved a question raised by H. K. Cheng

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concerning the validity of a parabolic approximation of a system of equations which is basically elliptic in nature, with the resulting elimination of the known physical influence of the downstream flow on the solution in the stagnation region. M. Van Dyke mentioned that he had carried out an investigation of this effect for the inviscid flow about a spherical nose and found that such a self-similar approximation resulted in errors in shock standoff distance of as much as 20%.

The final paper of the session, by F. K. Moore and W. J. Rae, titled "The Rayleigh Problem for a Dissociated Gas," considered a semiinfinite domain filled with a partly dissociated diatomic gas, initially at rest and in equilibrium. The bounding plane, represented in Fig. 1 of their paper is a solid surface with some given level of catalytic efficiency for recombination, initially at rest and at the same temperature as the gas. At some instant this surface is set impulsively in motion, thereby establishing a new constant condition at the surface. This action produces chemical nonequilibrium in a boundary layer which grows, with time, outward from the plate. The governing equations are linearized by assuming small disturbances throughout.

The general features of the heat-transfer results obtained for a temperature jump at a stationary wall are qualitatively the same as that found by Fay and Riddell in their calculations of the nonequilibrium stagnation-point boundary layer. If, instead, the plate temperature is held constant and the plate is set into motion, the atom concentration at the surface, and hence the heat-transfer coefficient, is the same both early and late in the time history of the flow. However, at intermediate times a transient dip in the heat-transfer coefficient results. On the basis of presumed analogy between the Rayleigh problem and the flat-plate problem, it was tentatively suggested that heat-transfer rates may not be greatly influenced by nonequilibrium effects. It should be pointed out, however, that this conclusion was made on the basis of a small-perturbation analysis and an assumed Lewis number of unity, and hence may not be completely realistic.

The chairman of the first session on experimental techniques was Peter P. Wegener. The first paper by J. Lukasiewicz, J. D. Whitfield, and R. Jackson, was titled "Aerodynamic Testing at Mach Numbers from 15 to 20," and concerned the current status of the von Karman Gas Dynamic Facility "Hot-shot" tunnels. Experimental results were presented concerning surface pressure distributions and drag measurements on simple two-dimensional and axisymmetric bodies as obtained with these facilities. It was indicated that the flow contamination associated with the direct heating of the working gas by an electric arc has been

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significantly reduced and that, while heat-transfer measurements still indicate considerable scatter, satisfactory force and pressure measurements can be obtained. Pressure-distribution data from slender blunted cones revealed the expected over-expansion and pressure overshoot along the conical surface, while drag data for cold-wall conditions exhibited drag levels as high as 15 times the inviscid drag, indicating very strong viscous-interaction effects.

The second paper, "Duration and Properties of the Flow in a Hypersonic Shock Tunnel" by D. W. Holder and D. L. Schultz, offered a very good discussion of the shock tunnel and indicated that, in spite of the brevity of the useful test time, significant results can be obtained if the tunnel is suitably designed. The dependence of the test time on such factors as the flow duration at entry to the expansion nozzle, the losses of testing time associated with the nozzle expansion process, and the establishment of steady flow past the model were considered. Also discussed were the dependence of test-flow properties on such factors as nozzle boundary-layer growth and the extent to which recombination or de-ionization occur in equilibrium with the local temperature when the flow is expanded. Very detailed results were given for cases where the shock tunnel was not operated under the usual tailored conditions.

A typical calculated wave pattern for shock-tunnel operation is shown in Fig. 9 of this paper, together with the associated pressure changes at the nozzle entrance. The figure indicates that after the first reflected disturbance successive disturbances are weak; the contact surface is brought effectively to rest and the pressure rapidly approximates the value computed on the assumption that the flow behind the first transmitted shock is brought isentropically to rest. These results suggest that if the time after the first reflected disturbance is used for test purposes, long running time can be achieved by reflected-shock operation even under conditions far removed from tailoring. The flow establishment past flat-plate models for dump chamber pressures of as low as 1 micron of mercury was illustrated by Schlieren photographs of remarkable clarity.

The third paper, "Evaluation of the Hypersonic Gun Tunnel" by K. N. C. Bray, was devoted to a critical evaluation of the free-piston-compression hypersonic wind tunnel. It was shown that, although early performance calculations were considerably over-optimistic, and the stagnation temperature is limited by piston strength requirements to values too low for the study of significant real-gas effects, such a facility may offer useful advantages in convenience and economy because of the comparatively long running time which may be obtained.

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### Wind-Tunnel Discussion

The fourth paper by F. S. Sherman and L. Talbot, on "Diagnostic Studies of a Low Density, Arc Heated Wind Tunnel Stream," was a characteristically interesting and well-presented discussion, the data of which had been obtained only one week previous to the conference, concerning some aspects of the operation of such a facility. Of particular interest were the electron density and temperature measurements obtained with the aid of a unique "double Langmuir" probe. The results were shown to agree with microwave measurements. Static-pressure surveys in the test section indicated an increase in pressure away from the centerline, possibly due to the chemistry of the flow.

The final paper of the session, "Initial Results from a Low Density, Hypervelocity Wind Tunnel" by J. L. Potter, M. Kinslow, G. D. Arney, Jr., and A. B. Bailey, concerned initial experiments designed to determine the characteristics of the flow in such a facility. Low Reynolds number effects on water-cooled impact pressure probes and static-pressure probes were shown. Preliminary work with a probe designed to measure local mass flow rate was outlined, and the results were shown to be in agreement with impact and static-pressure measurements. The extent of the boundary-layer growth in the nozzle was shown to be characteristically large, the diameter of the useful core of uniform flow being approximately one-sixth of the nozzle-exit diameter. Some rather unusual data were presented, indicating that a diffuser would be advantageous even for the very low Reynolds numbers characteristic of the facility. A useful correlation of data on sphere drag was included.

E. L. Resler, Jr. served as chairman of the session devoted to theoretical analyses of chemical kinetic effects in hypersonic flow.

S. H. Bauer in the opening paper, "Chemical Kinetics: A General Introduction," presented a lucid account of the fundamental assumptions which are usually introduced to obtain the chemical kinetics required in gas dynamics. The relationships between experimentally determined quantities and molecular parameters were discussed. Emphasis was placed on the diversity of phenomena encountered in the various gas-dynamic regimes. It was stated, for example, that in the low-density regime one should describe the system in molecular variables only; the chemical rate constants would then be replaced by averages over differential collision cross-sections (which are extremely sensitive to the molecular structure and the details of the collision). The advantage of the coupling of gasdynamics and chemistry was discussed and it was shown by means of selected examples that

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both disciplines can contribute a great deal toward a complete exposition of the dynamics of fluids at high temperatures.

### High-Temperature-Air Results

The second paper, "Chemical Kinetics of High Temperature Air," by K. L. Wray, presented a fairly comprehensive review of recent work carried out at the Avco/Everett Research Laboratory and by other workers in the field. Rate constants for eight significant reactions of the species  $N_2$ ,  $O_2$ ,  $N$ ,  $O$ ,  $NO$ ,  $NO^+$ , and  $e^-$  were determined on the basis of an evaluation of all available data. Computed concentrations and density- and temperature-time histories behind a normal shock were presented for three shock speeds. The regimes of importance of the various processes were discussed. In the discussion which followed, Glick of the Cornell Aeronautical Laboratory mentioned that the constant for the electronic reaction was not in agreement with their measurements, and emphasized the need for further experiments.

The third paper, "Chemical Effects in External Hypersonic Flows" by R. Vaglio-Laurin and M. H. Bloom, was an omnibus treatment of the external aerodynamics associated with axisymmetric bodies in a continuum, at flight conditions where local chemical equilibrium does not prevail. A simplified analysis of the significant effects was presented which will be extremely useful in hypersonic aerodynamic design. The flows considered were characterized by the existence of Rankine-Hugoniot shocks and distinct viscous and inviscid regions. An inviscid analysis was presented wherein the gas crossing the strong portion of the shock is assumed chemically frozen at near sonic velocity, while the gas crossing the weaker portions is considered frozen at post-shock equilibrium conditions. A combination of these calculations with one-dimensional rate calculations along streamlines led to reasonably accurate results for the inviscid portion of the flow. A qualitative discussion of the behavior of nonequilibrium boundary-layer flow was presented and a quantitative study of laminar and turbulent wakes, including the influence of both the inner core and shock-induced vorticity, was considered. An order-of-magnitude analysis for radiation and wake-region unsteadiness effects - two phenomena which are only beginning to receive serious attention - has been carried out.

C. E. Treanor, in a paper concerning "Radiation at Hypersonic Speeds," presented an excellent review of the data available for radiation from equilibrium high-temperature air. Several graphs of the absorption coefficients for the component species were shown. A large disagreement for some of the band systems was noted. In answer to a question by M. Bloom concerning the effect of these discrepancies on the bulk phenomenological

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emission coefficient, Treanor estimated a factor of three.

The final paper of the session was "Radiation From The Nonequilibrium Shock Front" by J. D. Teare, S. Georgiev, and R. Allen. An experimental investigation for nonequilibrium radiation from pure nitrogen and from air behind normal shocks with velocities up to 35,000 fps was presented. Results were given for two band systems. The nonequilibrium radiation effects on bodies reentering at supersatellite velocities were computed, and were compared with equilibrium radiation and convective heating.

### Other Interesting Papers

Henry T. Nagamatsu served as chairman of the second session on experimental techniques. The first paper, "The Free Flight Range: A Tool for Research in the Physics of High Speed Flight" by A. C. Charters, was an interesting presentation of some of the problems involved in modifying range techniques, originally developed for determining artillery-projectile characteristics, so that such facilities would be useful for hypersonic flight tests. The development of adequate launchers was discussed and the performance of a particularly effective accelerated-reservoir light-gas gun, diagrammed in Fig. 3 of Charters' paper, was presented in some detail. This gun has been used to fire models at velocities between 20,000 to 30,000 fps with surprisingly small erosion of the gun barrel. Development of necessary instrumentation was considered, not only for the flight-test chamber, but also for making measurements on the model itself during the flight and transmitting this information to receivers stationary in the chamber. A particular example was given of model instrumentation for measurement of stagnation-point heating.

S. C. Lin, in "Survey of Shock Tube Research Related to the Aerophysics Problem of Hypersonic Flight," presented a compendium of work carried out at the Avco/Everett Research Laboratory with this type of facility. Its usefulness as a source of high-temperature air in spite of its relatively low Mach number was emphasized.

The third paper, "Air Arc Simulation of Hypersonic Environments" by W. R. Warren and N. S. Diaconis, described the performance of various types of arc generators. A recently developed tandem Gerdian arc unit was discussed in some detail, and calibration results were described. The unit operates at very low contamination levels when used to drive an arc tunnel.

A. Hertzberg, always a delight to have as a speaker, excelled in the final presentation of the session. In a paper by him,

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C. E. Wittliff and J. G. Hall, "Development of the Shock Tunnel and its Application to Hypersonic Flight," the probable future development of such facilities were described. He reported on some recent calculations by the Cornell Aeronautical Laboratory group led by J. G. Hall of exact solutions for nonequilibrium expansions of air with coupled chemical reactions.

The final session of the conference was devoted to theoretical treatments of inviscid hypersonic flows, with Marten T. Landahl serving as chairman. The first paper, "Slender Wings at High Angles of Attack in Hypersonic Flow" by J. D. Cole and J. J. Brainerd, was essentially concerned with application of Newtonian theory to flat plates nearly normal to the free stream. It should prove to be quite useful for lifting re-entry vehicle aerodynamics. The analysis is basically two dimensional, the results being applied in spanwise strips for slender flat wings. Heat-transfer calculations were carried out on the basis of boundary-layer theory with Newtonian external flow conditions. The results for angles of attack differing slightly from 90 deg were calculated by what essentially amounts to a perturbation procedure; that is, a correction factor, small compared to the 90-deg Newtonian solution, was calculated. As the local angle of incidence is everywhere nearly 90 deg, the usual low pressure difficulties associated with curved surface Newtonian theory are avoided, and the results should be realistic. Indeed, fair agreement with experimental results for delta wings was found. It was brought out in the discussion that, as the angle of attack is sufficiently decreased, the shock will attach at the apex; then the use of this spanwise strip theory would not be proper. Rather, an appropriate conical flow analysis would be required.

The second and fourth papers, "Newtonian Theory of Hypersonic Flow at Large Distances from Blunt Axially Symmetric Bodies" by N. C. Freeman and "Theory of Entropy Layers and Nose Bluntness in Hypersonic Flow" by J. K. Yakura, became involved in what was probably the liveliest discussion of the entire conference. Both papers were concerned with finding a uniformly valid solution far downstream from the blunt nose of a slender body. Freeman used the direct approach of calculating a shock for a specified body, while Yakura solved the inverse problem where the shock is specified and the body is calculated. Both papers recognize the existence of two separate regions of flow: An inner entropy layer next to the body, originating from that portion of the flow which passes through the blunt portion of the shock, and characterized by high temperatures and small pressure gradients, and an outer layer next to the shock characterized by relatively cool temperatures.



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### Fundamental Assumption

Freeman's approach was to extend the Newtonian free-layer solution, known to be valid near the nose, in such a way that it becomes uniformly valid far downstream. He made the fundamental assumption that this validity is insured if the solution approaches the "blast-wave" solution - herein lies the point of controversy.

Yakura, on the other hand, made use of the similarity between the behavior of the entropy layer and a boundary layer and developed asymptotic expansions for both the inner and outer regions of flow. He further claimed that the blast-wave analogy is invalid within the entropy layer, a statement in direct contradiction to Freeman's approach. Numerical results were presented indicating that a paraboloidal shock is produced by a blunt body which grows as a small power of  $x$ , rather than by Freeman's hemisphere-cylinder configuration. While the nature of Yakura's inverse method prevents the direct determination of the shock shape for a hemisphere-cylinder body, his results nevertheless appear to be consistent with the numerical calculations of V. Van Hise, which gave a power-law exponent of 0.46, at a specific heat ratio of  $7/5$ , for the shock shape associated with a hemisphere cylinder.

The discussion following the two papers concerned mainly the fundamental question of blast-wave validity far downstream. Van Dyke objected to Freeman's assumption of blast-wave validity and referred to the results of both Van Hise and Sychev for support. H. K. Cheng felt that the reliance on numerical results, such as those of Van Hise, which were only carried a finite distance downstream to distinguish between expected exponents of 0.46 and 0.5 infinitely far downstream, were not satisfactory, and that such numerical results might indeed approach a value of 0.5 if carried far enough. J. Cole referred to L. Sedov's book, saying that if asymptotic flow fields due to point singularities are studied according to hypersonic small-deflection theory, there are actually two solutions, one being the blast-wave solution, and another giving an asymptotic power-law exponent of 0.46. He attributed this second solution to the influence of the large entropy layer thickness.

The third paper of the session, "Shock Layer Structure and Entropy Layers in Hypersonic Conical Flows" by R. E. Melnik and R. A. Scheuing, was concerned with the entropy layer associated with nonaxisymmetric conical flows in the thin-shock-layer limit. Solutions have been found in an extended region including the entropy layer, but excluding certain small regions near cross-flow stagnation points.

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In conclusion, the conference was distinguished by both the excellent quality of the papers and the significant and timely nature of the subject matter covered. A great deal of useful material was presented, both of a theoretical and an experimental nature. The discussion accompanying the theoretical papers was particularly lively. The only disappointing aspect of the conference was the cancellation of the session at which papers from the USSR were to have been presented.