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Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Aerodynamics of Hypersonic Lifting Vehicles

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Advisory Report No.246

TECHNICAL EVALUATION REPORT

on the

FLUID DYNAMICS PANEL SYMPOSIUM

on

AERODYNAMICS OF HYPERSONIC LIFTING VEHICLES

by

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ABSTRACT

This report reviews and evaluates the Fluid Dynamics Panel AGARD Symposium entitled "Aerodynamics of Hypersonic Lifting Vehicles" held 6—9 April, 1987 in Bristol, UK. The purpose of the Symposium was to assess the technology status in the field of hypersonics after a comparative lull in the past decade. The author addresses each of the papers separately and makes general comments on the 5 major topic sessions. The limitations of test facilities for experimental studies at high Mach numbers were clearly evident. New developments in computational fluid dynamics provide possibilities that did not exist in the past. The reviewer stressed the areas that need special emphasis in the future. The papers presented at the Symposium are published in AGARD Conference Proceedings CP-429 and are listed in an Appendix to this report.

* * *

RESUME

Le présent rapport passe en revue et évalue le symposium AGARD organisé par le Panel de Dynamique des fluides, du 6 au 9 avril 1987 à Bristol en Grande Bretagne sur le thème "L'Aérodynamique des véhicules sustentés hypersoniques". L'objet du symposium a été d'évaluer l'état de l'art dans le domaine de l'hypersonique, après l'accalmie relative de cette dernière décennie. L'auteur traite chaque présentation séparément, en faisant des commentaires sur les cinq grands thèmes de discussion. Les limitations des moyens d'essai à mach élevé prévus pour les études expérimentales sont clairement démontrées. Les récents développements dans le domaine du calcul en dynamique de fluides ont crée de nouvelles possibilités. Le rapporteur met l'accent sur les domaines qui mériteraient une attention particulière à l'avenir. Les présentations données lors du symposium sont publiées au Compte-rendu de conférence CP-429 et elles sont également mentionnées en annexe au présent rapport.

60th MEETING OF THE FLUID DYNAMICS PANEL SYMPOSIUM ON AERODYNAMICS OF HYPERSONIC LIFTING VEHICLES: TECHNICAL EVALUATION REPORT

by

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Summary

"Aerodynamics of Hypersonic Lifting Bodies" was the topic of the 60th Meeting of the Fluid Dynamics Panel of AGARD, held in Bristol, U.K. in April 1987. The status of work on hypersonics was revealed by the many good papers on high speed aerodynamics, but only a very limited contribution to key areas of hypersonic flight. The limitations of facilities for experimental studies at high Mach numbers and the emphasis on computation versus analysis was very noticeable. The Reviewer summarizes the papers, comments on the overall program, and makes some suggestions for further conferences in the area of Hypersonic Aerodynamics.

1. INTRODUCTION

The 60th Meeting of the Fluid Dynamics Panel was held from the 6th to the 9th of April, 1987, in Bristol, U.K. The main topic was a major symposium on the "Aerodynamics of Hypersonic Lifting Vehicles," which took place in the facilities of Bristol University. The program committee, Appendix A, developed the following theme:

> "Through the post Apollo reduction of the space effort in the USA and most other western countries, the subject of hypersonic aerodynamics has been neglected in favor of more pressing needs in areas like transonic aerodynamics. New developments on both sides of the Atlantic place both the facilities and the qualified personnel for hypersonics in very strong demand again. This is mainly because of the renewed strong interest in space applications such as space stations, atmospheric braking, reentry vehicles, transatmospheric aircraft, etc.
>
> This meeting will review the work of those centres that remained active in the quiet years of hypersonics, and will discuss the new scope of applications. In particular, the topics of the meeting will include simulation methods, measurement techniques, lifting body aerodynamics, control surfaces, plume flows, propulsion devices, missiles, and vortex formation. The high supersonic speeds down to Mach numbers of 3 and the transitional regimes between continuum and free molecule flow will also be included."

The symposium covered four days, including a half day of tours at either the Rolls Royce or British Aerospace Facilities located near Bristol. The Symposium was organized covering five major topics:

- Session I - Facilities
- Session II - Experimental Investigations and Techniques
- Session III - Propulsion
- Session IV - Computational Fluid Dynamics (CFD)
- Session V - Vehicles/Design

The full program is given in Appendix B (Paper #13 was unfortunately withdrawn). The Propulsion Session was quite brief with only four scheduled papers (including the one which was withdrawn). The Computational Fluid Dynamics Session was divided into two parts: the first focused on viscous flows, the second on inviscid flows. The session on Vehicles/Design was also given in two parts: the first concerning waveriders and flight mechanics, while the second part presented the data base established by the groups at Wright-Field in the USA, British Aerospace in Bristol, U.K., and RAE at Bedford, U.K., as well as two presentations on major current projects, Hermes, AMD-BA, St. Cloud, France and HOTOL, British Aerospace PLC, Bristol, U.K.

2. GENERAL COMMENTS

The planning and organization of the meeting was very well undertaken. The timing of the meeting was particularly appropriate and, to the author's knowledge, was the first time in many years that AGARD has had a meeting devoted to the topic of hypersonics. The attendees covered a wide range of background, experience, and age. There was a small group, generally physically defined as "white-hair or no-hair", who had worked on the programs of hypersonics during the 1950's and 60's. There was a much smaller group of people who have worked on hypersonics during the last fifteen years. There was a significant group of younger people who are now deeply involved in hypersonics, but have had only limited exposure time and, in some cases, not a very good knowledge of what had taken place in the major programs of the past. The Symposium provided an excellent vehicle for "mixing" of the attendees. The program, as defined by the "Theme" of the meeting, was very well organized, but showed a clear influence of the significant hiatus of research in this field over the past fifteen years. There were many excellent papers in the high speed aerodynamics area, but rather limited contributions which were focused on key problems of hypersonic flight. The limitations of facilities for experimental data at high Mach numbers and the emphasis on computation versus analysis was quite striking.

In the following sections, brief comments about the papers in each session are presented, followed by some general observations. The Technical Evaluation Report continues with conclusions drawn by the reviewer, including comments on the need for a hypersonic "overview."

3. SYNOPSIS OF THE PAPERS

3.1 Session I - Facilities

The four papers in this Session were primarily concerned with discussion of hypersonic facilities. The first two papers were surveys of the facilities in North America and in Europe. The last two papers were concerned with two specific facilities.

PAPER 1. WITLIFF surveyed the current state of hypersonic wind tunnels in North America and outlined their general performance characteristics. The current capability was compared to that available in the 1960's and 70's. Most of the facilities were located in the United States with one facility, a gun tunnel, located in Canada (re activated after some years of non-use). The decline in the capability was very significant. Two areas were particularly singled out as weak: a) high enthalpy facilities, primarily for the study of real gas effects, and b) high Mach number, low density facilities aimed at the problems of the high altitude flight regime. The typical charts of Mach number vs. Reynolds number, and velocity vs. altitude for possible vehicle flight paths were shown and compared to the available capacity to demonstrate the clear lack of ability to duplicate significant regions of hypersonic flight.

PAPER 2. WENDT presented a review of the facilities available in Western Europe. He started with a review of the requirements, which was an important contribution to the perspective of the meeting, and then went on to discuss the present situation, the gaps, and some suggestions for future facility development. Wendt pointed out that, in the Mach number 6-12 range, Mach number-Reynolds simulation is probably adequate. In the hypervelocity region, real gases are important, and chemical reactions become a key factor. This requires the duplication of the dimensional variables of *density* times length and velocity. In the rarefied regime, the effects of mean free path become important. He also noted the effect of wall temperature to freestream temperature ratio, which has an important effect on boundary layer thickness and the state of the boundary layer. He referred also to requirements, that were detailed more than a decade ago, which have not been satisfied by the work over the past decade. He pointed out the deficiencies in the capabilities at Mach numbers above 10, particularly the velocity enthalpy limitations of current facilities and the need for "quiet" facilities for boundary layer studies.

PAPER 3. CONSIGNY, PACOU, PAPIRNYK and CHEVALIER discussed the reconstruction of the arc heater for a hypersonic tunnel designated as R6CH. This tunnel, which was operational many years ago, has been shut down for some time. The detailed re-design of a new heater, which would provide a significant capability at high Mach numbers and high enthalpy, was discussed. The operating characteristics of this tunnel and the requirements for the flight of several vehicles, particularly Hermes, show that some significant part of the flight path can be duplicated by the proposed facility in the Mach number range of about 12 to 20. This tunnel, which is designed to operate up to 50 bars, would operate at a level of about 50 megawatts and would provide test times of several seconds, a set of characteristics which would enable a significant contribution to the data base for hypersonic flight. A new heater will probably generate a considerably enhanced flow quality as compared to the heaters of the past, but the flowfield details have to be examined with great care to assure that this flow quality is well defined.

PAPER 4. STALKER discussed his extensive work in the application of the free piston shock tunnel in simulation of real gas effects for hypersonic flight. He emphasized the simulation of stagnation enthalpy and the binary scaling parameter. Based on his extensive experience, he discussed the free piston reflected shock tunnel and the limitation of this facility's testing time with enthalpy increase. He then presented some exploratory data. He showed how to avoid the limiting radiation loss by considering a non reflecting mode which allows higher values of the binary scaling parameter but at the cost of considerably reduced test time. The non-reflecting mode, with prior steady flow developed, opens new possibilities for obtaining data in an area not here-to fore explored. He gave several examples of data obtained in this region, and also discussed a method of simulating the combustion process by a variation of the free piston shock tunnel.

General Comments on Session I

Although Papers 1 and 2 gave some general review of the requirements for hypersonic flight, the discussions were primarily concerned with full simulation of flight conditions. Paper 4 had a somewhat more limited view, but none of the papers considered the partial simulation with high resolution which is required for CFD validation and for fundamental understanding of the physics of the flows. There was also no discussion of the connection of facility testing to actual flight conditions. This is a major gap in the discussion of facilities for the new emphasis on hypersonic research. There is a critical need for the detailed flight results to check the validation of facilities. Although this has been done to some degree for blunt bodies, the Mach number - Reynolds number - stagnation enthalpy simulation for "hypersonic aerodynamics" is far from adequate. Conditions of the boundary layer and wall cooling, with real gases, are areas in which the data is very sparse or not available at all. The need for this simulation was a major lack in the facilities discussion.

3.2 Session II - Experimental Investigations and Techniques

This Session consisted of seven papers primarily concerned with aerodynamic studies and covering a range of Mach numbers as low as 2.4, with some results at Mach 20. Several of the papers were primarily "technique" oriented, while others present significant data sets. Unfortunately, several of the papers are at low enough Mach numbers that there is some question as to whether hypersonic effects are important. The two last papers considered low density problems in the Mach number of 10-20 range.

PAPER 5. OWEN gave an excellent discussion of the techniques required to carry out turbulence studies in continuous tunnels in the Mach 6 range. He used hot-wires of both the constant current and constant temperature type, and compared the results with LDV studies with significant discussions about particle paths and particle generation. The emphasis of the paper was on the requirements that must be satisfied to get good data in this crucial area. The paper presents probably the only discussion of this problem at a Mach number as high as 6, and included discussion of the data acquisition system and data reduction techniques. It also provided a comparison of data obtained in the NASA Ames facilities at Mach 7 with the primary results of the paper obtained at the AFWAL tunnel at Mach 6.

PAPER 6. The paper by HUMMEL was presented by HORNUNG. It consisted of a summary of an extensive series of tests being carried out in the hypersonic gun tunnel by the Braunschweig group. The tunnel has been in operation since the mid-60's and the current paper considered two key geometries: a blunt body with subsonic blowing at the stagnation point, and the flow in a corner of variable angle formed by plates with various sweep angles. The extensive data included pitot surveys, wall pressure distributions, wall heat transfers, and wall flow direction from surface visualization. The paper presents an excellent data set which was compared with computations for the blunt configuration and used to construct a proposed flow structure of the corner configuration.

PAPER 7. DOLLING and NARLO presented an excellent paper on a unique parameter not discussed by any other paper in the Symposium. It considered the unsteady phenomena; the shock boundary layer interaction at a Mach number of 5. Using a cylinder mounted vertical to a wall, the interaction of the shock structure and the turbulent boundary layer was studied by extensive high frequency wall pressure measurements and detailed analysis. Particular emphasis was placed on the algorithms used in the data reduction and the paper proposes a general model of the interaction to explain the low frequency unsteadiness of the phenomena.

PAPER 8. FOMISON and STOLLERY presented a study of a glancing shock wave turbulent boundary layer interaction. Detailed wall pressure distributions and surface flow visualization were used to construct possible flowfield structures and streamline patterns. The effect of sweep and bluntness on the extent of the disturbed flow and the pressure levels were examined in detail. The entire study was carried out at a Mach number of 2.4.

PAPER 9. JAEGGY, KOENEKE and KOERBER described the development of a new ultra high speed flow visualization technique which was originally developed for the study of transition of hypersonic wakes. The current extension of the technique permits a repetition rate which can be used for extensive studies of time histories, as well as holographic techniques. Some excellent examples of the capability of the system were demonstrated.

PAPER 10. RHYS-JONES presented a significant data set on a series of tests of cones at a Mach number of about 10 in the RAE low density tunnel. The tunnel uses pure nitrogen as a test gas. The tests were very carefully carried out to obtain results of sufficient accuracy to permit correlations to be evaluated. It provides an excellent set of data in the rarefied region, where Knudsen numbers are important, and provided the data base for a subsequent paper, number 19, with regards to computation.

PAPER 11. KOPPENWALLNER discussed a series of tests in the low density regime at Mach numbers of 7 and 20 in the DFVLR hypersonic vacuum tunnel, V1G, and in the Ludwieg tube tunnel at Gottingen, for somewhat higher Reynolds numbers at Mach numbers of about 7 and 10. The paper explains the problem of determining the pitching moment of vehicles in the transitional range. It used the shuttle results and a series of cone studies to show the center of pressure forward shift was not due to chemical reactions, but rather to the combination of free molecular and continuum flows over different parts of the body. The paper provided an excellent framework to show that studies in the transitional region are not necessarily approximated by looking at the results in either the free molecular or the continuum regime.

General Comments on Session II

Several of the papers did not consider problems of hypersonic aerodynamics. Studies of Mach number of 2.4, without any reference to Mach number effects, although useful in general aerodynamic studies, were not particularly pertinent to the hypersonic problem. All of the aerodynamic studies at high Mach numbers were purely aerodynamic, and did not include any effects of chemistry or even suggested what the effects of chemistry might be. The studies of turbulence at high Mach numbers is an important one because of the requirements for turbulence modeling, primarily for computation, and the results presented are the highest Mach number results known to this author. However, the effects of chemistry on this phenomena are totally unknown, and the problems of extending the modeling to higher Mach numbers is in serious question. The new techniques in optics were impressive, but the optical studies must be combined with other measurements if one is going to supply the detailed information for modeling the physics and for CFD validation. The unsteady character of turbulent boundary layer interactions, at a Mach number of 5, was a unique contribution, but the questions as to how this might be applied in the hypersonic regime is still an open question. It is a good lead into what should be done with all studies of turbulent boundary layers. The two papers on low density studies provided valuable insights into the problems of low density flows. However, the Reviewer believes that low density studies at low Mach numbers are not particularly appropriate, since all of the flight paths which are being considered have very high Mach numbers in the low density regime. The aerodynamic studies of the present investigations are good initial studies, but must be considered in the light of chemistry which takes place at the real enthalpys of high Mach number flight.

3.3 Session III - Propulsion

The papers in this Session were concerned with a limited view of hypersonic propulsion, probably because of the AGARD classical division of Aerodynamics-Propulsion. Unfortunately, Paper 13 was withdrawn. The three papers presented covered widely different areas; an historical prospective of ramjets, a mixing problem, and CFD studies of inlets.

PAPER 12. WALTRUP gave an excellent historical prospective of the subsonic combustion ramjet and its limitations at low speed (no thrust), and at high speed, poor performance above about Mach number of 6 (inlet performance and chemical kinetics). With supersonic combustion the high speed end of the performance can be enhanced and the addition of an ejector-ramjet is a possible solution to the low speed problem. Mr. Waltrup's discussion was limited to a Mach number of 3 to 6-7 range and he noted that computations were of some help for the inlet and nozzle flows, but could not handle the shock "isolation" section nor the combustion region and there was little data available. He particularly stressed the need for turbulence information for the supersonic and hypersonic flight condition, pointing out the particular importance in the effects on wall shear, heat transfer, boundary layer characteristics, fuel injection modes, and chemical kinetics. He stressed the engineering design data base requirements for the very low speed problem associated with take-off and for flight above Mach number of 8 where the data base is very sparse, or non-existent.

PAPER 13. The paper by EDWARDS, SMITH and CARNEGIE was unfortunately not presented nor was a copy of the paper available.

PAPER 14. SCHADOW, GUTMARK and KOSHIGOE presented a very interesting paper on the fundamental fluid mechanics of elliptic jets versus axially symmetric jets with particular emphasis on the mixing characteristics. Analyzing results at Mach numbers of 0.15, 1, and 1.3, Schadow et al., noted the enhanced growth mechanism of the elliptic jet. For supersonic underexpanded flow, they also noted that the three-dimensional shock structure was probably part of the mechanism enhancing mixing. They proposed that, linear stability analysis to the contrary, the elliptic jet provided a mechanism for enhanced mixing at higher Mach numbers. Unfortunately, the support for this statement was not available in the form of experimental data at higher Mach numbers.

PAPER 15. KUMAR presented state-of-the-art computations on supercomputers of complex geometry inlets in the high supersonic range (Mach number 4-7). He presented results of parametric studies using quasi three-dimensional applications of two-dimensional codes, and then a complete three-dimensional study of a specific two-strut scramjet inlet of fixed geometry. The calculations included an assumed algebraic turbulence model and "verification" of the computation were based on comparisons with limited pressure distributions. The experiments used for verification were all limited to Mach numbers of less than 7.

General Comments on Session III

The papers of this Session were primarily focused on what the present reviewer considers the supersonic regime. There was little emphasis or prospective on the problems of propulsion at high Mach numbers. The special problems of high Mach number flight including inlet geometries, boundary layer characteristics, mixing, and chemical kinetics were not covered, nor was there much in the way of projections from the present "low Mach number" results. Separation of propulsion and aerodynamics is not possible at high Mach numbers because of the requirements for integrated design. The inlet can not be considered as an entity since most of the forebody of the vehicle is part of the inlet. The inlet requires an integration of the aerodynamic forebody design to give the conditions at the beginning of the inlet. At the same time, if air breathing propulsion is to be considered as part of hypersonic flight, the propulsion system has such a large influence on the aerodynamic design that it probably has to be considered in the initial aerodynamic design and as an integrated part of the overall design.

3.4 Session IV - CFD Part 1 - Viscous Flows

The importance of CFD and the many different approaches being developed for hypersonic aerodynamics was the major focus of Sessions IV and V. The papers grouped in Session IV are primarily concerned with viscous computations, with the inviscid computations grouped in Session V. There are, however, several papers which consider both approaches. The papers in Session IV demonstrated the wide variety of approaches and philosophy covering current grid generation procedures, finite volume, space marching as compared to time marching, real gas effects on laminar flows, full 3-D hypersonic developments, and a comparison of inviscid versus viscous computations. Almost all of the computations were compared to some sort of experiments, primarily pressure distributions, but including some heat transfer data.

PAPER 16. RIZK, CHAUSSEE and STEGER considered an efficient numerical hyperbolic grid generation scheme applied to a three dimensional lifting configuration. They used the Reynolds averaged Navier-Stokes equations integrated through a time dependent factored procedure. Results were compared to the windward side pressure measurements on the shuttle at a Mach number of 7.9 at an angle of attack of 25°. Another set of calculations were carried out on a wing-body combination at a Mach number of 25 and an angle of attack of 5°, using a perfect gas with a gamma of 1.2 to simulate the real gas at the high Mach numbers. Although they showed that their code was robust, the comparison with the data available was not extensive, with the usual check between the measured and predicted pressure distributions being quite reasonable. However, critical measurements of heat transfer were not available for detailed comparison for the shuttle, and no data is available for the wing body computations that were made.

PAPER 17. RIEGER used a somewhat different approach by looking at the ideal gas laminar boundary layer using a space marching technique in the viscid and inviscid PMS and Euler codes. Good agreement was again found with the pressure distributions on a hypersonic compression ramp at Mach number 14 and in the supersonic conditions of a half angle cone at high incidence at a Mach number of 8.

PAPER 18. AUPOIX, ELDEM and COUSTEIX presented an excellent paper on a very well defined problem of hypersonics, the sensitivity of hypersonic boundary layer calculations to assumptions of the real gas effects. They examined the sensitivities of important parameters to real gas modelling. They used first order boundary layer equations with the pressure distributions given by Newtonian flow. They calculated the windward side of a hyperboloid body of revolution, examining the Mach number range from about 9 to 28, simulating part of the re-entry phase of a space shuttle. They found that the wall temperature effects were more important as the wall enthalpy increased and were more important for noncatalytic walls vs. catalytic walls. They were also more important at the end of the re-entry corridor, that is, at low velocity, than they were at high. They presented very convincing computations of the effect of catalytic vs. noncatalytic walls for different species modeling, and also demonstrated the effect of the conditions of the stagnation point with different Lewis and Prandtl number assumptions. The results showed the sensitivity to the physical phenomena and a lack of sensitivity to some of the chemistry modelling and to the values of Schmidt and Prandtl numbers that were assumed.

PAPER 19. RIEDELBAUCH, WETZEL, KORDULLA and OERTEL presented a very well developed and methodical approach to the development of computational tools for 3-D hypersonic flow problems. Their approach covered both the continuum region using the Navier-Stokes equation (integrated, time-dependent), while the low density flow problem was simulated by approximations to the Boltzman equation. Their approach was to use ideal gas initially, adding real gas effects later in the development. Of particular interest was the Direct Simulation Monte Carlo method which they preferred to the Molecular-Dynamics approach because of its computational efficiency. Several examples were given for typical blunt nose configurations for the continuum solutions and the flow around a circular cylinder for the low density calculations. The low density calculations were then extended to a typical blunt nose configuration. They stressed the need for experimental data, particularly at high Mach numbers, for validation of the future computational approaches which will add real gas effects.

PAPER 20. [illegible] and RICHARD carried out a very interesting set of numerical experiments of the hypersonic flow beneath a cone delta wing combination. They solved the compressible Navier-Stokes equation using very fine grids and an assumption of "local conicity", an assumption which has yet to be validated for high supersonic and hypersonic conditions. Again, the computations, when compared to experimental pressure distributions, appeared to be quite good, but the accuracy of the heat transfer calculations were not as good and became worse with increasing angle of attack. The authors showed a very interesting comparison between their viscous calculations and the result of an Euler computation for the same configuration. Although the authors noted the quite different flowfield characteristics for the viscous flow as compared to the inviscid flow, they made no attempt to determine the sensitivity of the flowfield to the viscous modelling assumptions inherent in the Navier-Stokes solutions, simply stating that the effects were due to viscous effects.

General Comments on Session IV - Part 1

The papers in this Session demonstrated the power of CFD, but spotlighted the limitations which are primarily concerned with viscous modelling and real gas effects. The experiments required to validate the computations are clearly not available. Pressure distributions are not critical tests since all computations appear to give good results in this area. The lack of detailed heat transfer, skin friction, and flowfield details limits the ability to critically evaluate the computations. Even laminar computations are not adequately validated on the basis of current experiments.

3.5 Session IV - Part 2 - Inviscid Flows

Part II of the CFD Inviscid Flow Session consisted of four papers. The first three were primarily concerned with the Euler equations, in either approximate or full form, and methods including real gas effects and the evaluation of these effects vis-a-vis the perfect gas approximation. The last paper was much broader than the Session title implied, and covered a review of the NASA-Ames work on aerothermodynamic research covering both a description of the facilities and a brief outline of the many research programs which have been underway for many years.

PAPER 21. DAVIS and BLOTTNER presented a very interesting paper on their attempts to obtain an approximate solution of the Euler equations for particular application to the hypersonic flow over a blunt body. They used a spatial marching scheme and the Vigneron pressure gradient approximation in the momentum equation in the direction along the body surface. They compared their results to the complete Navier-Stokes solution and found reasonable agreement. Their approximation solution, when completed, should be much faster than the usual time-dependent code solution.

PAPER 22. PFITZNER and WEILAND discussed their three-dimensional Euler solutions for hypersonic speeds, covering the range from Mach number 4 to 30. They worked with both the steady and unsteady Euler equation and their formulation used a fitted bow shock, but they captured the imbedded shocks.

They included real gas effects through equilibrium chemistry and the calculations are limited to the continuum regime. A calculation using ideal gases, with gammas of 1.4 and 1.2, were compared to real gas calculations using the "effective gamma" technique for the solution of the full equations of a blunted cone at about Mach number of 15. They used a generalized equation of state and temperature dependent specific heats. At low Mach numbers of 4 to 6, they found no real gas effects. At very high Mach numbers, they found that the pressure at the stagnation point was not affected by the different approximations, but the pressures back on the model (the blunted cone) were off by as much as 50% from the equilibrium calculations when calculated using an "effective gamma" model. Their calculations seemed to indicate that this technique cannot be used when there are strong gradients. The stagnation temperature was overestimated by 130% using ideal gas assumptions.

PAPER 23. HILLIER discussed his computation of flow past conical hypersonic wings using a second-order Gudonov method. Unfortunately, no copy of the paper was available for detailed review. He applied the Euler equation to steady conical flows and applied his solution to a flat delta at a Mach number of about 3.5. Although the calculations were carried out using the Euler equation, it should be noted that all such Euler calculations include a "numerical viscosity" which develops a pseudo boundary layer in supposedly inviscid calculations.

PAPER 24. DEIWERT presented a general review of aerothermodynamics research at NASA Ames. This program, which has been underway for many years, is of significant magnitude and covers 1) advanced mission and concept studies, 2) computational aerothermodynamic flowfield code development, 3) thermochemical non-equilibrium reacting gas models, and 4) code validation experiments. This latter area covered the major shock tubes, ballistic ranges, and a 3.5 ft. hypersonic wind tunnel which has, in recent years, been brought back into operation. The advanced mission and concept studies particularly focussed on the potential of aero assisted technology for enhancing orbital operations in planetary missions by using the aerodynamic forces produced by grazing passes through the upper atmosphere. Discussions of aerobreaking AOTV's, high lift AOTV's, and air breathing TAV's were all included. The extensive program in computational aerothermodynamics has concentrated on solution of the compressible Navier Stokes equations, the parabolized Navier Stokes equations, and Euler, boundary layer, and viscous shock layer approximations. For the very high Mach number applications which are Ames main thrust, real gas effects, which include thermo chemical, non equilibrium, and radiative transport, are important parameters. Outlines of the methods used and applications were detailed. Their work on non equilibrium chemistry and computational chemistry is a significant element for very high speed flight problems. The description of the experimental program and the facilities included a brief discussion of a new flight experiment called the AFE Aero assist Flight Experiment, which is planned to probe high altitude, high velocity, thermochemically non equilibrium conditions. This experiment, in the vicinity of 10 kilometers per second, will provide new data in a region where such data is very sparse.

General Comments on Session IV Part 2

Computations using the Euler equations should be noted, again, as not being truly inviscid. "Numerical viscosity" is an inherent element of such calculation and the effects of this viscosity is not clearly defined. The inclusion of real gas effects, through several approximate techniques, shows significant effects in many cases at high Mach number. The use of the Euler equations has been driven by the fact that they are much faster than solutions of the Navier Stokes equations, and the use of approximate Euler solutions are even faster yet. Design information from such calculations appear to be beyond the abilities of these techniques. The major programs at NASA Ames provide a wide range of important studies for hypersonic flight.

3.6 Session V Vehicles Design Part 1 - Wave Riders and Flight Mechanics

The five papers of this Session included three concerned with wave rider performance. These vehicles capture the bow shock as part of the geometry to increase the lift coefficient for a given L/D. The last two papers were concerned with the dynamics and control of slim axially symmetric geometries. It should also be noted that the last three papers of this session use approximate methods of computation, such as the integral boundary layer or Newtonian approximation, as compared to the Navier-Stokes and Euler solutions of earlier sessions.

PAPER 25. GANZER and SZODRUCH presented a very interesting paper concentrating on the vortex formation of delta, double delta and wave rider configurations. Unfortunately, the study was limited to supersonic speeds. The extensive experimental program was an extension of a basic study of vortical flows on delta wings, with the experiments being carried out at Cranfield, Cambridge, and NASA Ames. The studies included many surface flow visualization and qualitative flowfield studies by vapor screen/laser techniques. The authors proposed a very detailed classification of the flows on the basis of "separation" patterns from the surface visualization. The surface visualization patterns has somewhat limited physical rationale, in the Reviewer's opinion, because of lack of understanding of the sensitivity of the technique and the lack of information on the stability of the vortical flows which are generated. There are also questions of Reynolds number effects and leading edge details, but the paper clearly presented an overall view of the complexity of the flowfields generated by such bodies.

PAPER 26. LONG considered a very important parameter of hypersonic wave riders which potentially has significant applications to hypersonic flight. Aerothermodynamic heating, propulsion integration, and off design performance have not been investigated in any great depth. Long concentrated on the off-design performance, using two generic wave riders, the Rasmussen and Lockheed flat bottom configurations. His calculations used nonlinear inviscid Euler equations, an extension of some original work of Jameson, and he made detailed comparison between the computations and the experiments. His computations predicted lift drag ratio, pitching moment, and surface static pressure distributions. He hopes to include the effects of aerothermodynamic heating, skin friction, and displacement thickness by extending the code to solve the Reynolds averaged Navier-Stokes equation, with future extensions to real gas inclusion.

PAPER 27. BOWCUTT and ANDERSON described their computations of conical flow wave riders which include viscous effects. Previous work on wave riders have been based on inviscid calculations, which were subsequently corrected for skin friction effects. By including the viscous effects in the design procedure, using a non linear simplex optimization technique, the authors have computed performance that exceeds previous studies and resulted in quite different shapes. They proposed that an optimum vehicle would have half viscous drag and half pressure drag. It was noted that the details of the viscous effects, for example, transition or the distribution of shear stresses over the surface, can have a significant effect on the geometry of the configurations obtained. In the ensuing discussions it was noted that the procedure, as described, does not give the "optimum" shape. The calculations clearly show the significant effect of the viscous effects that were included.

PAPER 28. EAST and HUTT compared several simplified prediction methods with some experiments on hypersonic static and dynamic stability of axisymmetric shapes. The calculations were all based on Newtonian flow. The first, the classical Newtonian impact theory, the second the "imbedded Newtonian" flow, which takes into account the reduced dynamic pressures and low speed flow in the flow field downstream of strong shock waves, and third, the imbedded Newtonian Busemann computations, which include the effect of the centrifugal pressure effects, important in the limit of Mach number approaching infinity. The three analyses were compared to a series of experiments carried out at a Mach number of 6.8 covering a series of cones with different nose bluntness, flare geometry, angle of attack, and center of gravity location, with one degree of freedom of oscillatory motion. It was found that the imbedded Newtonian method gave quite good agreement with the experiments if the general flow structure does not change. Where there are significant discrepancies between the experiment and the imbedded Newtonian computations, they were traced to viscous effects and boundary layer, transition, separation, and vortical flows. The use of the imbedded Newtonian Busemann theory does not seem warranted in light of the present studies, although it should be noted that the experiments are at relatively low Mach number. Experiments in the high Mach number range are clearly needed to evaluate whether the present view can be extended.

PAPER 29. [illegible] and VAN ROESSEL continued the discussion of the Newton Busemann theory of dynamic stability applied to hypersonic conical lifting vehicles. Unfortunately, no paper was available at the meeting for detailed review. They presented an excellent historical review of the Newtonian approach and carried out some computations of the hypersonic dynamic stability of cones essentially using the unsteady Newton Busemann approach for small amplitude pitching motion. The results seem to be in reasonable agreement with the experiments. There was [illegible] discussion by [illegible] regarding the Newtonian values for sharp cones which are needed [illegible] the blunt shape [illegible] an inherent part of the prediction technique.

Some [illegible] Comments on Session [illegible] Part [illegible]

The papers in this session were concerned with vehicles, particularly wave riders, and [illegible] performance. The wave rider configurations are particularly sensitive to leading [illegible] boundary layer conditions. Although this was [illegible] by the authors there is not adequate [illegible] to [illegible] the present analysis and general design information. The stability of hypersonic vehicles is a key element [illegible] from simple [illegible] shapes to actual flight vehicles. Methods of prediction and verification by experiment of the dynamic characteristics of more complex bodies are important parts of developing hypersonic vehicles. The attempts [illegible] have been limited to simple shapes [illegible] more complex models have yet to be discussed.

[illegible] Design Part 2

The [illegible] papers of this session constituted a [illegible] The problems of the actual design of a vehicle for high speed hypersonic flight was the focus of development and engineering staff, as opposed to the [illegible] of most previous papers. The first three papers were concerned with extensive data sets and analysis, and included one paper concerning the use of a major current computer program. The last two papers were concerned with two specific programs of hypersonic vehicles which are planned for orbital flight.

PAPER 30. DRAPER and [illegible] reviewed a [illegible] effort of the Flight Dynamics Laboratory at Wright Field on the study of lifting bodies for very high speed flight. The program started in the early 60's and culminated [illegible] years [illegible] in the X-24 series. This research vehicle was [illegible] extensively researched through computation and force, moment, pressure, and temperature tests through the Mach number range up to 20. The authors also outlined two major flight programs which were completed ASSET and PRIME. ASSET was conceived as an [illegible] flat bottomed vehicle with a 70° sweep delta wing. This wing was blended with a cone cylinder lifting body on the top surface. It was flown at altitudes of about 160,000 to 210,000 feet at 13,000 to 19,000 feet per second with three main goals: 1 correlation of flight and wind tunnel tests, 2 verification of analytic and prediction techniques, and 3 evaluation of structural concepts and materials. PRIME was an ablating body designed to explore the hypervelocity range at a maximum velocity of over 25,000 ft. per second at altitudes to 100,000 ft.

The authors attempted to optimize vehicles which had maximum volume with high aerodynamic efficiency, but the program was aimed primarily at vehicles which did not include air breathing propulsion. The vehicles were rather simple and amenable to calculation, but clearly had to be stable, controlled, and trimmed. Many of their configuration studies, which included wind tunnel tests, also were the subject of intensive computation. The computational efforts spanned the full range from Supersonic/Hypersonic Arbitrary Body Program (S HABP), PANAIR (a higher order paneling program using linearized potential flow), Euler (the most sophisticated of the inviscid codes which gave lift and drag reasonably well for streamlined bodies but was inadequate for interference and separated flows), PNS (found to produce most of the essential design information at about 1/5th the cost of Navier Stokes solutions, but it could not compute time dependent phenomena nor configurations with any significant separation). Because of the speed and simplicity of PNS, the authors suggested it would probably be the first to contain real gas capability. Finally, Navier-Stokes solutions (which is the limit of a macroscopic representation of the continuum flow). Navier Stokes calculations are limited by efficiency, but so far as the authors of this paper were concerned, they found no limit to the ability of Navier Stokes to duplicate experiments, except in the transition and turbulent boundary layer regime. The authors also defined a set of challenges which they felt were the important areas for future research.

PAPER 31. FISHER described the experiences using the Douglas Supersonic/Hypersonic Body Program, S/HABP, which British Aerospace, PLC, was evaluating as part of their efforts in the design of hypersonic vehicles. This program has a very complex structure which includes a large variety of aerodynamic prediction methods for many different types of problems. The program also includes a large data base, much of it derived from shuttle flights. The technique is a quasi-empirical one. The operator picks the specific method that best approximates the available data. Solutions with S/HABP requires an examination of the various methods available and comparisons with the data bank. British Aerospace found that user experience was needed for accuracy, and the data base limits going outside of the tested ranges or configurations which are in the computer. This is, to the reviewer's knowledge, the first time that the transferability of a major hypersonic code has been evaluated.

PAPER 32. HODGES and WARD reviewed RAE's program in generating a data base for missile performance at high Mach numbers, and its use in assessing CFD methods. Unfortunately, the present effort is limited to the low Mach number range, 2.5 to 4.5, because of the lack of adequate wind tunnels to explore the higher Mach number range. The extensive experimental set is being compared to solutions of Euler codes using space marching techniques, SWINT. The primary emphasis is to supersonic missile applications and extrapolation of these results into the hypersonic regime are not possible. The experimental program is being carried out in a 3 ft. x 4 ft. continuous wind tunnel where an extensive set of bodies, controls, and wing combinations are being examined in a very methodical framework. There are problems concerning boundary layer transition which, in these tests, is fixed at the nose of the body and at the leading edge of wings. Therefore, some question exists as to the boundary layer conditions which are clearly turbulent in this Mach number range. Comparisons of the results of the Euler calculations and some of the experiments are presented in detail. Quite reasonable results are obtained in some regions, while significant differences are noted in other regions, primarily where viscous effects become important.

PAPER 33. PERRIER and CAUPENNE gave a review of the concept of the aerodynamics and thermodynamics of Hermes, the French proposal for a vehicle to go into orbit and return. Comparison of the Shuttle and Hermes flight programs and general characteristics were detailed. The Hermes is about half the size of the shuttle and is designed to land in Europe. It, therefore, requires a somewhat better L/D and better handling characteristics, in particular, a considerable lower approach speed. The small size increases the heat transfer and stability problems. The authors outlined a series of wind tunnel tests which are being considered, including cryogenically cooled models to simulate wall cooling effects. They discussed the "modelization" using CFD which they believe was required to reduce the risk of poor pre flight prediction and to reduce the cost of design. They also presented the methodology of the development which included two flight demonstrators and a proposed flight of Hermes in 1992. The authors stressed the research and technology needs and asked the group to consider a workshop near the end of 1988, sponsored by ESA. Eight topics were suggested as important elements:

1) Comparison of experiment to experiment, CFD to experiment, and CFD to CFD by other techniques,
2) Low Reynolds number and rarefield flows, which was the responsibility of CNRS,
3) Real gas effects which would be studied by the Australians,
4) Boundary layer shock wave interactions would be the responsibility of ONERA,
5) Corner flow problems to be studied by DFVLR,
6) Leeside flows to be considered by FFA,
7) Chemistry to be carried out by ECD,
8) Transition to be the responsibility of ONERA.

PAPER 34. WAKE discussed the hypersonic aerodynamics for HOTOL, a British vehicle proposed to fly into orbit and return. Comparison of the Shuttle and proposed HOTOL trajectories were discussed, noting that the re-entry conditions were the critical ones. The author discussed the "infernal" triangle, which limited the range of possibilities for such a vehicle. The elements are: 1) trim, 2) cross range requirements, and 3) heating limitations. The proposed HOTOL program is currently in a two-year study phase which, if successful, will lead to a five year enabling technology program to optimize the design for possible flight in 1998. The present concept uses a unique air breathing system (which was not discussed) for Mach number up to about 5, and then converts to rocket propulsion. Wind tunnel tests of inlets are currently being carried out at about a Mach number of 4. The author laid out the aerodynamic technology requirements as they were currently seen in both the continuum and rarefied flow regime, noting the regions which needed major work for successful completion of the program.

General Comments on Session V - Part 2

The papers of this session began to discuss the real problems of the design of hypersonic vehicles. This requires a combination of aerodynamics, heat transfer, dynamics and control, and propulsion. The most sophiscated codes of the researchers were no longer applicable, and the more easily used approximate methods, which had some validation in data sets, provided the realism needed for design. Ground tests, flight tests, simulation, and computation are all used and even then, not sufficient, well established bases for design are really available. The discussion of real vehicles, such as HERMES and HOTOL, clearly demonstrated the crucial engineering details which are needed for the design of such vehicles.

4. REVIEWERS CONCLUSIONS

The Symposium on "Aerodynamic of Hypersonic Lifting Vehicles" provided many excellent papers, although only a few were focussed on "Hypersonics" rather than "Supersonics". This is probably a very realistic view of the "state of the art" as of 1987. There were noticable gaps in the material presented. Particularly important was the lack of high Mach number high enthalpy experimental data, and hypersonic boundary layer studies. Both of these could be due to the lack of facilities, operational in the hypersonic range, over the past decade. There was also a noticeable lack of analytic papers, but a wealth of papers on computation. The major analytic studies of hypersonics of the 1950's and 1960's seem to be either unknown, or unused. They could be significant factors in extrapolating the high supersonic area studies to hypersonic conditions.

With regards to the facilities, there was very little which seemed to be connected with the problems of hypersonics, as we see them now, rather than attempts to resurrect facilities designed thirty and forty years ago. Although many of these facilities would be useful for testing, there are serious question as to whether the problems of hypersonics are the main drivers for new facilities and new concepts of experimental studies. An exception to this statement is the work of STALKER in Australia. Clearly, facilities and the ability to get crucial data will be a major limitation to future progress. The discussion of facilities seems to be primarily based on attempts to get full duplication of hypersonic flight conditions. The reviewer suggests that a more useful, and perhaps practical, effort would be to attempt to simulate key elements of hypersonics and try to provide information on the fundamental physics, data for modelling and, most important, data for computational validation. Many opportunities in this area are within reach.

The reviewer was concerned about the lack of emphasis on hypersonic boundary layer characteristics. There seemed to be little in the way of fundamental work on boundary layers. Problems of transition (initiation, characteristics, length), wall cooling effects, effects of gradients and three dimensional flows, and the effects of chemistry on "aerodynamic" boundary layer data and calculations are important elements of hypersonic design. There are major questions on how the experiments and knowledge of low speed and supersonic boundary layers can be extended to hypersonics. The problems of turbulence modelling, for both boundary layer and shear layers (a key element in mixing problems for combustion) did not seem to get the attention which the reviewer felt the area warranted. The problems of real gases, not only for calculations but to evaluate the effects on the boundary layers, was attempted in only a few papers. This effect, and the problems of low density, were only a small part of a present program and should command major attention in the near future.

Although there were several papers on configurations, the real problem of hypersonic vehicle design is the integration and interaction of the power plant, heat transfer, aerodynamics, stability and control, and materials and structures. These are all strongly interactive in hypersonic vehicle design. A few of the papers began to approach this problem, but only the real vehicle designers are forced to face this total integration, a unique and very strong factor in the design of hypersonic vehicle.

In retrospect, the reviewer believes the program might have been helped with a significant "tutorial" or "overview" of hypersonics problems. Such an overview could have focussed the attention on hypersonic problems, as compared to supersonic problems. Some prospective of the past, what is known and what is unknown, would have been helpful. Several papers included some elements of such a perspective, but a major introductory paper might have been of significant help to the diverse groups at the meeting.

Clearly the topic of Hypersonic Aerodynamics deserves continuing further attention by the AGARD community since it will continue to be a topic of major concern to many nations. The subject Symposium provided an excellent first step in what the reviewer believes should be a continuing series of meetings focussed on aspects of hypersonic flight.

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APPENDIX B. LIST OF PAPERS

Session I - FACILITIES

1. C. E. Wittliff, "A Survey of Existing Hypersonic Ground Test Facilities - North America."
2. J. F. Wendt, "European Hypersonic Wind Tunnels."
3. H. Consigny, C. Pacou, O. Papirnyk, and J. P. Chevalier, "Essais Probatoires d'un Generateur de Plasma pour l'Alimentation d'une Soufflerie Hypersonique."
4. R. J. Stalker, "Shock Tunnels for Real Gas Hypersonics."

Session II - EXPERIMENTAL INVESTIGATIONS AND TECHNIQUES PART 1

5. F. K. Owen, "Turbulence Measurements in Hypersonic Flow."
6. D. Hummel, "Experimental Investigations on Blunt Bodies and Corner Flow Configurations in Hypersonic Flow."
7. D. S. Dolling and J. C. Narlo II, "Driving Mechanism of Unsteady Separation Shock Motion in Hypersonic Interactive Flow."
8. N. R. Fomison and J. L. Stollery, "The Effects of Sweep and Bluntness on a Glancing Shock Wave Turbulent Boundary Layer Interaction."

Session II EXPERIMENTAL INVESTIGATIONS AND TECHNIQUES PART 2

9. B. Jaeggy, A. Koeneke and G. Koerber, "Une Methode Cinematographique Ultra Rapide pour l'Etude des Sillages en Tunnel de Tir Hypersonique."
10. T. J. Rhys Jones, "The Drag of Slender Axisymmetric Cones in Rarefied Hypersonic Flow."
11. G. Koppenwallner, "Low Reynolds Number Influence on Aerodynamic Performance of Hypersonic Lifting Vehicles."

Session III - PROPULSION

12. P. J. Waltrup, "Hypersonic Airbreathing Propulsion: Evolution and Opportunities."
13. D. G. Edwards, R. M. Smith and W. D. Carnegie, "Computations of the Flow Field Inside Three Dimensional Ducts Associated with Supersonic Hypersonic Air Breathing Propulsion Systems."
14. K. C. Schadow, E. Gutmark and S. Koshigoe, "Combustion Related Shear Flow Dynamics in Non Circular Supersonic Jets."
15. A. Kumar, "Numerical Analysis of Flow Through Scramjet Engine Inlets."

Session IV - CFD Part 1 - VISCOUS FLOWS

16. Y. Rizk, D. Chaussee and J. Steger, "Numerical Simulation of the Hypersonic Flow Around Lifting Vehicles."
17. H. Rieger, "Solution of Some 3 D Viscous and Inviscid Supersonic Flow Problems by Finite Volume Space Marching Schemes."
18. B. Aupoix, C. Eldem and J. Cousteix, "Couche Limite Laminaire Hypersonique, Etude Parametrique de la Representation des Effets de Gaz Reels."
19. S. Riedelbauch, W. Wetzel, W. Kordulla and H. Oertel Jr., "On the Numerical Solution of Three-Dimensional Hypersonic Flow."
20. Q. Ning and B. E. Richards, "Numerical Experiments with Hypersonic Flows Beneath a Cone-Delta Wing Combination."

Session IV - CFD - PART 2 - INVISCID FLOWS

21. R. T. Davis and F. G. Blottner, "A Spatial Marching Technique for the Inviscid Blunt Body Problem."
22. M. Pfitzner and C. Weiland, "3 D Euler Solutions for Hypersonic Free Stream Mach Numbers."
23. R. Hillier, "Computation of Flow Past Conical Hypersonic Wings Using a Second-Order Godunov Method."
24. G. S. Deiwert, "Aerothermodynamics Research at NASA Ames."

Session V - VEHICLES/DESIGN - PART 1 - WAVE RIDERS & FLIGHT MECHANICS

25. U. Ganzer and J. Szodruch, "Vortex Formation Over Delta, Double-Delta and Wave Rider Configurations at Supersonic Speeds."

26. L. N. Long, "The Off-Design Performance of Hypersonic Wave Riders."

27. K. G. Bowcutt and J. D. Anderson Jr., "Numerical Optimization of Conical Flow Waveriders Including Detailed Viscous Effects."

28. R. A. East and G. R. Hutt, "Hypersonic Static and Dynamic Stability of Axisymmetric Shapes A Comparison of Prediction Methods and Experiment."

29. W. H. Hui and H. J. Van Roessel, "Newton-Busemann Theory of Dynamics Stability of Hypersonic Conical Lifting Vehicles."

Session V - VEHICLES/DESIGN - PART 2

30. A. C. Draper and M. L. Buck, "Lifting Bodies - An Attractive Aerodynamic Configuration Choice for Hypervelocity Vehicles."

31. C. M. E. Fisher, "Experiences Using the Mark IV Supersonic/Hypersonic Arbitrary Body Programme."

32. J. Hodges and L. C. Ward, "The RAE Experimental Data Base for Missiles at High Mach Number and Its Use in Assessing CFD Methods."

33. P. Perrier and P. Caupenne, "Concepts Generaux Aerodynamiques Aerothermiques d'HERMES."

34. A. J. Wake, "Hypersonic Aerodynamics-Applications for HOTOL."

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14. Abstract

This report reviews and evaluates the Fluid Dynamics Panel AGARD Symposium entitled "Aerodynamics of Hypersonic Lifting Vehicles" held 6—9 April, 1987 in Bristol, UK. The purpose of the Symposium was to assess the technology status in the field of hypersonics after a comparative lull in the past decade. The author addresses each of the papers separately and makes general comments on the 5 major topic sessions. The limitations of test facilities for experimental studies at high Mach numbers were clearly evident. New developments in computational fluid dynamics provide possibilities that did not exist in the past. The reviewer stressed the areas that need special emphasis in the future. The papers presented at the Symposium are published in AGARD Conference Proceedings CP-429 and are listed in an Appendix to this report.

This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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