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RESEARCH OF THE AEROPHYSICS INSTITUTE
FOR THE STRATEGIC TECHNOLOGY OFFICE (DARPA)

FINAL REPORT

by

MARTIN H. BLOOM

1 SEPTEMBER 1969 THROUGH 30 JUNE 1974

U. S. ARMY RESEARCH OFFICE

CONTRACT NO. DAHC04-69-C-0077

POLYTECHNIC INSTITUTE OF NEW YORK

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ABSTRACT

A report is presented of technical activities and results for the period 1 September 1969 - 30 June 1974, during which the Polytechnic Aerophysics Institute was engaged in continued support of the program of the Strategic Technology Office of the Defense Advanced Research Projects Agency. Areas of concern involved atmospheric and flow-generated plasmas and flow characteristics as they related to high speed flight and explosions in the field and laboratory, and to lasers and undersea simulation. Specific topics of theoretical and experimental nature included: numerical analysis of flows, ion-collecting probes, laser-Raman-scattering and laser-Doppler diagnostics, near-wake behavior, turbulent mixing, surface-cooling, a novel aerodynamic test method, plume gas-dynamics, plasma diffusion and diagnostics, laser brightness and stratified-flow undersea simulation in an air wind-tunnel. Fifteen senior investigators participated in the program during the subject period.

This constitutes a formal final report being submitted to the Army Research Office, which has been administering a Defense Advanced Research Projects Agency program at the Polytechnic Institute of New York (formerly Polytechnic Institute of Brooklyn). The contract designation has been Contract No. DAHC04-69-C-0077 based upon ARPA Order No. 1442. This summary document is occasioned by the termination of the current contract period. A change in the contract administration agency will also be effected for the new contract period starting 1 July 1974. At that time the Office of Naval Research will become cognizant. In technical matters, the program is within the purview of ARPA's Strategic Technology Office. It is organizationally structured within the Polytechnic as an Aerophysics Institute.

The purpose of the program is to provide an integrated, interdisciplinary effort of theoretical and experimental nature, relevant to problems of importance to ARPA. It is academically based, but sensitive to problems in the field. At the outset of the program, major emphasis was placed on electromagnetic and communication problems associated with plasma environments. Later, attention was transferred to the aerodynamic features of plasmas and flows generated by high-speed vehicles and otherwise, including turbulent effects, entrainment, and relevant diagnostics. Most recently, subject-areas of significance have pertained to: rocket plane behavior, mainly at high altitudes; entrainment phenomena of high altitude expolsions; laser phenomena and diagnostic techniques: and the fluid dynamics of submarine wakes.

A sequence of 9 semi-annual technical summaries of research has been submitted covering the subject period 1 September 1969 through 30 June 1974. This reportage depicts the results obtained, publications generated, personnel involved, and other relevant acitvities.

No undue technical or management problems were encountered during the course of the contract.

In the period 1 September 69 through 30 June 74, covered by this report, the subject program was significantly concerned with the aerodynamic and physical features of plasmas and of flows generated by high-speed vehicles in flight, as well as by comparable flows in ground-based experiments. These subjects were typically relevant to missiles during launch, high-altitude flight and entry, to the aftermaths of explosions, and to a limited extent the behavior of undersea vehicle wakes. The regions of flow of interest included the shock-layers, boundary-layers, and wakes of vehicles, and atmospheric regions affected by explosions. Both theoretical and experimental investigations were involved. Salient features of several studies in these areas are given in the ensuing sections:

1. Numerical analysis of shock-layers and related flows.

2. Properties and applications of electrostatic ion-collecting probes in low-density hypersonic flows.

3. Laser Raman scattering applications and laser doppler velocimetry.

4. Hypersonic near-wake experiments and theory.

5. Turbulent mixing.

6. Explosions.

7. Film cooling.

8. Slingshot: an aerodynamic test facility.

9. High-altitude plume gas dynamics

10. Plasmas.

11. Laser brightness.

12. Stratified flow.

The concluding section 13 contains a list of personnel who were engaged in this program during the 5-year subject period. Further details concerning seminars held at the Polytechnic in support of the program, participation in

1. Numerical analysis of shock-layers and related flows.

In the early part of the subject contract period, the use of large-scale digital computation was emerging as an important analytic tool by which complex flow properties could be studied. The Polytechnic's program was in the vanguard of these developments, which required careful attention with regard to the intricacies of technique. It was necessary to provide accurate calculations, economically, particularly when it was necessary to represent shocks in the flow. The proper numerical treatment of boundary conditions was also important, as was the minimization of spurious diffusive effects engendered by certain numerical discretization techniques.

This problem was described by G. Moretti in an early paper entitled: "The Importance of Boundary Conditions in the Numerical Treatment of Hyperbolic Equations" (Physics of Fluids, Suppl II, 12, 12, Pt. II. Dec. 1969). In this work rigid walls, arbitrary boundaries of partial computational regions of subsonic flows, and shock waves were analyzed as to physically proper numerical treatment. Several examples relative to the following flows were discussed: The blunt-body shock layer, transonic flow in a nozzle, transient flow past a cylinder and in a Laval nozzle.

Further applications of these numerical approaches have been reported, viz: by G. Moretti in a report entitled "Transients and Asymptotically Steady Flow of an Inviscid, Compressible Gas Past a Circular Cylinder," PIBAL Report No. 70-20, Apr. 1970; by M. Pierucci in a report entitled "An Axisymmetric Near Wake Analysis Using Rotational Characteristics," PIBAL Report No. 70-4, Feb. 1970; by G. Moretti in a report entitled "Complicated One-Dimensional Flows," PIBAL Report 71-25, Sept. 1971; and by G. Moretti in a paper entitled "A Critical Analysis of Numerical Techniques: The Piston-Driven Inviscid Flow," published in NATO/AGARD Lecture Series

48 on "Numerical Methods in Fluid Dynamics" AGARD-LS-48, May 1972.

A series of related papers in this general area has been completed in connection with other programs at the Polytechnic, and is available for reference.

This work had a substantial influence on subsequent work in this field. At that time it was in a seminal stage, and led to further developments and refinements of the numerical treatment of complex flow field. The active role of Polytechnic investigators in the development of numerical methods for flow analysis led to their ultimate leadership in establishing the "International Journal of Computers and Fluids" published by Pergamon Press; M. H. Bloom, Editor.

An ARPA/Polytechnic workshop in "Gas Dynamics from a Numerical Viewpoint" was held in New York City in January 1970.

2. Properties and Applications of Electrostatic Ion-Collecting Probes in Low-Density Hypersonic Flows.

The electronic characteristics of flows aroung high-speed, high-altitude missiles and satellite vehicles were of substantial interest in this program. Ionization effects were created by the shock-wave heating when the ambient was not pre-ionized, say below the ionosphere. They were also evident in flight through the ionosphere and in the pre-ionized flow created within shock-tubes and shock-tunnels which were used to simulate hypersonic flow effects in the laboratory. Finally, ionization effects were present in high-temperature boundary layers and wakes. These phenomena were important in connection with radar detection, tracking and discrimination signatures.

In this connection the electrostatic probe was in important diagnostic tool. It developed at that time, that classical probe theories were not necessarily applicable for the hypersonic conditions of interest for the problems outlined above. The Polytechnic program was instrumental in providing experimental data on the behavior of electrostatic probes in a range of conditions created in a hypersonic shock-tunnel which had not been covered before. Pertinent descriptive parameters in this regard included probe dimensions relative to neutral mean-free-path and Debye length, ion temperature, electron temperature and probe bias.

During this period of the program there was not available a clear understanding of the role of end effects, probe orientation and probe shape. A number of experiments at other laboratories gave results which apparently differed in some respects from those of the Polytechnic experiments. These experiments were made with plasma jets and shock-tunnels. However, it was sometimes difficult in these tests to determine the test-flow conditions accurately. Ultimately the various differences were reconciled, and the theories also became better developed. The Polytechnic results were validated.

The Polytechnic program also contributed to the theoretical analysis of ion-current collection, including transients.

The experimental program concerning properties of ion-collecting probes and their use in measuring the ion and electron distribution around bodies is described by S. Lederman, M.H. Bloom and J. Avidor in a paper entitled: "The Electrostatic Probe: Some Applications to Hypersonic Flow Diagnostics" which appeared in the Proceedings of the Twelth Israel Annual Conference on Aviation and Astronautics, March 1970, Weizmann Press; and further by J. Avidor and S. Lederman in a paper entitled "Flow Field Diagnostics in Rarefield Slightly Ionized Hypersonic Flow" which appeared in the Proceedings of the Fourteenth Israel Conference on Aviation and Astronautics, 1972, Weizmann Press.

The Theoretical aspect of the problem was contained in papers by C.H. Shih and E. Levi entitled: "The Effect of Collisions on Cold Ion Collection by means of Langmuir Probes: AIAA Journal, v. 9, n. 9, September 1971; "Determination of the Collision Parameters by Means of Langmuir Probes," AIAA Journal v. 9, n. 12, December 1971; and "Transient Performance of Negatively Biased Langmuir Probes", AIAA Journal v. 10, n. 1, January 1972.

At one time consideration was given to the possibility of employing MHD effects to influence the ionized flow fields around bodies. In this spirit, a theoretical analysis was pursued of the shielding of current-carrying plasmas by means of space charge sheaths. Necessary and sufficient conditions were established for such shielding. These conditions reduced to Bohm's shielding criterion in the particular case of zero current for which the theoretical results agreed with those obtained by Langmuir probe experiments. The results of this study by H. Friedman and E. Levi were published in a paper entitled "Plasma Shielding," Physics of Fluids, v. 13, n. 4 April 1970.

Since it may not be feasible to immerse a cylindrical or spherical electrostatic probe in a flow, current collectors which are mounted flush to a surface over which the flow moves are important in practice. S. Lederman and J. Avidor have studied the behavior of such probes experimentally as described in a paper entitled: "The Application of Flush Mounted Electrostatic Probe to Flow Diagnostics," Israel Journal of Technology v. 9, 1-2, 1971. S. Lederman and R. W. Bushman pursued this experimental work further as reported in "Flush Electrostatic Probe in a Continuum Regime," PIBAL Report No. 70-54, Dec. 1970.

Finally J. Bornstein and S. Lederman evaluated the "Effect of Collisions on Electrostatic Probe Measurements," in PIBAL Report 71-32, Nov. 1971.

3. Laser Raman Scattering Applications and Laser Doppler Velocimetry

In the early part of this contract period an extremely important part of the Polytechnic program evolved. It concerned a demonstration of how the laser-Raman-scattering effect, little known to those concerned with flow properties and behavior at that time, could be used to great advantage for remote flow diagnostics. This application was demonstrated through the work of S. Lederman and his co-workers. An early report on the method was reported by S. Lederman and G. F. Widhopf in a paper entitled: "Specie Concentration Measurements Utilizing Laser Induced Raman Scattering," presented at the AIAA Eighth Aerospace Science Meeting in New York City, January 1970, and published in the AIAA Journal v. 9, n. 2 February 1971. This paper was indicative of the Polytechnic's leading role in establishing this powerful technique as a tool for flow diagnostics. It is the first of a series of papers describing the development and application of the method, as a result of intensive work during the ensuing years.

It is recalled that the laser-Raman method is an optical technique which permits the in-situ measurement, in a non-perturbing fashion, of species concentrations of Raman-active molecules (single-atomic species are not Raman-active) and of temperatures. Thus, under many conditions of importance, gaseous species, density, temperature and hence pressure can be measured with good spacial resolution (1 mm) and instantaneously (10-20 nanoseconds per frame with pulsed lasers). Currently temperatures and concentrations can be measured with about 5% accuracy, although this can be improved upon in special circumstances.

As a necessary companion to the LRS method, when flow systems are of concern, velocities can be measured by means of laser-Doppler-velocimetry (LDV). This method requires continuous-wave laser illumination. It also has been implemented at the Polytechnic laboratories to augment appropriately the laboratories' diagnostic capabilities.

The laser-Doppler effect depends upon Mie-scattering from minute particles suspended in the flow. These particles may stem from the natural environment of the flow (dust, condensate, etc.) or from artificial seeding. The extent to which the scattering particles follow the actual flow is thus important if one wishes to determine the flow velocity, particularly under fluctuating conditions of high frequency as appear in turbulent flow. A theoretical study of this effect as it bears upon the accuracy of LDV measurements has been presented in a report by P. K. Khosla and S. Lederman entitled: "Motion of a Spherical Particle in a Turbulent Flow," PIBAL Report No. 73-22, Nov. 1973. In this document it is shown, for example, that particles larger than 1 micron in diameter fail to follow velocity fluctuations when frequencies exceed the order of 1 kHz (1,000 cycles/sec) under flow conditions of general interest. The study covers a range of velocity and thermal conditions parametrically and points to the desirability of obtaining reliable experimental data on this subject.

A related problem concerning the application of LDV methods emerges from the recognition that LDV response depends upon scattering from an entrained particle passing through the local volume being observed, as required for spacial resolution. Thus, if strong velocity gradients are present, or perhaps rapid turbulent fluctuations, which bring into the field of view flow-samples which are devoid of particles due to a non-uniform distribution of these entrained scatterers, the velocities of these clean fluid segments will not be sensed as one monitors the Doppler shift. Consequently, mean-values of velocity, based upon time-averages over a series of individual scatterings in the vicinity of a point, may be biased in favor of the velocity levels of the particle-bearing of fluid elements, with the level of the non-particle-bearing elements being omitted. Clearly much remains to be done to place LDV technology on a firm basis for use in complex flow situations. The work done at the Polytechnic during the current contract period should be of benefit in this regard.

Yet another problem associated with the presence of particulates in a flow being observed, concerns their possible interference with the LRS signals when concentrations and temperatures are being measured. Such particulates are present naturally in rocket exhausts due to material erosion and to condensation. They are also present in the spray injection region of liquid fuel combustors, the coolant injection region of cooled surfaces, and over surfaces subject to ablation. Also as previously mentioned, particles may be artificially introduced to assist in LDV measurements. In all of these cases, it may be desirable to apply LRS diagnostics.

An experimental study, carried out on a limited basis, to obtain an idea of the order of magnitude of possible particulate interference in LRS, was carried out and reported by S. Lederman in a report entitled: "Raman Scattering Diagnostics In The Presence of $A\ell_2 0_3$," PIBAL Report No. 72-39, Dec. 1972. On the basis of this check, it was judged that under most practical conditions such interference would not prevent the acquisition of valid data on concentrations and temperatures within the usual accuracy.

In the context of studying the effectiveness of liquid-film cooling of missle and other surfaces, LRS methods were applied with the objective of measuring species concentrations and both liquid and gas phase components in the vicinity of the liquid film. This multiphase flow experiment would lead to an understanding of the manner in which the film breaks down and exerts an effect downstream, particularly in supersonic flow. The first part of this study was devoted to the construction of apparatus which would furnish controlled droplets of water, and to demonstrating the feasibility of applying illumination with a 100 megawatt pulsed ruby laser. It was desired to distinguish liquid and gas phases and to measure their concentrations. A report on the initial work by E. J. Kawecki and R. Cresci is expected during the coming year.

Finally, the LRS technique was employed to measure molecular polarizability invariants α^1 and γ^1 which are used to calculate equivalent Raman scattering cross-sections. The feasibility of the technique was verified by measurements in oxygen and nitrogen, as reported by S. Lederman and E. J. Kawecki in a report entitled: "Determination of Molecular Invariants," PIBAL Report 72-26, Aug. 1972 and Proceedings of the 38th Supersonic Tunnel Assoc. Meeting, Sept. 1972.

4. Hypersonic Near Wake Experiments and Theory

The character of the near wake of blunt-based vehicles has been a matter of prime concern in connection with observables sensed by radar or optical instruments. The relevant chemical-physical phenomena are coupled to the pattern of flow. Hence a knowledge of the basic flow behavior, even in the absence of chemical effect, is important and has been the subject of much study. The wake behind the body stems from the shock-layer and boundary-layer over the front of the body. Thus the structure of these portions of the flow, particularly their transitional or turbulent state, is important along with the wake itself.

During the prior contract period, experiments in this regard were conducted in the Polytechnic's Hypersonic Facility, primarily at a Mach number of 8, over a range of Reynolds numbers, on a sharp cone with 10° half-angle. It was possible to produce, over the rear of the cone-surface, conditions varying from laminar to fully-turbulent detailed wake measurements of mean values were made by pitot probes and thermocouples in a region up to 10 base-diameters downstream of the base under varied conditions. The results of this work were published as previously reported. They were significant in relation to other laboratory work carried on elsewhere, and in relation to field data, and were widely discussed in attempts to resolve a number of different kinds of observation of wake phenomena.

In the present contract period a method was evolved to provide a theoretical treatment of near-wake flow by means of relatively large-scale computer techniques. The theoretical results compared favorably with the previous mean-flow experiments, as shown by M. Pierucci in a report entitled: "An Axisymmetric Near Wake Analysis Using Rotational Characteristics," PIBAL Report No. 70-4, Feb. 1970. The computational methodology was complex, however, and could not be considered to be a "production program" which could be employed reliably by a person not well-versed in wake aerodynamics.

Another project on the near-wake involved experiments utilizing hot-wire anemometry to examine the turbulent fluctuations of velocity. This investigation was of limited nature and was not completed within the scope of the present program, since wake-studies were not continued under the program plan. The work was reported by P. Rosner in a masters thesis of the Polytechnic entitled: "Hot-Wire Turbulence Measurements In The Near Wake of A Slender Cone, June 1971.

An additional facet of the near wake problem involved unsteadiness, particularly in the recirculation zone. This was significant in connection with the time required for relatively steady conditions to become established after a transient condition arises. Such transients can be due to changes in the motion of the body, and due to unstable behavior of the flow itself. A theoretical approach to this subject was treated by P. M. Sforza and R. Valentine in a paper entitled: "Unsteady Flow Within A Circular Cavity," Proceedings of the IUTAM Symposium on Unsteady Boundary Layers, Laval University Press, Canada, 1972.

5. Turbulent Mixing

The mixing of adjacent streams of different velocities, temperatures and composition is a phenomenon of importance in systems of interest in this program, particularly when the flows are turbulent. The entrainment of one stream by another is basic to the growth of boundary layers, to make interactions, to the aftermath of explosions, and to the chemistry and energetics of jets, boundary layers, wakes and explosion plumes.

The studies of this problem were initiated by a critical review of the state of knowledge and interpretation of chemical reactions in turbulent mixing. They indicated the rather primitive state of affairs with regard to theory and diagnostic methods, as reported by R. F. Mons and P. M. Sforza in a paper entitled "Chemical Reactions in Compressible Turbulent Mixing Flows", AIAA Paper 69-537, 1969.

Also reported in that paper were initial results of an extended series of experimental studies of turbulent mixing mean flow properties. These were based upon requisite improvements in instrumentation, including an isokinetic gas sampling probe and associated equipment for concentration measurements in binary mixtures, and enthalpy flux and temperature probes. These results tended to affirm the phenomenological theory referred to as the "inductive theory of free turbulence of Reichardt".

Further detailed studies of mass, momentum and energy transport in free jets were reported by R. F. Mons and P. M. Sforza in "Turbulent Heat Transfer in Axisymmetric Jets", PIBAL Report 71-14, 1971. In this work, the significant influence of initial conditions was given careful attention.

Studies were also continued of wake-like flows generated by cylinders aligned with the flow and protuberances normal to the flow. In these, the effects of surface heating leading to temperature and density variations were examined, and also the effects of large-scale vortex-like superstructures were observed. The density variations resulted in "flattening" of the initially-round, horizontal wakes. These, and other non-axisymmetric effects were studied. The importance of initial conditions, and disturbances therein were carefully considered throughout. As a result of this careful experimentation, the results of previous work was validated and augmented, and the combined results considered to be suitable for final presentation. The prior work was encompassed in the report by N. P. Trentacoste and P. M. Sforza entitled "Studies in Homogeneous and Nonhomogeneous Free Turbulent Shear Flows" PIBAL Report 69-36, 1969, and the recent work summarized in a paper by P. M. Sforza entitled "Mass, Momentum and Energy Transport in Free Turbulent Mixing", Fourth Canadian Congress of Applied Mechanics, Montreal, May 1973.

6. Explosions

In addition to the studies of turbulent mixing and entrainment, a laboratory version of a spherical explosion was simulated by means of a confined exhaust from the end of a shock-tube. This experiment was reported by S. Lederman, E. F. Dawson, and P. K. Khosla in "Creation of a Spherical Shock Wave in The Atmosphere by Using a Shock Tube" PIBAL Report 72-38, Dec. 1972. Corallary to this, a computer program was set up for the behavior of spherical blast waves, particularly emphasizing the early-time history of the explosion. The details are described in a masters thesis by N. T. Truncellito entitled "Unsteady Flows Initiated by Explosion" June 1973.

7. Film Cooling

As previously mentioned in connection with the section on laser diagnostics (Section 3), the cooling of cone-tips by means of locally injected water has been studied experimentally and theoretically. A theory based upon the assumption of a steady film, including vaporization effects and mass entrainment into the boundary layer did not explain the experimental results satisfactorily. An unsteady film stability analysis was then developed and compared to the experiments. The tests were performed on a 20° half-angle cone with a hemispherical nose, at Mach 8 and per-foot Reynolds numbers between 0.2 and 1.4 million. This was reported by R. J. Cresci and J. Starkenberg in a paper entitled "Liquid Film Cooling on Hypersonic Slender Bodies", Astronautica Acta, v. 18, u. 1, 1973.

8. "Slingshot", An Aerodynamic Test Facility

In usual wind-tunnels the achievment of high Mach numbers is accompanied by diminished Reynolds numbers. A novel method of obtaining both high Reynolds numbers and high Mach numbers has been devised. The concept consists of accelerating a capsule of test gas in a gun barrel, and passing the contents of the capsule over a stationary model. The flow in the simplest form of this device is of short duration, but methods of extending the flow-times are possible. To date, 2 in. diameter capsules, 12 in. long have been accelerated to 3800 ft/sec at atmospheric densities, and test-data obtained for the heat transfer to cones. Theoretical analyses have been made of the most effective acceleration programs, and numerical studies carried out to examine shock-formation within the capsule. If the acceleration is initially low and increases with time, shock-free flow can be maintained.

This work has been described by M. H. Bloom, R. J. Cresci, G. Moretti and J. Librizzi in a paper entitled "Slingshot - An Advanced Aerodynamic Test Facility" in the Proceedings of The Seventh International Shock Tube Symposium, U. of Toronto Press, Canada, 1970. After additional work, a further paper was presented by J. Librizzi, D. Landsberg, R. J. Cresci and M. H. Bloom in "Experimental and Analytic Performance of the Slingshot Pilot Facility", AIAA Paper 72-168, 1972.

9. High Altitude Plume Gas Dynamics

Taking cognizance of existing engineering approximations to continuum plume gas-dynamics, and of complex computer analyses of the problem, a theoretical study has been carried out with emphasis on analytic approaches. This was intended to serve as a guide and comparison for approximations and numerics, and also to deal with certain intricacies such as the triple-point interaction which arises in retro-plumes. The analytic approach should also facilitate the evaluation of viscous and far-field effects. The results of this work are given in a doctoral thesis by J. T. Kelly entitled, "The Interaction of a Hypersonic Plume With an External Hypersonic Stream", June 1973 and PIBAL Report 73-12, 1973. S. Rubin served as principal advisor in this work.

Since non-continuum effects are also important for certain high altitude plumes, an analysis has been made of a rearward-facing jet which emerges from the continuum regime in the near-field and proceeds through the transition region to the rarefied regime. An analytic approach has been employed which obviates several assumptions made in related kinetic studies of subjects. It may be applied to more complex retroplume and three-dimensional configurations. The results have been presented by P. K. Khosla in "Interaction of Spherical Source Flow and Axisymmetric Free Jet with a Rarefied Background", PIBAL Report 72-25, May 1972.

10. Plasmas

The behavior and effects of plasmas in this program have been viewed from several different standpoints. One concerns the effects of shock-wave-induced radiation and thermal ionization in producing precursor ionization, as is observed in the bow-shock region of hypersonic flows over blunt bodies and retroplumes. A second concerns the breakdown phenomenon in gases adjacent to microwave antennas, particularly when the gases are pre-ionized and at elevated temperatures. A third involves the ionization effects produced by high altitude explosions in the atmosphere. A fourth involves the ionized flow produced in the shock-layers, boundary layers and wakes of high-speed vehicles. Not only the flow properties themselves, and associated observables, are of interest here, but the diagnostics for measuring flow properties reliably are of concern. For the latter, Langmuir probes, mass-spectrometry and electron beams have been employed. Finally, a small effort has been devoted to clarifying some basic points in the kinetic theory of plasmas.

These plasma-related topics are discussed in sequence.

10.A Plasmas: Precursor Effects

In prior work measurements were made of the nature of precursor ionization produced in argon and in air by shock waves exceeding March 10, in a pressure-driven shock tube. In these experiments both Langmuir probes and microwave cavities were employed as diagnostics. The present work was geared to examining the effect of microwave radiation on this precursor ionization. For this purpose, the shock tube was used as a waveguide for pulsed X-band microwaves, with peak power of several kilowatts, traveling upstream toward the oncoming shock. A range of microwave power levels was used in the experiments. Generally it was found that the velocity of the ionization wave was significantly increased in the presence of microwave radiation, and that the microwave radiation is partly absorbed by the precursor. This work is reported in a paper by E. F. Dawson and S. Lederman entitled "Effect of Microwave Radiation on a Shock-Produced Electron Precursor," The Physics of Fluids, v. 16, n. 2, Feb. 1973.

10. B Plasmas: Microwave Breakdown

Microwave breakdown in gases is a significant phenomenon in connection with antenna performance. Experiments were made to produce and examine this phenomenon at an open-end waveguide antenna, which was operated at 9.4 GHz under pulsed conditions in the presence of various gases at pressures of 0.3 and 30 Torr. The gases employed were air, argon, nitrogen, carbon dioxide and methane. An interesting feature of this set of experiments was the observation of double minima in the variation of breakdown field strength with gas pressure for certain gases at low pulse rates. This work is reported in a paper by E. F. Dawson and S. Lederman entitled "Pulsed Microwave Breakdown in Gases with a Low Degree of Ionization," Journal of Applied Physics, v. 44, n. 7, July 1973.

10. C Plasmas: Plasma Cloud Diffusion

Plasmas in the atmosphere may be produced naturally as well as by events such as explosions, releases, and high-speed vehicles. In some cases, interactions with the earth's magnetic field may be significant. Thus, an improved understanding of phenomena such as weak plasma turbulence, and the formation of striations associated with drift instabilities, can benefit the understanding of plasma cloud behavior and observation.

Studies along these lines have been carried out and reported by K. M. Chung in a paper entitled "Formation of Striations in an Electrodeless Plasma," Journal of Applied Physics, v. 40, p. 3885, 1969. They have also been reported by E. Levi in the Proceedings of Project Secede Studies of 1969 and 1970.

In connection with weak turbulence, a hollow cathode arc plasma was studied. It was shown that an increase in density fluctuation level from 1% to 25% was correlated with a 3 order-of-magnitude increase in diffusion across the magnetic field; whereas in the quiescent regions classical diffusion magnitudes were observed. The correlation time of the fluctuations correspond to the transit time of the ions along the device, indicating that the unstable modes did not reach saturation and that the effect could be amenable to linear analysis.

In connection with striations produced in laboratory experiments, it was found that field-aligned striations could be controlled, thus affecting both the growth rate and the non-linear saturation level of drift instabilities.

10.D Plasmas: Electron Beam Diagnostics of Plasma Fluctuations

A combined experimental and theoretical study has been carried out of an electron beam as it passes through a plasma which fluctuates due to noise and/or turbulence. It was of interest to relate changes in the beam to local fluctuations in the plasma along its path. The beam was passed through couplers before it entered the plasma and after it emerged. This permitted signals to be detected or impressed on or removed from the beam at these points. The most desirable plasma for this study was found to be a thermionically heated, low voltage arc discharge.

The theory was first based upon an idealized model consisting of a lateral infinite cold beam and warm plasma. Later a finite beam was considered. An explanation was evolved of the dependence of the beam-modulation on the transverse propagation constant and frequencies of the turbulent plasma.

This work has been reported in a paper by R. Eichler, R.C.E. Hutter and E. Levi entitled "Interaction Between an Electron Beam and a Turbulent

Plasma," Journal of Applied Physics, v. 43, n. 7, July 1972. A further report by R. G. E. Hutter entitled "Beam-Plasma Experiments" has been likewise submitted to the Journal of Applied Physics for publication.

10.E Plasmas: Kinetic Theory

A series of works carried out privately by T. Koga, was prepared for publication partially within the scope of this program. The work dealt with the "Difficulty and Possibility of Kinetic Theory of Quantum-Mechanical Systems" as reported in PIBAL Reports 70-26, 70-35, 70-36 dated 1970. The ideas were ultimately published in a book by T. Koga entitled: 'Introduction to Kinetic Theory: Stochastic Processes in Gaseous Systems,' Pergamon Press, New York, 1970.

11. Laser Brightness

The brightness (watts - cm^{-2} - $steradian^{-1}$) of high power lasers, such as gas dynamic and chemical lasers, is generally reduced from the optimum performance of diffraction-limited output operation. Possible contributing factors to this diminished performance are refractive index gradients and turbulence within the lasing media, and high gain of the media. It was desired to run a modest experiment to examine these factors taking advantage of the existing laser facilities at the Polytechnic, which include a visible high-gain copper-vapor laser, which is pulsed and achieves nearly diffraction-limited performance with the use of a high-loss resonator (see for reference: Chimenti, R. and Walter, W. T.: "Coherence Properties of the Pulsed Copper Vapor Laser" Bull. Amer. Phys. Soc. v. 16, p. 41, 1971). Thus it would be possible to uncouple the effects of high-gain, refractive index gradients, and turbulence, and to examine them in the visible spectral region, which then would be indicative of comparable effects in the infra-red regime.

The experiments consisted of blowing a series of controlled turbulent jets transverse to the optical cavity of the laser, thus providing defined bands of gas whose composition could be varied to influence the refractive-index pattern and turbulence level in the cavity. For comparative purposes, optical cavities of plane-parallel Fabry-Perot type and high-loss resonator type were employed. Output beam properties were monitored as to power, quality and divergence.

The initial results indicated little change in the near-field output beam pattern when a striped refractive pattern was introduced in the high-reflectance end of the Fabry-Perot cavity whose output beam divergence is much greater than the diffraction-limit because of the high gain in the lasing medium. The far-field was not examined initially. It was of interest to determine whether the non-coherent multi-modal nature of the output resulted in an integrated intensity which was not substantially different from the basic output. The introduction of a high-loss optical resonator would lead to a reduced number of transverse modes and yield information in this regard. Since increases in the magnification factor are associated with decreased sensitivity to distortion, these two factors would be traded-off in the experiment.

This effort has been led by W. T. Walter and J. LaTourrette.

12. Stratified Flow Experiments

In connection with studies of flow-fields of submerged vehicles in the stratified regions of the ocean, it was desired to establish the feasibility of simulating the appropriate conditions in the laboratory using a relatively large air-wind-tunnel as an alternative to less-convenient and costly water experiments. The Polytechnic made available its low-speed stratified-flow wind tunnel for this purpose. The test-section dimensions are 4x5x20 ft. Vertical thermal and density gradients are produced by upstream differential heating with electrical resistance elements. The tunnel was originally set up for experimentation relevant to the atmosphere, and had been calibrated with this in mind.

For the simulation of oceanic conditions, including stratification, as expressed by such parameters as the Richardson number, Vaisalla frequency and Froude number, it is necessary to establish very low velocities on the order of several feet-per-second, and to maintain the thermal gradients with significant accuracy. To this end, improvements in the heating and control system were made. Moreover, refinements in the instrumentation system were initiated. The instrumentation will involve flow-visualization with a smoke-generator, pitot-pressure and hot-wire probes on vertical and horizontal traverses, and laser-doppler velocimetry.

Since experiments of this type are difficult at best, substantial care will be required in establishing the feasibility of the method, its advantages and limitations. Items of importance range from simultaneous requirements of appropriate magnitudes of Richardson and Reynolds numbers, the nature of turbulence produced in the tests, the effects of the tunnel walls with regard to secondary currents and reflection of internal waves etc. Few if any serious attempts have been made to deal with these questions in connection with undersea simulations in air-wind-tunnels.

R. J. Cresci, G. Strom and M. H. Bloom are leading this effort.

13. Participants in the Program

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Faculty and Senior Scientific Staff	
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G. Moretti	Professor
S. G. Rubin	Associate Professor
P. M. Sforza	Associate Professor
W. T. Walter	Research Scientist