PROGRAMME OF THE

1959 DIVISIONAL MEETING

OF THE

DIVISION OF FLUID DYNAMICS

AMERICAN PHYSICAL SOCIETY

23-24-25 NOVEMBER 1959

UNIVERSITY OF MICHIGAN

ANN ARBOR, MICHIGAN

NOTE: The abstracts of the papers presented at this meeting are to appear in a forthcoming issue of the Bulletin of the American Physical Society. Any corrections which the author may wish to make must be handed to R. J. Emrich during the meeting or be mailed to him (Department of Physics, Lehigh University, Bethlehem, Pennsylvania) and reach him not later than 4 December 1959.

GENERAL PROGRAMME

<u>Sunday, November 22</u>

8:00 P.M. - 10:00 P.M. Advance Registration at Michigan Union

(Registration fee $2.50 for non-members of the Division)

$0.50 for Division Members

<u>Monday, November 23</u>

8:15 A.M. - 12:00 noon Registration at Rackham Amphitheatre
9:00 A.M. Morning Session (F. N. Frenkiel presiding)
2:30 P.M. Afternoon Session (F. H. Clauser presiding)

<u>Tuesday, November 24</u>

9:30 A.M. Morning Session (Otto Laporte presiding)
2:30 P.M. Afternoon Session (S. A. Schaaf presiding)
8:00 P.M. Divisional Banquet at Ann Arbor Town Club (W. M. Elsasser presiding)

<u>Wednesday, November 25</u>

9:00 A.M. Morning Session (G. B. Schubauer presiding)
2:30 P.M. Afternoon Session (A. M. Kuethe presiding)

ALL SESSIONS IN THE AMPHITHEATRE

HORACE RACKHAM SCHOOL OF GRADUATE STUDIES

DIVISION OF FLUID DYNAMICS

AMERICAN PHYSICAL SOCIETY

Division Formed June 20, 1947

The organization of the Division was authorized by the Council of the American Physical Society in response to a petition sponsored by the Society's Committee on Fluid Dynamics: H. L. Dryden, H. W. Emmons, J. G. Kirkwood, C. B. Millikan, R. J. Seeger (chairman), Th. von Karman and J. von Neumann.

PAST AND CURRENT OFFICERS

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J. W. Beams 1948
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H. W. Emmons 1948
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S. Chandrasekhar 1954-1957
B. Lewis 1954-1956
J. C. Evvard 1955-1957
S. A. Schaaf 1955-1958
R. J. Emrich 1956-
A. M. Kuethe 1957-1959
W. M. Elsasser 1958-
P. P. Wegener 1958-
Lester Lees 1959-

*R. W. Ladenburg deceased was succeeded by J. O. Hirschfelder as chairman and by W. Bleakney as new member of Exec. Committee.

**G. B. Schubauer was appointed after O. Laporte resigned (during his tour of duty in Japan).

MONDAY MORNING AT 9:00

WELCOME: Ralph A. Sawyer, Vice-President for Research and Dean of the Graduate School, University of Michigan. Chairman, Governing Board, American Institute of Physics.

Chairman: F. N. Frenkiel, Applied Mathematics Laboratory, David Taylor Model Basin.

A1. On the Hydrodynamics of Liquid Helium II. C. C. LIN, M.I.T. Institute for Advanced Study. (45 min).

A2. The Damping of an Oscillating Disk in Helium II.* R. J. GRIBBEN, M.I.T. (introduced by C. C. Lin). - A theoretical explanation of the experiments performed by A. C. H. Hallett on the damping of an oscillating disk in Helium II is offered on the basis of a new boundary condition on the superfluid component at the wall proposed by Lin. This boundary condition states that the superfluid component will slip along the surface to an extent that is determined by the amplitude of the oscillation and the temperature. Thus for small amplitudes there is almost complete slip and for large amplitudes almost complete adherence of the superfluid component. In a simple model where the equation for the superfluid component is considered separately and which may be expected to hold for very low temperatures (so that the concentration of normal component approaches zero) an approximate solution of the nonlinear system of equations and boundary conditions is presented. Secondly the full equations for the two components are solved in the limiting cases of small and large amplitudes and, by using experimental results, approximate values are deduced for the viscosity coefficients of the two components of Helium II.

* Supported in part by the Office of Naval Research.

A3. Theory of Transport in a Moderately Dense Rigid Sphere mixture. R. A. HARRIS and S. A. RICE, University of Chicago. A modified Boltzmann equation suitable for the description of the single distribution function in a moderately dense mixture of rigid spheres has been derived from Liouville's equation by the use of time smoothing and phase space distribution functions.[1] The solution of this equation, and the calculation of the flux vectors and the transport coefficients will be discussed. The return to equilibrium of a small perturbation in momentum space is calculated, including the first density correction to the relaxation time.

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[1] S. A. Rice, J. G. Kirkwood, J. Ross and R. W. Zwanzig, J. Chem. Phys. 31, 575 (1959).

A4. Half-Range Collision Integrals for Maxwellian Molecules. S. ZIERING, Raytheon Co. - In previous reports[1,2] treating the problems of linear shear and heat flow in parallel plate geometry, a half-range moment expansion of the distribution function was given for arbitrary values of the Knudsen number. The general case of molecules interacting with an inverse law of force $F = Kr^{-s}$ was considered. Numerical results were presented for the case of hard sphere molecules ($s = \infty$). We now give the half-range collision integrals for Maxwellian molecules ($s = 5$) which have been evaluated numerically. The problems of shear and heat flow are reconsidered in this light.

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[1] E. P. Gross and S. Ziering, Phys. Fluids I, 215 (1958).

[2] E. P. Gross and S. Ziering, "Heat Flow Between Parallel Plates," to appear in Phys. Fluids.

A5. Diffusion of a Fully Ionized Gas Confined in a Strong Magnetic Field.* TOYOKI KOGA, University of Southern California. We treat the transport phenomena of a fully ionized gas in the presence of a strong magnetic field. It is shown that there is a certain domain in the density-temperature space where the Boltzmann equation is valid. The mean free path is assumed to be longer than the mean Larmor radius. We construct an average of the Boltzmann equation along a circular trajectory of gyrating particles. By this method of coarse-graining, the Boltzmann equation is reduced to the equation of diffusion. It is not assumed that the distribution function is close to the Maxwell function. A special case of constant average energy per particle is treated in detail. The results are similar to those published by other authors, in spite of our making no specific assumption concerning the distribution function: The effect of the collisions between similar particles is negligible, and the ions and electrons diffuse almost at the same velocity. It is easily possible to apply the method to more general cases.

* Supported by Office of Scientific Research, United States Air Force.

A6. Heat Transfer and Geometry Effects in Viscous Aerodynamics.* S. A. SCHAAF, University of California. - At moderately low densities laminar boundary layer effects become of importance in altering the aerodynamic characteristics of wings and other configurations. These modifications are brought about by skin friction and displacement pressure effects, both of which are of the same general order of magnitude. It follows that heat transfer conditions may seriously affect the aerodynamic characteristics. In the present paper, theoretical calculations are carried out to determine the viscous aerodynamic characteristics of a series of simple two-dimensional wedge-shaped air foils covering a wide range of Mach and Reynolds numbers, of heat transfer conditions, and of geometry from the blunt to the slender case. The results give insight into the relative importance of the various parameters and the implications for scaling wind tunnel results to free flight conditions.

* This work was sponsored jointly by ONR, AFOSR, and GEMSVD.

A7. Studies of Sputtering by Beam Techniques.* F. C. HURLBUT, University of California and R. P. STEIN, Lockheed Missile and Space Division. - The removal of surface atoms by ion or neutral particle bombardment has become a subject of interest to the Aeronautical scientist since the energies of particle impact at satellite velocities are of the same order as the energies of chemical binding. Careful experimental work is required to provide adequate tests of the theories. In this paper an apparatus for the study of the sputtering of alkali metals as a function of beam energy and the angular parameters is described and the preliminary results are discussed in light of a simple two body collision theory.

* Work partially supported by the Office of Naval Research.

MONDAY AFTERNOON AT 2:30

Chairman: F. H. Clauser, The Johns Hopkins University.

B1. Collision-Free Shock Waves. A. KANTROWITZ, AVCO Research Laboratory. (30 min.).

B2. An Approximation to the Plasma Density Near a Spherical Satellite. C. L. DOLPH, University of Michigan (introduced by K. M. Siegel). - A first approximation to electron and ion density near a spherical satellite at an altitude of 300 miles has been computed from the solution of the collision and force free Boltzmann equation obtained by S. Wang Chang (Transport Phenomena in Very Dilute Gases, II, UMH-3F-University of Michigan, December 1950.) under the hypothesis of electrical neutrality for diffuse boundary conditions on the sphere. More explicitly, it is argued that because of the small charge on the sphere, the ions will in the first approximation follow the same density distribution as neutral particles and that the large static electrical forces present in a fully ionized plasma will in turn force the electron distribution to be of approximately the same form as the ion distribution. The result of this calculation reveals the existence of a cavity behind the satellite extending approximately fifty radii down stream for a molecular speed ratio of five. The Chang distribution and the results obtained from it will be used as the starting point of a perturbation process in subsequent work.

B3. Steady State Solutions of the Radiofrequency Discharge with Flow. MARY F. ROMIG, Convair Scientific Research Laboratory. The electron density distribution and diffusion length has been investigated analytically for a radio-frequency discharge acting over a finite portion of an infinite cylinder in which there is a uniform axial gas flow. This geometry simulates to some extent flow in a plasma tunnel.[1] The peak of the electron density distribution shifts downstream as a function of the gas flow parameter but never leaves the region of production. A quantitative relationship has been obtained for the influence of active cylinder length and gas flow parameter upon the diffusion length.

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[1] H. U. Eckert, J. Aero/Space Sciences 26, 8 (1959).

B4. Plasma Flow Over a Thin Charged Conductor. H. YOSHIHARA, (introduced by J. Bond) - The flow of a dense plasma over a two dimensional thin conductor is investigated where the free stream velocity is subsonic and supersonic with respect to the electron and positive ion thermal speeds respectively. Magnetic effects are assumed to be absent, and only electrostatic effects are considered. By postulate the governing equations for the ion motion are taken as the Euler equations whereas for the electrons, thermodynamic equilibrium under the electrostatic force field is assumed. Poisson's equation completes the system of equations. By assuming the existence of a velocity potential for the ion motion the basic equations can be reduced to a single, linear, fourth-order partial differential equation for the electrostatic potential or the ion velocity potential which is two-fold elliptic and two-fold hyperbolic. The flow over a sinusoidal wall is then analyzed, and the results used to determine the flow over a symmetric cusped body formed by segments of the sinusoidal wall. The results show that the electrostatic potential field divides into two regions, the Debye boundary layer adjacent to the wall, and the field external to this. Within the Debye layer the potential reflected predominantly an "elliptic" character (exponential attenuation normal to the wall) being directly related to the surface charge. In the external region the character of the field was of the "hyperbolic" type with a modified characteristic speed. The potential field here was independent of the electrostatic state of the wall, being shielded by the Debye layer. The Coulomb drag was found to be zero in this case, while the fluid pressure drag corresponded to the Ackeret value for a neutral particle gas at the reduced plasma Mach number.

B5. Magnetohydrodynamic Channel Flow of a Perfect Gas for the Generation of Electrical Power*. G. W. SUTTON, General Electric Company. - The steady quasi-one dimensional inviscid flow of a gas with a scalar conductivity is considered in a channel with mutually perpendicular electric and magnetic fields at right angles to the flow direction. The solution for constant area flow and constant electrical conductivity has been previously obtained.[1] The solutions for constant temperature, constant pressure, constant density, and constant velocity flow are presented; the last for a conductivity that possesses p power dependence on temperature. The equations are specialized to the case of generation of electrical power by the induced electromotive force. Calculations are made of the lengths required to extract a given fraction of initial total enthalpy as electrical power. The constant velocity flow yields the minimum length while the constant pressure flow has the least increase in cross sectional area. Limitations of the calculations are discussed.

* Sponsored by the U. S. Air Force, Ballistic Missile Division.

[1] E. L. Resler and W. R. Sears, J. Aero. Sci., 25, 235.

B6. Radial Plasma Accelerator. B. PODOLSKY and G. BORMAN, General Electric Company Flight Propulsion Laboratory. - A problem of radial acceleration of a conducting inviscid ideal gas was solved by a numerical integration of the appropriate differential equations. Using cylindrical coordinate system (r, Θ, z) the electric field was assumed to be constant and in the z-direction and the magnetic field in the Θ-direction and inversely proportional to r. The following simplifying assumptions were made: conductivity was assumed to be a constant scalar, the flow was assumed to be radial in direction and a function of r only, magnetic Reynolds number was assumed small and thermal conductivity was assumed to be zero. Analysis of the results showed the existence of a simple asymptotic form of solution applicable within the range of interest in space vehicle propulsion.

B7. Plasma Propulsion.* G. L. CANN and A. C. DUCATI, Plasmadyne (introduced by G. Giannini). - The results of two years of experimental and analytical studies on plasma propulsion are presented. Emphasis is placed on the over-all system capabilities of various propellant substances. Propellants have been chosen for detailed study using the criteria of: specific impulse capability, efficiency of converting electrical power into effective jet power, ease and efficiency of storage, availability and cost, and flexibility of propulsor performance. The propulsion studies can be broken down as follows: (1) A generalized rocket analysis was made to determine desirable specific impulse, ratio of propellant-to-powerplant mass, ratio of total rocket-to-payload mass, effect of propellant tank structure constant and other relevant parameters as a function of the mission requirements;

(2) A number of substances that looked promising from preliminary considerations were picked and their thermodynamic properties have been computed and plotted on Mollier charts. To date, argon, helium, lithium, lithium hydride and hydrogen have been completed. Methane, water and ammonia are being worked on at present; (3) A rather elaborate facility has been designed around a cantilever suspension of the plasma jet head, constructed and put into operation for actually measuring the specific impulse, electric energy to jet energy conversion efficiency, and other relevant parameters for plasma jets exhausting into an ambient pressure as low as one mm of mercury. Specific impulses of 1100-1200 seconds at efficiences of 50-60 per cent for helium and 1500 seconds for hydrogen have been measured to date in this equipment. Fundamental studies of energy and momentum exchange between the electric field and the gas have been initiated in order to increase the efficiency of the energy transfer process. To obtain a more detailed knowledge of the jet, a total pressure probe has been designed and used to measure the radial distribution of total pressure. Thrusts have been computed from these measurements and correlated with the actual thrust measurements.

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* Supported by the United States Air Force.

B8. A Generalization of Kutta-Joukowsky-Filon Theorem to Magnetohydrodynamics. HIDENORI HASIMOTO, The Johns Hopkins University (introduced by L. S. G. Kovasznay). - A cylindrical body immersed in an incompressible viscous electrically conducting fluid having a parallel uniform velocity and a parallel uniform magnetic field at infinity (they may form an arbitrary angle but they are both perpendicular to the generator of the cylinder) is the subject of the analysis. Contour integrals of the velocity and of the magnetic field can offer formulae for the lift and drag in an analogous manner to the well known theorems for non-conducting fluids.

B9. Shock Tube Studies of Electric Breakdown in High Temperature Nitrogen. D. R. WHITE, A. H. SHARBAUGH, P. K. WATSON, T. H. LEE and A. GREENWOOD, General Electric Company. - In a series of exploratory experiments, an 18 μsec voltage pulse was used to produce a semi-uniform electric field between plane electrodes 1 cm. apart in an 8.25 cm. shock tube. In most cases an incident shock wave technique was used, so that gas temperature and velocity were not independent, maximum values of 3000°K and 2×10^5 cm./sec. being obtained. A density of 0.25 amagat was maintained throughout so that a constant value of breakdown potential would be expected according to Paschen's Law. The breakdown voltage was observed to rise with increasing shock strength, reaching a maximum at about 1000°K which is about 15% above the static value. With further increase in temperature the strength falls, and at 3000°K is about one-half its static value. The initial increase is attributed to the effect of gas velocity, probably enhanced by the non-uniformity of the electric field; and the subsequent decrease, to thermal ionization. The arc drop increased rapidly with time behind the incident shock; however, in the reflected shock experiments the arc drop remained relatively constant in the nearly stagnant gas.

TUESDAY MORNING AT 9:30

Chairman: Otto Laporte, University of Michigan.

C1. Stability and Instability Phenomena in Rotating Fluids.

DAVE FULTZ, University of Chicago. (30 min.).

C2. Nonlinear Effects in Convection Problems. F. E. BISSHOPP, Brown University (introduced by W. H. Reid). - The nonlinear equations governing thermally induced convective motions in a plane liquid layer of infinite extent have been examined with the intent to determine solutions by a perturbation theory. The problem has been treated in the Boussinesq approximation and the following assumptions have been made: (1) that the motions appear in a periodic array of regular polygonal cells and that they are time-independent; (2) that in the Fourier decomposition employed in the description of the horizontal periodicity the terms derived from the fundamental wave-vectors all have the same functional dependence on z; (3) that the harmonic terms in the expansion are less than the fundamental terms by at least an order of magnitude. In addition to giving the form and amplitude of the motions, the theory admits the explicit evaluation of the change in size of the cells in the finite-amplitude region. Though the change in size appears to be negligible in practice, the manner in which it enters the theory demonstrates that it cannot be entirely disregarded, for it is among the most fundamental aspects of this and similar problems.

C3. Viscous Force and Torque Constants of a Cylindrical Particle. S. BROERSMA, University of Oklahoma. - The viscous flow constants of a cylinder have been calculated on the basis of the Oseen-Burgers method, including width/length (b/a) terms. With these constants being inversely proportional to $\log(2a/b)-\gamma$, the average result for γ is 1.4 for the case of rotation 1.1 for translation lengthwise and 0.2 for translation sideways. Experimental results obtained with macrosopic models agree within the precision of γ (± 0.2). This is 10% if the constants of the cylinder and the corresponding ellipsoid do not differ more than about 50%. Values found for the rotational diffusion constant of a cylindrical virus in water (O'Konski and Haltner) also fit within 10%. Using Oberbeck's equations it can be shown that the O-B method is exact to a first order. Furthermore, second order terms enable us to satisfy the condition of non-slipping at the surface for the velocity components perpendicular to the principal direction. The corresponding second order term in the equation for the principal velocity thus can be obtained. For objects with sharp edges a machine computation with a limited number of force centers is to be preferred over an approximate analytical solution.

C4. Epihydrodynamics: The Dynamics of Liquids Under the Action of Surface Tension Forces. E. T. BENEDIKT, Norair. - Situations in which gravity (or, equivalently, inertial forces) suddenly cease to act upon liquids with free surfaces frequently present themselves in space technology. In such cases, the liquid will move under the action of surface tension forces in such a manner as to change its initial configuration to one (generally a sphere) corresponding to a minimum of surface energy. The dynamics of such processes will be discussed. Examples confirming the results of previous estimates[1] will be reviewed.

[1] E. T. Benedikt, Scale of Separation Phenomena in Liquids under Conditions of Nearly Free Fall, ARS Journal, 29, 150 (1959).

C5. On the Role of Large Eddies in Shear Layers. R. WESKE, University of Maryland. - Investigation of the structure of vortices extending across the shear layer along a plate proves these to be of special significance since their analysis shows that direct mutuality exists between these vortices and a mass transport normal to the surface. The process of formation of these vortices and the three-dimensional flow within them can be related to the mechanics of rotational flows and of the pattern of viscous flow in vortices. Relations for the size of individual vortices and for their spacing within the shear layer have been defined and determined experimentally.

C6. Analysis of Multipoint-Multitime Correlations and Diffusion in Decaying Homogeneous Turbulence. R. G. DEISSLER, Lewis Research Center, NASA (introduced by J. W. Blue). - A two-point, two-time correlation equation is obtained by considering the Navier-Stokes equations for two points in a turbulent fluid at two different times. By neglecting the triple correlations in the equation, a solution is obtained for the final period of decay. It is found that the time correlation coefficient is independent of time separation for that period. The spread of the diffusion wake from a line source in a decaying turbulent stream is also calculated approximately. The analysis is extended to earlier times by considering the Navier-Stokes equations at three points in the fluid at three different times. The resulting set of equations is made determinate by neglecting the quadruple correlations in comparison with the triple correlations as in a previous paper.[1] The time correlations at still earlier times could be obtained by considering the turbulent fluid at a larger number of points and times.

The theoretical results for diffusion from a line source are similar to those obtained experimentally.

[1] R. G. Deissler, Phys. Fluids 1, 111 (1958).

C7. Decay of Temperature Fluctuations in Homogeneous Turbulance Before the Final Period. A. L. LOEFFLER, JR., and R. G. DEISSLER, Lewis Research Center, NASA. (introduced by J. W. Blue). - A previous analysis (1) of homogeneous turbulence for times before the final period has been extended to the case of temperature fluctuations in a homogeneous turbulence. The method consists essentially of simultaneous solution of the 2- and 3- point Fourier-transformed temperature equations after neglecting the fourth order correlations in comparison with the second and third order correlations. Results are obtained for the convective transfer function, the spectral "energy" Comparison is made between the analysis and experimental data obtained using air (2). The decay law obtained may be written $\overline{T^2} = A(t-t_o)^{-\frac{3}{2}} + B(t-t_o)^{-5}$ where $\overline{T^2}$ is the total "energy" (the mean square of the temperature fluctuations), t is the time and A and t_o are constants determined by the initial conditions. The constant B depends on both initial conditions and the fluid Prandtl number. For large times the last term becomes negligible leaving the -3/2 power decay law for the final period previously found by Corrsin (3).

(1) R. G. Deissler, The Physics of Fluids 1, 111 (1958).

(2) R. R. Mills, et. al., NACA TN 4288, August, 1958.

(3) Stanley Corrsin, Journal of the Aeronautical Sciences 18, 417 (1951).

C8. On Laminar Free Convection Flows in Cavities.* V. C. LIU and HOWARD JEW, University of Michigan. - A theory is developed for the velocity and temperature fields due to laminar free convection in two dimensional cavities, closed at the bottom and opening into a reservoir of cool fluid at the top . The outstanding feature of the present problem concerns the effect of confinement and heat conduction at the walls on the laminar free convection flow of a fluid in an external force field. It thus involves the interaction of the velocity and the temperature field. In an earlier study by Lighthill,[1] some estimates of the useful heat transfer and flow parameters for special cases were obtained by approximate methods of solution (of the Karman-Pohlhausen type) to the boundary layer equations. The present paper gives a general solution of the flow by solving the boundary value problem with the Navier-Stokes equations and the equation of heat transfer. A numerical method is developed based on the use of orthogonal polynomials which reduces the solution of the governing equations to the numerical solution of two sets of coupled algebraic equations. The numerical analysis by iteration process is accomplished with an electronic digital computer. Streamlines and isothermals have been plotted for various values of Rayleigh number. The basic postulates used in the previous approximate analyses of the problem[1] are examined based on the results of the present exact analysis.

* Supported in part by the U.S. Signal Corps and Air Force Cambridge Research Center.

[1] M. J. Lighthill, Quart. J. Mech. & Appl. Math. 6, 398 (1953).

C9. A Boundary Layer Related to the Bath Outflow Problem. R. F. CHISNELL, M.I.T. (introduced by George Backus). - A circular disc is considered for a mainstream $U = -m/r^2 + \Omega/r$, where r is the distance along the disc from its centre. This mainstream represents a sink at the centre of the disc and a line vortex passing through the centre of the disc. The radial momentum equation is satisfied on the disc and integrals of the radial and transverse momentum equations, based on Timman's profiles, are also used. Two ordinary differential equations are solved numerically for a form parameter in the radial velocity and the ratio of the radial and transverse boundary layer thicknesses as functions of r. The integrations are performed for several values of the parameter $\Omega r_1/m$, where r_1 is the radius of the disc. The author believes that the transport of vorticity in the boundary layer toward the centre of the disc is connected with the growth of the vortex above the plug-hole in outflow from a bath.

TUESDAY AFTERNOON AT 2:30

Chairman: S. A. Schaaf, University of California.

D1. Plasma Turbulence. L. S. G. KOVASZNAY, The Johns Hopkins University and Space Technology Laboratories. (30 min.).

D2. A Magnetically Insulated Shock Tube. R. G. FOWLER and E. B. TURNER, Space Technology Laboratories. - Preliminary results are reported on a type of electrical discharge shock tube utilizing a longitudinal magnetic field. The purpose of the field is to inhibit heat transfer to the walls of the tube thereby allowing a higher temperature plasma in the electrical discharge section of the tube and reducing the attenuation of the resulting shock wave. A linear geometry is used to simplify the analysis. The magnetic field of up to 18,000 gauss is produced by a capacitor discharge through a solenoid coil enclosing the tube. The shock tube is made of 1-inch pyrex pipe 3 ft long. The gaseous discharge from a 50 μf, 8kv capacitor bank takes place between a ring electrode and a button electrode spaced 6 inches or 9 inches apart. The electrodes are split to admit the magnetic field. Experimental results show a decrease in the resistance and inductance of the gaseous discharge with an increase in field. The latter is due to inhibiting a pinch with the longitudinal magnetic field. The shock velocity at 30 cm from the ring electrode, for example, is increased from $M_s = 26$ to 46 by a 12,000 gauss field at 150μ pressure of D_2. At 40μ pressure and 18,000 gauss a luminous front moving at more than 20 cm/μsec is observed.

D3. Electrons as a Shock Driver*. R. G. FOWLER and G. W. PAXTON, University of Oklahoma. - The electric shock tube, under close scrutiny, generally exhibits two basic, consecutive luminous fronts which display the superficial characteristics of shocks. Careful timing studies have shown that the first of these is set in motion much too promptly to originate in energy stored in the thermal motion of the massive particles of the system although the second one is delayed by the appropriate time to be a thermal shock. Other characteristics also seem to indicate that the early front is related to the electron temperature rather than gas temperature, so that in some sense at least we believe that the first front is driven by the pressure of the electron gas.

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* Supported by the United States Office of Naval Research.

D4. Nonstationary Electron Diffusion Processes Ahead of Strong Shock Waves.* H. D. WEYMANN, University of Maryland. - Detailed investigations with a previously developed electrostatic probe[1] showed that a strongly nonstationary electron diffusion process accompanies the propagation of strong shocks (M_s about 10) into argon. The signals obtained with the electrostatic probe show rather sharp fronts, the velocities of which have been determined as a function of the distance from the shock front and the time. Between the breaking of the diaphragm and the first appearance of the diffusion signal there is a delay time which depends in a characteristic way on the diaphragm material and the relaxation time for ionization of the gas.

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* Supported in part by the Air Force Office of Scientific Research.

[1] H. D. Weymann, "On the mechanism of thermal ionization behind strong shock waves", Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park, Tech. Note BN-144, July 1958.

D5. Electrostatic Effects in Shock Tube Flow.* F. A. GROSSE, Lehigh University (introduced by David Weimer). - A narrow copper foil wrapped around the outside of a Lucite or glass shock tube is connected to the input terminal of an oscilloscope. There is no closed circuit to ground. With the arrival at the foil of the shock in nitrogen gas, a voltage pulse is observed. The magnitude and duration of this pulse vary with shock strength, typical values being 0.025 volts for $M_s = 1.2$ and 5 volts for $M_s = 7$. The form of the pulse depends upon the distance of the foil from the diaphragm. Following the initial pulse, irreproducible voltage variations are observed as the cold front approaches the foil. The charge conveyed to the foil during the first few hundred microseconds is of the order 10^{-10} coulombs. Equilibrium ionization in nitrogen at the shock strengths involved is such that even complete separation of ions and electrons from the entire body of hot gas would supply only 10^{-30} coulombs. Even such an easily ionized impurity as sodium could not account for the charge accumulated for the weak shock case. One wonders whether there is charge separation with the establishment of shear flow in the gas boundary layer.

* Supported by the National Science Foundation.

D6. Studies of the Luminous Gas Behind Reflected Shock Waves: I. L. R. DOHERTY, University of Michigan (introduced by Otto Laporte). - The stationary gas volume produced by strong shock reflection in a one-dimensional shock tube is now a familiar spectroscopic source. Uniform flow theory predicts the state of this gas from the primary shock speed alone; however, wall effects in the primary flow require that corrections of this state be made, particularly for experiments in which the details of line spectra are sensitively dependent on the thermodynamic variables. The disagreement between predicted and observed reflected shock speeds in neon has been used to evaluate an added momentum term in the conservation equations. This term provides empirical corrections of the state variables for that portion of the flow which is brought to rest in the spectrographic line of sight. The agreement of spectroscopic and hydrodynamic temperature in the stationary gas has also been investigated. Calculations of radiative and collisional rates of atomic excitation show that the absence of a Planck radiation field produces only small deviations from thermodynamic equilibrium at typical shock tube densities. Time-resolved spectra of the luminosity near the end wall in neon-hydrogen mixtures have been photographed and calibrated with a carbon arc. Absolute intersities and line widths for H_β are consistent with a model of the stationary gas using equilibrium radiation laws and the proposed hydrodynamic corrections.

D7. Studies of the Luminous Gas Behind Reflected Shock Waves: II. T. D. WILKERSON, University of Michigan. - Time-resolved emission spectra of CrI and CrII are obtained from the gas behind primary and reflected shock waves in a one-dimensional shock tube. The pre-mixed test gas is neon with at most 3/10 % $Cr(CO)_6$ vapor. Heterochromatic photometry is applied to measurements of CrI line intensities behind the reflected shock. Films are calibrated with a standard carbon arc and a General Electric FT-230 xenon flash lamp. In experiments for which the chromium abundance (and hence the optical depth) is small, CrI excitation temperature $T \sim 5000$°K., then $T_E \sim T$; but, contrary to expectation, T_E is only about 6000°K. for T $\sim$ 10,000°K. This discrepancy is not caused by a severe failure of the shock equations or by a lack of thermal equilibrium, but is due instead to (1) extreme CrI ionization at high temperature and low abundance, and (2) the existence of a thermal transition layer which insulates the main body of gas from the tube walls. Over 95% of the emitted light originates in the transition layer at an effective temperature of 6000°K. to 6500°K. A lower bound on the layer effects is provided by an isobaric, zero-velocity heat conduction model which includes the temperature variation of thermal conductivity. Discussion will also be given of pressure measurements with a Kistler PZ-6S transducer.

D8. Heat Transfer from Dissociated Oxygen in a Shock Tube.* R. A. HARTUNIAN and P. V. MARRONE, Cornell Aeronautical Laboratory, Inc. (introduced by C. E. Treanor). - Measurements of the heat transfer from dissociated oxygen to the sidewalls of a shock tube and to the stagnation point of a circular cylinder have been made with up to 40% dissociation in the former and 90% in the latter experiments. In most of the experiments the gas was in thermochemical equilibrium throughout. Extensive numerical solutions of the equilibrium shock-tube wall boundary-layer equations have been obtained using several values of the Lewis and Prandtl numbers. Variation of the product of the density and viscosity through the boundary layer was included. Comparison of the sidewall and stagnation point experimental results with the appropriate theoretical solutions leads to information on the transport properties of dissociated oxygen. Modifications to the thin-film thermometer technique were developed whereby the effects of surface catalytic efficiency on the heat transfer from a dissociated gas could be studied. The results of exploratory experiments using this technique will be discussed.

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* This research was supported by the United States Air Force.

D9. Shock-Initiated Detonations. R. A. STREHLOW and ARTHUR COHEN, Ballistic Research Laboratories. - The initiation of detonation is being studied using a 4-inch I. D. shock tube which has been specially constructed to prevent premature detonation of highly exothermic gas mixtures. The initiation is observed behind the reflected shock using an 8-inch schlieren system which can look at flow behavior (x - t photographs) at the back wall of the shock tube. Data have been taken in hydrogen-oxygen-argon mixtures containing 70 percent or more argon. Results indicate that the detonation is formed from a pressure wave generated by an adiabatic explosion occurring near the back wall. In the hydrogen-oxygen system the detonation wave is followed by a well defined reaction zone which slowly approaches the detonation front. In weak mixtures (ca. 94% argon) the pressure wave has not been observed to form a separate detonation but simply accelerates the reflected shock wave. This pressure wave is followed by a reaction wave which slowly approaches the reflected shock. The measured delays to adiabatic explosion are being used to study the over-all kinetics of the hydrogen-oxygen reaction.

D10. Ionization In Seeded Detonation Waves.* S. BASU and J. A. Fay, M.I.T. - Using a vertical detonation tube, aerosols of fine Potassium Acetylide (C_2HK) were generated in equimolal oxy-acetylene mixtures at 1/10 atmosphere initial pressure. The concentration of the powder at the test section was determined by a sedimentation technique. Detonations were initiated in the aerosol and the electrial conductivity of the gas behind the detonation front was measured using Lin's method.[1] The measured values were compared with theoretical results based on thermodynamic equilibrium calculations, which included the cooling effect due to the heat capacity of the additive. Predicted and measured conductivities have approximately the same dependence on the mole fraction of Potassium which was varied from 10^{-3} to 10^{-1}. With a value of 10^{-15} sq. cm. for the electron-gas (CO, H, and H_2) collision cross section, absolute values agreed within a factor of two, the agreement improving with increasing mole fraction of Potassium. A value of 2 x 10^{-15} sq. cm. gave good agreement between theory and experiment. The maximum measured conductivity was 2.7 mho/cm and occurred at 3% Potassium in the product gases.

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* This work supported by the Office of Naval Research.

[1] S. C. Lin, E. L. Resler, and A. Kantrowitz, J. Appl. Phys. 26, 95 (1955).

TUESDAY EVENING AT 8:00

BANQUET OF THE DIVISION

Ann Arbor Town Club, 210 W. Washington Street

Chairman: W. M. Elsasser, Scripps Institution of Oceanography, University of California

Speakers:

G. E. UHLENBECK, University of Michigan, President, American Physical Society.

REMARKS

MARSHALL TULIN, formerly Scientific Liaison Officer, Office of Naval Research, London Branch.

FLUID DYNAMICS RESEARCH IN EUROPE

WEDNESDAY MORNING AT 9:30

Chairman: G. B. Schubauer, National Bureau of Standards.

E1. On a Nonlinear Theory of Three-Dimensional Oscillations in Shear Flows.* D. J. BENNEY and C. C. LIN, M.I.T. - Three-dimensional periodic oscillations in the shear flow region between two parallel streams are considered up to the second order of the oscillation amplitude. It is shown that, as an integral part of the oscillation, there is a steady secondary flow in the nature of a longitudinal vortex. The intensity of this secondary flow is everywhere of the order of $a^2(\alpha R)^{1/3}$, where a is spanwise variation of the amplitude of the oscillation outside of the critical layer, and $(\alpha R)^{1/3}$ is the familiar factor associated with its thickness (R being the Reynolds number of the basic flow, and α being the wave number of the primary oscillation). It is suggested that this is one of the important features of three-dimensional effects in the process of transition and fully-developed turbulence. Despite the dissimilarity in the profile of the basic flow, several of the principal features of the calculated results can be compared with those observed for the Blasius flow by Schubauer, Klebanoff and Tidstrom at the National Bureau of Standards.

* Supported in part by the Office of Naval Research.

E2. The Growth of Localized Disturbances in a Laminar Boundary Layer. W. O. CRIMINALE, JR. and L. S. G. KOVASZNAY, The Johns Hopkins University. - The classical laminar instability theory predicts the growth (or decay) rate and phase velocity of two-dimensional small disturbance waves. In order to study the growth and "diffraction" of a localized spot-like disturbance, the initial disturbance is synthesized from all possible waves whose propagation velocities and amplification rates follow from the two-dimensional theory by Squire's generalization. The initial period can be solved explicitly and the asymptotic behavior is also predicted. Further inferences can be made concerning the role which localized disturbances can play in ultimate transitions to turbulent motion.

E3. Cross Waves. L. N. HOWARD, M.I.T. (introduced by C. C. Lin). - A study has been made of standing water waves of finite amplitude in a deep rectangular box, using the second-order theory of surface waves. The waves can be thought of as driven by periodic motion of the ends of the box, near the resonant frequency for a two-dimensional wave. Under certain conditions it is found that besides the ordinary two-dimensional standing wave, there is another solution, with a three-dimensional character, usually at half the driving frequency. With suitable values of the amplitude of the driving oscillation and the ratio of width to length of the box this three dimensional wave consists principally of a two dimensional half-frequency standing wave with crests perpendicular to the vibrating ends. In general the "cross-wave" solution is possible only if the driving amplitude is relatively large, but in special cases it can be excited very easily and can attain an amplitude much larger than that of the ordinary two-dimensional wave. Cross-waves at the full frequency are also possible under suitable conditions. A few qualitative observations of this phenomenon have been reported incidentally by G. I. Taylor in his experimental study of standing waves of large amplitude.

E4. Experiments on Transition to Turbulent Flow in a Tube.*
A. M. KUETHE, University of Michigan and K. R. RAMAN, Lockheed Missile and Space Division. - Hot-wire measurements of velocity fluctuations, Reynolds stresses, and shearing stresses at the wall in the transition region of a tube are presented. Transition was excited by annular projections at the wall and by annular wire rings at different radial positions in the fully-developed laminar flow 620 diameters downstream of the entrance. The results show that the transition Reynolds number is a function of the magnitude of the disturbance. Measurements at a Reynolds number of 6000 show further that the velocity fluctuations, Reynolds stresses and the wall shearing stress during the early stages of transition can reach values considerably higher than those in the fully-developed turbulent flow. Implications are pointed out regarding possible causes for the high temperature recovery factor during transition in high speed flow over surfaces.

* This work was supported by the U. S. Air Force Office of Scientific Research.

E5. Measurements of the Pressure Field at the Boundary of a Fully Developed Turbulent Pipe Flow. G. M. CORCOS and W. VON WINKLE, University of California (introduced by L. Talbot). - Some characteristics of the turbulent pressure field at the wall of a pipe have been measured. They include root-mean square pressure levels, frequency spectra, longitudinal space-time correlations and some preliminary measurements of lateral space-time correlations. The data demonstrate a close similarity to those of Willmarth[1] for corresponding measurements at the wall of a boundary layer. The magnitude of the R. M. S. pressure levels is found to be of the same order in both cases. Longitudinal space-time correlations exhibit in the pipe (as well as in the boundary layer) the existence of an apparent downstream convection of the pressure field at a rate which is a fixed fraction of the characteristic mean discharge velocity of the pipe flow. However, evidence was found that the pressure field is not only convected but also dispersed within time intervals smaller than the (convective) time scale: The frequency spectral resolution of the longitudinal space-time correlation yields a relationship between convection velocity and frequency, higher frequencies being convected more slowly than lower ones. Preliminary measurements indicate that a characteristic length for lateral space correlation is of the same order as that for longitudinal space correlation for simultaneous measurements.

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[1] W. W. Willmarth, "Space-time correlations and spectra of wall pressure in a turbulent boundary layer," NASA Memorandum 3-17-59W.

E6. Theoretical Investigations of the Effects of the Uniform Injection of Gases into the Laminar Boundary Layer of a Supersonic Stream of Air in a Tube. S. I. FREEDMAN, J. R. RADBILL and JOSEPH KAYE, M.I.T. and Aerojet-General Corporation. - Theoretical calculations of the effects of diffusion of helium, air, argon and iodine into the laminar boundary layer of a supersonic stream of air in a tube are reported. Transport properties were calculated using the N.B.S. values for air and a Lennard-Jones 6-12 potential for the other gases. Results for perfect gas behavior indicate the effect of variations in the thermodynamic and transport propeties of a binary mixture on the temperature recovery factor. Calculations for the recovery factor along the tube with uniform air or uniform argon injection agree within 1% with experiments, to be reported in detail separately. Calculations for uniform injection of helium predict an 8% rise in the recovery factor while experiments show a 1% rise. This difference, between theory and experiments for uniform injection of helium, may be attributed to an inadequacy in the usual combination rule for the depth of the potential-well parameter of a helium-air mixture. These results for uniform injection agree with experiments and show only very small (2%) changes in the recovery factor in contrast to the large (40%) reductions predicted for injection with the rate inversely proportional to the square root of the distance from the leading edge.

E7. Velocity Measurements in Thin Boundary Layers.* S. J. LUKASIK, C. E. GROSCH, Stevens Institute of Technology. - Conventional probe techniques for measuring fluid velocities in boundary layers encounter difficulties when the boundary layer is thin, i.e. of the order of the probe dimension. Following the work of Geller[1] a technique has been developed employing electrolytically generated bubbles that avoids this difficulty and is, furthermore, well adapted to making rapidly complete velocity profile measurements in unsteady flows. A motion picture camera is fitted with a commutator to generate an electrical pulse at each shutter opening. Every 10th pulse is written on a recorder to provide a speed record and every 100th pulse triggers a current discharge through a 0.003 in. Pt wire immersed in an electrolytic fluid. The camera photographs the subsequent motion of the bubbles that are formed. Analysis of the resultant photographic record provides a complete velocity profile within a time interval of the order of 10 frames and a profile is obtained at time intervals of 100 frames. Measurements of the velocity profile in the flow of water between infinite parallel plates of 1/2 in. separation and at mean velocities of the order of 1 in/sec will be presented. The processes of bubble formation, release from the wire, acceleration in the flow and the application to the measurement of the boundary layer under a shallow water wave will be discussed.

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* Work supported by the U. S. Navy, Bureau of Ships.

[1] E. W. Geller, M. S. Thesis, Mississippi State University (1954).

E8. Study of Shock Tube Boundary Layer Structure with Oil Drop Tracers.* CHE-JEN CHEN and R. J. EMRICH, Lehigh University. - Octoil-S loaded with titanium dioxide powder is sprayed into a glass walled shock tube channel with an atomizer. After all droplets larger than 1 micron have settled out (about 4 minutes), the shock tube is operated and a flow is established in the air containing the fog of oil drops. Motion of some droplets is measured by a micrographic camera (magnification 16), focused on a plane within the tube which is illuminated by an oscillating spark. Scattered light from the particles produces a series of streaks for each. Since a 1 micron particle acquires 99 percent of the flow velocity within 5 microseconds, it is felt that the velocity distribution of the droplets is a good measure of the flow. Both laminar and turbulent profiles have been plotted. In the region y/δ less than 0.1, the profiles depart markedly from Mirels' laminar prediction and the 1/7 or 1/10 power turbulent profiles usually used. It appears that the velocity at the wall is not zero, since the observed velocity at 5 microns from the wall is 50 times the velocity predicted by Mirels using the no-slip condition.

* Supported by ONR and NSF.

E9. A Theory for the Laminar Sublayer of a Turbulent Flow. J. STERNBERG, Ballistic Research Laboratories. - We find that the laminar sublayer is the region where the large scale eddies containing most of the turbulent energy are damped by viscosity; the existence of such a dissipative layer near the wall was first deduced by Townsend.[1] As a first approximation, the turbulent fluctuations in the laminar sublayer satisfy the same equations as the fluctuations in a laminar boundary layer in the viscous region near the wall. In accordance with the present theory, Taylor's hypothesis does not apply to the large scale eddies near the wall. This conclusion rests on both theoretical considerations and existing experimental correlation data. The $\overline{u^2}$ spectra, and the u' variation through the sublayer, can be computed from one measurement of the $\overline{u^2}$ frequency spectrum within the sublayer at a known distance from the wall. Comparisons of the theory with existing measurements show reasonably good agreement. The variation of the turbulent shear stress $\overline{\rho uv}$ entering the sublayer and other experimentally observed features outside the sublayer are quantatively consistent with this model. Using this theory to examine the effect of free stream turbulence on laminar boundary layer transition, it appears that the physical model underlying Taylor's parameter is incorrect.

[1] A. A. Townsend, Proc. Cambridge Phil. Soc. 47, 375 (1951).

E10. On Calculating Momentum Thickness of Turbulent Bounday Layers. - E. M. DRAM, United Aircraft Corporation. - The transformation $\Theta = \theta R_{\theta}^{k_1}$

originally applied by Buri enables solution of the von Karman momentum equation by simple quadrature. Maskell and others further justified the use of this transformation for the calculation of the momentum thickness for two-dimensional airfoil flows. In this author's attempt to apply this transformation to axisymmetric conical and annular diffuser flows and paeudo-two-dimensional channel flows, it was determined that each type of flow dictates a different coefficient for the transformed differential equation for such flows is obtained if the transformation $\bar{\Theta} = \Theta L R_\Theta^{k_2}$ is used, where L denotes a characteristic length such as the diameter for conical flows or the diffuser height or breadth for channel flows. The solution takes the form

$$\Theta = \left\{\frac{1}{L}\left(\frac{\nu}{U_1^{5.105}}\right)^{0.2155}\left[0.060 \int_{x_o}^{x} U_1^{5.105} dx + \left(\Theta L R_\Theta^{0.2155} U_1^{5.105}\right)_{x_o}\right]\right\}^{\frac{1}{1.2155}}$$

where L and Θ are expressed in inches. Calculations using this expression have been found to agree with experimental data within ±10%.

WEDNESDAY AFTERNOON AT 2:30

Chairman: A. M. Kuethe, University of Michigan

F1. Streak Interferometry. F. D. BENNETT, S. D. SHEAR and H. S. BURDEN, Ballistic Research Laboratories. - A modification of the Mach-Zehnder interferometer is described which permits streak interferometry of transient axi-symmetric flows. Examples are shown of interferograms taken of flows produced by exploding fine metallic wires. Prominent features of the interferograms include 1) clearly defined shock waves, 2) a narrow, transparent, flow region behind the strong shock where fringes may be seen, 3) an opaque region presumed to be caused by the dispersed metal and 4) luminous regions associated with the second shock wave and electronic excitation of the material near the axis of symmetry.

F2. Spectrophotometry of Nitric Oxide at 2000°K.* E. FREEDMAN, J. W. DAIBER and W. H. WURSTER, Cornell Aeronautical Laboratory. - Time-resolved absorption experiments in shock-heated nitric oxide have been performed using a four-channel photoelectric detector placed in the focal plane of a medium quart spectrograph. These channels monitor the transmitted radiation in the NO (0,2) gamma band-head and in several of the O_2 Schumann-Runge vibrational bands simultaneously. These band systems have been separately photographed in absorption behind reflected shock waves, using flashlamp continuum radiation and a large Littrow spectrograph. The photelectric records yield a time history of both the NO and the O_2 absorption, from which the kinetics of the decomposition of NO can be obtained. Results on the direct measurement of the rate of decomposition of NO near 2000°K will be presented, and will be compared with reaction rates that have been obtained at higher temperatures.

* This research was supported by the U. S. Air Force Office of Scientific Research.

F3. The Effect of Compressibility on the Reading of a Surface Pitot-Tube Used for Skin Friction Measurement. B. R. VASUDEVA, The Johns Hopkins University (introduced by L. S. G. Kovasznay). - The reading of a rectangular surface pitot-tube in a compressible turbulent boundary layer can be predicted from the geometry of the pitot-tube and from the semi-empirical laws governing the velocity distribution in turbulent boundary layers. As a result the low-speed calibration of the surface pitot-tube can be used for the determination of skin friction in high subsonic and transonic Mach number ranges by applying only a small correction. The results of the calculations were verified by experiments in a turbulent boundary layer on a flat plate in the Mach number range of $0 \leq M \leq 0.85$.

F4. Interferometric Study of the Hypersonic Blunt Body Problem I. G.I. KAHL and RAYMOND SEDNEY, Ballistic Research Laboratories. - An experimental investigation of the flow fields around spheres in free flight was made using the optical interferometer. Data were taken for Mach numbers approximately 5 in argon, nitrogen, and air. A discussion of the accuracy of the density measurements is given. It is found that, in a small region near the shock, the inaccuracy can be appreciable; near the axial streamline the error is at most 2%; but over most of the field the error is at most 1%. For the temperatures existing behind the shock in nitrogen, vibrational excitation should occur but is not found. This is explained, using a simple but fairly accurate model of the flow, by the long relaxation time compared to the scale of the experiment. If relaxation occurs at all it will be confined to a thin layer contiguous to the body. Evidence of molecular vibrations is found for the case of flow through air but slightly more than would be expected assuming that oxygen is excited and the nitrogen frozen.

F5. Interferometric Study of the Hypersonic Blunt Body Problem II. RAYMOND SEDNEY and G.H. KAHL, Ballistic Research Laboratories. - A procedure, which uses interferometric density measurements and measured shock wave position, was developed for finding all other flow variables of interest in the region between a body and its bow shock wave. The method uses only the principles of conservation of mass and energy. The procedure was set-up for a high-speed computer and an analysis of error propagation was made. It has been applied to the data obtained in Part I and representative results are shown. The position of the sonic line can be determined to within 2%. The results are compared with three recently developed numerical methods for computing the flow over blunt bodies. Two of these are inverse methods and one is a direct method. The comparisons are favorable except in certain regions of the flow: near the body for the inverse method and near the shock for the direct method.

F6. Evidence on the Fluid-Dynamic Mechanism of Pit Formation in Ablating Bodies. D. T. WILLIAMS, University of Florida. - A recent article by Cheng[1] proposes the mechani m of a Taylor instability to account for the pitting of meteorites. In contrast, Williams[2] proposes a fluid-dynamic mechanism involving bound vortices that appear in certain regions in the flow over any ablating body of bluff and nonsymmetrical shape. In connection with the latter work, pits were formed on salt cakes in steady motion through water in the manner proposed as constituting fluid-dynamic geometry similar to the subsonic pit-forming flow in the boundary layer over meteorite surfaces. A series of measurements were made of the air flow within a pit of this type, at the same Reynolds number as that of the water flow that formed the pit. Inside the pit, a vortex of the predicted type was observed, having essentially constant angular velocity about the vortex axis. The maximum airspeed inside the pit was two-thirds that outside; however a boundary layer of half the thickness of that outside the pit was found. The unusually thin boundary layer would seem adequate to account for the accelerated rate of ablation in the pit as compared to that outside. The observations here reported, coupled with the fact that the pits were formed under conditions where no Taylor instability is possible, are concluded to support the hypothesis of reference 2 as opposed to that of reference 1, as explaining certain types of meteorite pitting.

[1] Sin-i Cheng, ARS Journal 29, (8) 579 (1959).

[2] David T. Williams, Smithsonian Contributions to Astrophysics 3, (6) 47 (1959).

F7. Mass Transfer Cooling of a Porous Hemisphere at Mach Number = 5. G. E. ANDERSON and C. J. SCOTT, University of Minnesota (introduced by R. Hermann). - Results are presented of a theoretical and experimental investigation of the effects of injecting helium and air into the boundary layer of a porous hemisphere in a M = 5 airstream. An analytical prediction of the injection distribution required to produce a constant surface temperature is compared with measured temperature distributions. Local heat transfer coefficients and recovery factors were measured and compared with available theoretical predictions. Microschlieren photographs were taken of the boundary layer at various stations. Magnification of the system was sufficient to clearly see the injection boundary layer even at the stagnation point.

F8. Evaporative Film Cooling of Blunt-Nose-Models at M = 7 with Air Stagnation Temperatures up to 3000°R. R. HERMANN, W. L. MELNIK and J. O. A. STANKEVICS, University of Minnesota. - Heat transfer to an evaporating water film continuously supplied through a single orifice at the stagnation point, was measured on blunt-nose-models in the 12 x 12 inch Hypersonic Wind Tunnel at Mach number 7 and air stagnation temperatures from 1100 to 3000°R. Details of the flow field were determined from measurements of static pressure and Schlieren photographs. The experimental results are compared with existing theories. Characteristic ice formation is observed at the rear of bodies caused by a condensation of water vapor in the diffusion boundary layer. It will be shown in movie strips.

F9. Theory of Ground Interference on Slender Rocket Sleds of Arbitrary Cross-Section. R. HERMANN, W. L. MELNIK, and J. YALAMANCHILI, University of Minnesota. - The pressure distribution on a smooth, slender, three-dimensional rocket propelled sled body moving along the ground is computed for subsonic velocities and moderate supersonic Mach numbers. The flow is approximated by superposition of locally tangent conical fields along the axis of the body and its image. The normal force loading and lift coefficient are obtained from an integration of the pressure distribution on an advanced sled configuration for a specific height above the ground.