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Project

# HYPERVELOCITY IMPACT OF MICROPARTICLES


F. C. Todd, Principal Investigator

L. J. Perry, Graduate Research Assistant

B. A. Hardage, Graduate Research Assistant

R. D. Payne, Former Graduate Research Assistant

R. E. Bruce, Former Graduate Research Assistant



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Enclosures:

Reprints of Articles Published in 1966

1. Effect of Body Porosity on Hypervelocity Impact removed

   B. A. Hardage and F. C. Todd

2. A Spectrograph for the Far-Ultraviolet - removed

   R. D. Payne and F. C. Todd

Xerox Copies of Published Abstracts

1. Density of Ionization of Hydrogen by Four Approximations

   R. E. Bruce, F. C. Todd, and W. M. Alexander

2. Equation of State for an Aluminum Plasma

   R. E. Bruce, F. C. Todd, and W. M. Alexander

Copies of Papers Submitted for Publication

1. Design and Construction of a Q-Switched Laser removed

   L. J. Peery and F. C. Todd

2. Preliminary Solution for the Hypervelocity Impact of a removed Porous Stone Sphere on Solid Aluminum

   B. A. Hardage and F. C. Todd

## PAPERS SUBMITTED FOR PUBLICATION AND PUBLICATIONS

### INTRODUCTION

This is the twenty-fourth Quarterly Progress Report on Project NASr-7. The title of the project is "Shock, Flow and Radiation from the Hypervelocity Impact of Microparticles". The analytical and experimental phases of this project are concerned with the phenomena that occur with the hypervelocity impact of microparticles on a massive target, which may be solid, or layered. The overall objective is to obtain a sufficiently fundamental understanding of the physical mechanisms in the hypervelocity impact of a microparticle so the momentum and the energy transferred from the particle to the target may be ascertained and, possibly, the density of the incident microparticles may be estimated.

This Progress Report consists of the formal submission to NASA of two papers that have been accepted for publication in the Proceedings of the Oklahoma Academy of Science for 1967. These papers have already been presented with the permission of our Project Scientist at NASA. This is their first submission to NASA in the form of a Progress Report. The enclosed two papers were submitted--with some corrections--for publication and have been accepted. They are not yet set in type and they may be withdrawn if there is any objection by NASA. Several corrections in phrasing, English, and punctuation were made in these papers in collaboration with the reviewers prior to submission. The papers submitted in this report have not been corrected to agree with the final form that is to be published.

The two papers are quite different in subject matter. One paper

is an analytical study which describes the first results from a computer study of the hypervelocity impact of a sphere. This paper is on the impact phase of this project. In contrast, the second paper describes the design, construction and preliminary operation of a two-ruby, Q-switched laser which was performed on the plasma phase of this project. A short abstract is presented of each paper.

The reprints of these papers do not become available until about January of 1968. The papers are issued in the annual volume of the Proceedings of the Oklahoma Academy of Science early in December of 1967. This explains the time which is available for NASA Administrators to direct cancellation of publication if they consider it desirable.

PUBLICATIONS WHICH WERE REPORTED PRIOR TO PUBLICATION

Since the reprints are now available from the papers that were published in the Proceedings of the Oklahoma Academy of Science for 1966, reprints of two papers are enclosed. The papers were formally submitted to NASA in a Progress Report so their enclosure is merely to complete the record. The papers are:

"Effect of Body Porosity on Hypervelocity Impact"

B. A. Hardage and F. C. Todd

Proc. Okla. Acad. Sci. 46, 96-102 (1966)

"A Spectrograph for the Far-Ultraviolet"

R. D. Payne and F. C. Todd

Proc. Okla. Acad. Sci. 46, 115-121 (1966)

In addition, the published abstracts of papers that were presented to meeting of the American Physical Society are enclosed.

"Density of Ionization of Hydrogen by Four Approximations"

R. E. Bruce, F. C. Todd, and W. M. Alexander

Bull. Am. Phys. Soc. 11, 505 (1966)

"Equation of State for an Aluminum Plasma"

R. E. Bruce, F. C. Todd, and W. M. Alexander

Bull. Am. Phys. Soc. 12, 802 (1967)

## DESIGN AND CONSTRUCTION OF A Q-SWITCHED LASER

A two-ruby, Q-switched laser has been designed, constructed and operated in the regular mode. The application of the laser beam is basic to the design requirements. The giant pulse from this laser is to be employed to produce a plasma so the assembly includes means for projecting the laser beam onto an aluminum plate in a vacuum. In order to employ the results for a check on the analytical calculations, it is desirable that the beam be as uniform in intensity across the section as it is feasible to obtain.

In order to fulfill these requirements, a two-ruby, laser was constructed with Q-switching in order to obtain a giant pulse and high power, as distinct from high energy. The two rubies are used to minimize moding and to give a large, well shaped pulse of energy in the beam. Each ruby is 1/2 inches in diameter by 6 inches long. Each ruby is excited by the discharge of a condenser through a helical flash lamp. The condenser bank for each flash lamp may be charged to a maximum of 26 kilojoules. Efficiency is sacrificed by employing the helical flash lamp, but this method of excitation does insure a more uniform intensity distribution across the cross-section of the laser beam. The laser is Q-switched by a 1 mm thick solution of cryptocyanine in methanol. The concentration is $9 \times 10^{-6}$ molar.

The components have been assembled and operated in the regular mode with excitation from the discharge of about 13 kilojules. In the regular mode, the total laser output was 11 joules. It is not established whether this was for both rubies, or just for the amplifier ruby.

## HYPERVELOCITY IMPACT OF A POROUS STONE SPHERE ON SOLID ALUMINUM

Dust particles collected by the "Venus Flytrap" and other results indicate that micrometeorites are generally, but certainly not always, fluffy agglomerates of certain silicates. Densities of the order of unity are often observed and a density as low as 0.05 grams per cubic centimeter have been reported. The general solution for the impact of a micrometeoriod on the aluminum shell of a space ship is considered to be comparable, for the purposes of a computer calculation, to the hypervelocity impact of a porous stone sphere on a slab of solid aluminum.

The solution of the problem for shock propagation requires five relations, according to the standard text by Frederich and Courant. Three of the five relations are the conservation equations: conservation of mass, of momentum and of energy. These equations are basic for obtaining the computer solution for shock propagation. The viscous terms are included in the equations that are presented in this paper. These viscous terms may be included, or omitted, for the calculations on the earlier stages of the hypervelocity impact. They are omitted in the early stages of the calculations on the impact in this paper. They are omitted in most other papers except in a limited amount of work by Riney of the General Electric Company. The viscous terms must be included in solutions in the region of plastic flow.

The necessary fourth relation is an equation of state for the materials that are involved. The Tillotson, semi-empirical equation of state is employed for aluminum. A more complicated equation of state is required for the porous rock. It is based on an equation of state for quartz. The effect of porosity is based on some original studies by the Russians which were somewhat modified and expanded by other authors, in particular by McClosky's work. The fifth relation requires that the entropy of the material be increased in the compression by the initial shock. It is usual for this condition to be contained in the equation of state and this is true for the preceding equations of state. The subject requires some discussion which is presented in a thesis by Hardage. This thesis was recently completed.

This paper concludes with a few comments on the problem and the methods which are employed to program the problem for solution. Some conclusions and some curves of the computer output are presented. It is not feasible to discuss the many basic methods and assumptions in a paper of this length. The thesis from which this paper was taken is now complete and will be contained in a future progress report.

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# bulletin

## OF THE AMERICAN PHYSICAL SOCIETY

INCLUDING THE PROGRAMME OF THE

**1966 SUMMER MEETING IN THE EAST**

**UNIVERSITY OF MINNESOTA, MINNEAPOLIS • 20-22 JUNE 1966**

**IN THIS ISSUE:**

**PROPOSED AMENDMENTS TO THE CONSTITUTION AND BYLAWS OF THE AMERICAN PHYSICAL SOCIETY submitted to members by the Council for consideration and comment. Council is authorized (Constitution Article X) to modify these texts in the light of such comments and to submit the modified versions for balloting by the membership-at-large.**

favorably with the spread in the breakdown voltage reported by other workers.

* Work sponsored by the Advanced Research Projects Agency, U. S. Department of Defense.

**H6. Density of Ionization of Hydrogen by Four Approximations.*** R. E. Bruce, F. C. Todd, and W. M. Alexander,† *Oklahoma State University.*—The variation in the lowering of the ionization potential is a basic requirement for a study of the expansion of an initially high pressure and temperature plasma, such as results from hypervelocity impact. With an assumption of thermodynamic equilibrium, the density of ionization for all ionic species is obtained from the effective ionization potential and the electronic partition functions. The effective ionization potential may be found from the excess Helmholtz free energy that represents the energy in the microfields.[1] In order to compare with published results, the density of ionization for hydrogen is compared over a wide range of densities whn it is calculated in the following ways: (1) simple Debye–Huckel fields, (2) Ecker and Kröll approximation by mean fields,[1] (3) Schrödinger equation with Yukawa potential,[2] (4) cluster integral evaluation of the 2-body interaction for the fields. The distance of closest approach parameter is considered.

* Research supported by the National Aeronautics and Space Administration.
† Goddard Space Flight Ctr.
[1] G. Ecker and W. Kröll, Phys. Fluids 6, 62 (1963).
[2] R. E. Bruce and F. C. Todd, Proc. Okla. Acad. Sci. (1964).

**H7. Simplified Theoretical Model for the Condensed Radio-Frequency Arc.** Mark P. Freeman, *American Cyanamid Company.*—The governing relationships for the atmospheric-pressure *H*-type radio-frequency discharge (the condensed arc used in the radio-frequency plasma jet[1]) are presented. They are made soluble by use of the "channel model," a simplified arc model known to account in a fairly satisfactory way for the electrical characteristics of the dc arc, and analytically evaluated using the minimum principle of Steenbeck as generalized by Peters.[2] Numerical examples calculated for argon and nitrogen plasmas using empirical, and where necessary, calculated material functions are presented. The calculated electrical characteristics for argon are seen to be in substantial agreement with some crudely determined plasma-jet characteristics, while those for nitrogen correspond similarly to crude measurements made on nitrogen, air, and oxygen. The predicted scaling behavior of such a discharge is also discussed.

[1] T. B. Reed, J. Appl. Phys. 32, 821 (1961).
[2] T. Peters, Z. Physik 144, 612 (1956).

**I1. Charge-Transfer Cross-Section Measurements in the eV Energy Range.** P. Mahadevan, C. E. Carlston, and G. D. Magnuson, *General Dynamics/Convair Division.*—The total inelastic collision cross sections for $He^+$ in He and $N_2$ have been measured in the energy range 1–200 eV, using a simple dc technique. The low-energy primary ion beams are obtained by floating the entire collision chamber at a variable potential above ground. By this method, it is possible to get reasonably large ion currents in the eV region with simple focusing. The measurement involves slow charge collection by a conventional parallel plate condenser. The width at half-maximum of the energy distribution of the ion beam is determined to be 0.35±0.15 eV, using a parallel-plate analyzer designed by Hutchinson.[1] The cross sections tend to increase rather rapidly as the beam energy decreases below about 40 eV. For a 2-eV ion beam, the cross section for $He^+$ in He is about 40 Å² and for $He^+$ in $N_2$ about 50 Å². Cross sections at thermal energies obtained by extrapolation are compared with data from afterglow measurements. The $He^+ + N_2$ reaction appears to be more probable at low energies than the symmetric resonant reaction $He^+ + He$. Some preliminary measurements of cross sections for $NO^+$ in atmospheric gases are presented.

[1] D. A. Hutchinson, Conf. Electron. At. Collisions, 2nd, Boulder, 1961.

**I2. Study of Ion–Molecule Reactions by a Photoionization Mass-Spectrometer Technique.*** P. Warneck and W. P. Poschenrieder, *GCA Corporation.*—Rate constants for the following reactions

$$H_2^+ + H_2 \rightarrow H_3^+ + H \qquad k = 1.8\times10^{-9} \text{ cc/molecule sec},$$
$$N_2^+ + O_2 \rightarrow O_2^+ + N_2 \qquad k = 1.7\times10^{-10} \text{ cc/molecule sec},$$
$$N_2^+ + O_2 \rightarrow NO^+ + NO \qquad k \leq 0.7\times10^{-13} \text{ cc/molecule sec},$$
$$A^+ + O_2 \rightarrow O_2 + A \qquad k = 1.7\times10^{-10} \text{ cc/molecule sec}$$

have been measured. A new experimental technique was employed using a photoionization mass spectrometer coupled to a ½-m Seya uv monochromator for photon energy selection near the ionization onsets. Differential pumping permitted ion source pressures in the 0- to 200-$\mu$ range. These high pressures necessitated the experimental determination of ion source residence times which was accomplished by a pulse method. The present results are discussed and compared with similar data obtained from electron impact and afterglow studies.

* Partial support by the National Aeronautics and Space Administration.

**I3. Reaction of Atomic Oxygen Ions with Vibrationally Excited Nitrogen Molecules.** A. L. Schmeltekopf, F. C. Fehsenfeld, G. I. Gilman, and E. E. Ferguson, *Institute for Telecommunication Sciences and Aeronomy.*—The flowing afterglow reaction device in our laboratory has now been extended to measure reactions involving vibrationally excited $N_2$. The vibrational temperature of the ground electronic state of $N_2$ has been analyzed in a unique way by employing the $He(2^3S)$ metastable as an excitation source and observing the radiation from the 1st negative system of $N_2^+$. The reaction

$$He(2^3S) + N_2(v) \rightarrow N_2^+ B^2\Sigma_u^+(v) + He + e \qquad (1)$$

has been found to follow the Franck–Condon factors, which have been calculated using the RKR method. By using the vibrational distribution measured by the above method, reaction-rate measurements involving known vibrational temperatures can be made. The atom–ion interchange reaction

$$O^+ + N_2(v) \rightarrow NO^+ + N \qquad (2)$$

has a larger rate constant when the $N_2$ is vibrationally excited. For a Boltzmann distribution of $N_2$ vibrational states such that $T_{vib} \approx 2500°K$, the rate constant for (2) is increased by a factor of about 20 over the rate constant for the ground vibrational state of $N_2$.

**I4. Some Recently Measured Thermal-Energy Ion-Neutral Reaction Rates.** F. C. Fehsenfeld, A. L. Schmeltekopf, G. I. Gilman, L. G. Puls, and E. E. Ferguson, *Institute for Telecommunication Sciences and Aeronomy.*—Several additional rate constants have been measured in the pulsed discharge-flowing afterglow reaction tube at 300°K. These include

$$N_2^+ + H_2 \rightarrow N_2H^+ + H \qquad k = 2\pm1\times10^{-9} \text{ cm}^3/\text{sec}, \qquad (1)$$
$$CO^+ + H_2 \rightarrow COH^+ + H \qquad k = 2\pm1\times10^{-9} \text{ cm}^3/\text{sec}, \qquad (2)$$
$$O^+ + H_2 \rightarrow OH^+ + H \qquad k = 2\pm1\times10^{-9} \text{ cm}^3/\text{sec}, \qquad (3)$$
$$N^+ + H_2 \rightarrow NH^+ + H \qquad k = 7\pm3\times10^{-10} \text{ cm}^3/\text{sec}, \qquad (4)$$

and several other positive-ion reactions. The system also has been extended to the measurement of negative-ion reaction-rate constants. Reactions reported include

$$H^- + O_2 \rightarrow OH^- + O,\ \rightarrow O^- + OH \qquad k = 1.5\pm0.7\times10^{-9} \text{ cm}^3/\text{sec}, \qquad (5)$$
$$O^- + H_2 \rightarrow (H_2O + e)? \qquad k = 1.5\pm0.7\times10^{-9} \text{ cm}^3/\text{sec}, \qquad (6)$$
$$O^- + NO \rightarrow (NO_2 + e)? \qquad k = 5\pm2\times10^{-10} \text{ cm}^3/\text{sec}. \qquad (7)$$

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# bulletin

## OF THE AMERICAN PHYSICAL SOCIETY

INCLUDING THE PROGRAMME OF THE

**1967 SUMMER MEETING AT TORONTO, CANADA**

**21-23 JUNE 1967**

**JOINT MEETING OF**
**THE AMERICAN PHYSICAL SOCIETY**
**SOCIEDAD MEXICANA DE FISICA**
**CANADIAN ASSOCIATION OF PHYSICISTS**

7E-1 AN EXPERIMENTAL INVESTIGATION OF THE TRANSPORT PROPERTIES OF ARGON IN A PULSED, HIGH CURRENT ARC

P. W. Schreiber (introduced by J. W. Birkeland), Aerospace Research Laboratories,

In order to investigate the applicability of the single fluid equations of plasma dynamics to high power arcs, a 1-inch diameter, electric arc in a vycor tube at atmospheric pressure was studied for current pulses up to 1500 amperes and 0.7 sec. in duration. Fastax films indicated that stable conditions existed for flow rates less than 1.4 gm/sec. In addition, time resolved spectrometric studies showed that the argon plasma reached a quasi-stationary state within 0.1 sec., and it was relatively pure for 0.4 sec. During the stationary state, arc current, voltage, field strength, total radiation, wall heat flux, and the temperature distribution were measured. These results were compared with calculated values obtained by using Emmons' transport properties for argon.[1] These calculated results compared well with the experimental measurements.

[1]H. W. Emmons, Harvard University Engineering Sciences Laboratory, TR 23 (December 1965).

7E-2 MICROWAVE ABSORPTION IN A SLIGHTLY IONIZED GAS

L. Wald (introduced by D. R. Bach), University of Michigan

The absorption of 12 GHz microwaves has been measured in a slightly ionized ($N_e \sim 10^{11}$/cc) gas of helium and neon. The measurements were made along the axis of a 12.4 cm diameter by 13.6 cm long cylindrical chamber which contained the radio-frequency excited (7.1 MHz) gas. In the interpretation of this experiment, one can employ three analytical methods: The classical Lorentz formula, the transport theory of Milne,[1] or the transport theory of Osborn and Klevans.[2] These theories differ significantly for electron densities in the range $.2 < \omega_p^2/\omega^2 < .7$. The attenuation data obtained appears to agree with the Osborn-Klevans theory. The transport theory of Milne does not give nearly as good agreement but most of the attenuation data lies within the possible error of the measurements. The classical Lorentz formula is significantly in error over the electron density range given above. An effective probability of collision for momentum transfer $p_m$ of 24/cm was measured, and is in reasonable agreement with values measured with scattering experiments.

[1]Milne, Handbuch der Astrophysik Halfte 1 Teil 3 pg 72 ff.

[2]E. K. Klevans, "Theory of Photon Transport in Dispersive Media," Thesis, University of Michigan, 1962.

**7E-3. Nonlinear Interaction between an rf Electric Field and an Electron Plasma.*** J. F. DECKER and J. L. HIRSHFIELD, *Yale University.*—We previously reported[1] the observation of the nonlinear interaction of applied rf electric fields with an electron plasma. Using Gaussian-shaped distributions, qualitative comparisions were made between the measurements and a one-dimensional quasilinear solution of the Vlasov equation describing the spatial evolution of the time-averaged distribution function. Particularly simple distributions, $f(E) = A - BE$, have since been effectively produced, allowing a quantitative comparision with the theory. The interaction is observed by applying a nearly longitudinal rf electric field to a cloud of drifting electrons by means of an eleven-wavelength periodic structure. The electron-energy distribution is measured as a function of amplitude and phase velocity of the applied field after the electrons have emerged from the structure. Deformation of the distribution in a narrow range of velocities near the phase velocity of the applied field is observed. Agreement between theory and experiment is within the experimental error.

*Research sponsored in part by the National Science Foundation, in part by the National Aeronautics and Space Administration, and in part by the U.S. Air Force Cambridge Research Laboratories, Office of Aerospace Research.

[1]J. F. Decker and J. L. Hirshfield, Bull. Am. Phys. Soc. 11, 375 (1966).

7E-4 EQUATION OF STATE FOR AN ALUMINUM PLASMA*

R. E. Bruce (introduced by F. C. Todd), F. C. Todd and W. M. Alexander, Oklahoma State University

A computer solution estimates an equation of state for an aluminum plasma over an extended density range and for plasma temperatures over 1 eV. By repeated iteration, the computer distributes the energy of the plasma between the degrees of freedom according to standard relations. The density of ionization is found from a modified Saha equation which includes the ionization potential reduction.[1] The total energy in the plasma is divided between kinetic; ionization; excitation; interaction by cluster integrals for radially symmetric forces; plasma electron oscillations; radiation density and the electron-degeneracy correction. The rigid sphere model is employed with the closest approach parameter adjusted so the analytical solution coincides with the Thomas-Fermi statistics at high temperatures and densities, and merges with the ideal gas values at low densities.

*This work was supported by NASA.

[1]R. E. Bruce and F. C. Todd; Proc. Okla. Acad. Sci., 1966.

7E-5 TEST WAVES IN NON-LINEAR THEORY*

R. E. Aamodt (introduced by W. E. Drummond), Center for Plasma Physics and Thermonuclear Research, The University of Texas

A statistical theory of the Vlasov equation is studied in which the non-linear effects are determined by the superposition of a sequence of test waves solutions. The difference in principle and in fact between this approach and the usual amplitude iteration procedure is discussed.

*Work supported by the U. S. Atomic Energy Commission.

**7E-6. Radially Dependent Diffusion Coefficient during Ohmic Heating in the Model C Stellarator.** A. HABERSTICH, *Princeton University.*—The elec-