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"INVESTIGATION OF HIGH-SPEED IMPACT PHENOMENA"

By J. F. Friichtenicht

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INVESTIGATION OF HIGH-SPEED IMPACT PHENOMENA (III)

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FOREWORD

Members of the Meteoritics Department of TRW Systems (formerly TRW Space Technology Laboratories) have been actively engaged in laboratory research programs on various aspects of micrometeoroid simulation since 1957. Early work led to the development of a two-million-volt electrostatic accelerator capable of projecting micron-size particles to near-meteoritic velocities. Late in 1960 a NASA-sponsored research program (Contract NAS5-763) was undertaken to utilize this equipment in the study of various aspects of high-speed impact phenomena. This study was followed by three more programs (under Contracts NASw-269, NASw-561, and NASw-936) supporting research in the same general field of inquiry. The technical data acquired under the sponsorship of these programs is summarized in this report.

Much of the material discussed in this report has been disseminated previously in one form or another. Abstracted versions of published papers arising from or related to work conducted under these programs are given at the end of Volume I of this report. A number of oral presentations at Hypervelocity Impact Symposia have been given also. Since the Proceedings of these Symposia have been published, reference is made to them in the Bibliography as well. Finally, a number of informal technical reports have been submitted in compliance with the conditions of the various NASA contracts. These contain detailed technical information and may be used as reference material. The technical reports are bound in a separate volume and are referred to as appendices in the text of Volume I.

INTRODUCTION

The advent of the space age has provided new and useful methods for the study of the space environment. Prior to the launching of earth satellites the existence and properties of meteoroids could only be inferred from studies of zodiacal light and observations of meteor trails in the earth's atmosphere. It is now possible to make direct measurements on meteoroids in their natural habitat. Studies of this kind are significant for two reasons: (1) by providing scientific data on the properties of meteoroids, they lead to increased knowledge of the cosmology of the universe, and (2) the information they provide is applicable in assessing the hazard to spacecraft posed by meteoritic bombardment. To implement these new research programs, it became necessary to develop suitable measurement techniques and to understand more fully the phenomena associated with the impact of high-velocity meteoroids on surfaces.

As was predicted, a large fraction of the total meteoroidal material has been found to be in the form of small particles, termed micrometeroroids. Although large meteoroids exist, they represent only a small hazard to spacecraft because they occur infrequently. Neither do extremely small micrometeoroids (on the order of a few microns or less in size) present a major hazard because they are incapable of penetrating spacecraft walls. Micrometeoroids of about 50 microns or greater in size, however, are present in sufficiently large numbers and have a great enough penetration power to be a serious hazard.

Few measurements of micrometeoroids in this size range have been made, partially because they are not present in sufficient numbers to be easily measurable. To date the only vehicle capable of providing statistically significant samplings of engineering penetration data is the recently launched Pegasus spacecraft. Most spacecraft micrometeoroid measurements have been made with relatively small sampling areas (i.e., on the order of 100 cm^2), and in order to obtain reasonable counting statistics, it has been necessary to make measurements on the extremely small micrometeoroids.

The development of measuring techniques has been hindered by the lack of laboratory facilities capable of producing particles having the same parameters as naturally occurring meteoroids. Most traditional hypervelocity impact facilities, utilizing light gas guns, shaped charges, etc., produce projectiles with a practical upper velocity limit of about 10 km/sec, in contrast with the mean velocity of 30 km/sec for natural meteoroids. Often these devices are restricted to the use of projectiles considerably too massive to be of general interest for simulation of meteoroid impact, and a further limitation concerns the integrity of the projectiles or particles, which may be damaged in the launching process.

The deficiencies of these systems led to the development of an electrostatic particle accelerator. The first useful accelerator of this type operated with an accelerating voltage of 120 kv. Favorable results led to the development of a two-million-volt accelerator, which was completed in late 1960 and has been in continuous operation since then. While this facility does not produce particles matching the natural meteoroid spectrum, it does possess unique features that make it particularly useful in meteoroid simulation work. Among these features are the following:

1) The entire experiment may be conducted in a vacuum environment.
2) The frequency and number of particles injected are controlled electrically.
3) The particle parameters of each particle are measured electronically prior to impact.

4) High repetition rates may be obtained for rapid data acquisition.

5) Because of the nondestructive accelerating technique, reliable operation is obtained with minimum down time.

Late in 1960 a series of NASA-sponsored research programs concerned with meteoroid simulation and general problems of hypervelocity impact phenomena was begun. This final report summarizes the work carried out under these programs. A variety of experiments have been conducted under the auspices of these programs, and significant advances have been made.

A major fraction of the work has been devoted to developing equipment and observational techniques. The resulting improvements in facilities and techniques have usually assisted materially in the acquisition of more valuable information; for example, the development of more sensitive particle-parameter detectors has increased the effective upper velocity limit of accelerated particles from 10 km/sec in 1960 to well over 30 km/sec today.

While much of the material in this report consists of descriptions of techniques and procedures that have been developed over the years, no attempt has been made to describe the chronological evolution of these items. The trials encountered in their development have been thoroughly discussed in the progress reports submitted under the various contracts.

The remainder of this report is organized into two main parts: The first, gives a comprehensive discussion of the accelerator facility and measurement techniques common to all experiments and the second is a narrative description of the various types of experiments that have evolved. A supplementary volume contains more detailed accounts of many of the topics discussed below. These technical reports are referred to as Appendices in the text.

FACILITIES AND TECHNIQUES

Description of Electrostatic Accelerator

The electrostatic particle accelerator is similar in most respects to conventional low-energy ion accelerators, the only major difference, other than the particles themselves, being the mechanism by which the particles are charged. The conversion of a conventional ion accelerator to a particle accelerator is straightforward and has been described in the literature.[1] In making this conversion, the ion source and its control circuits are replaced by a charged-particle injector and associated circuitry.

Charged-particle injector.

In the particle-charging mechanism developed by Shelton et al[2] (see Fig. 1), particles are charged by coming into contact with a small charging electrode that is maintained at a high positive voltage with respect to surrounding surfaces. The particles to be charged, which are in the form of a fine powder, are stored in a box-like cavity. Into this cavity protrudes a flat rectangular plate supported in a plane parallel to the surface of the powder. When a voltage pulse is applied to this tongue, which is normally maintained at the same electrical potential as the powder, the electric field produced between the tongue and the uppermost particles induces a charge on the particles. When the electrical forces are strong enough to overcome intermolecular and gravitational forces, some particles are lifted from the powder and propelled toward the tongue. Those that strike the tongue then become charged in the opposite direction and are repelled. The effect of a voltage pulse is

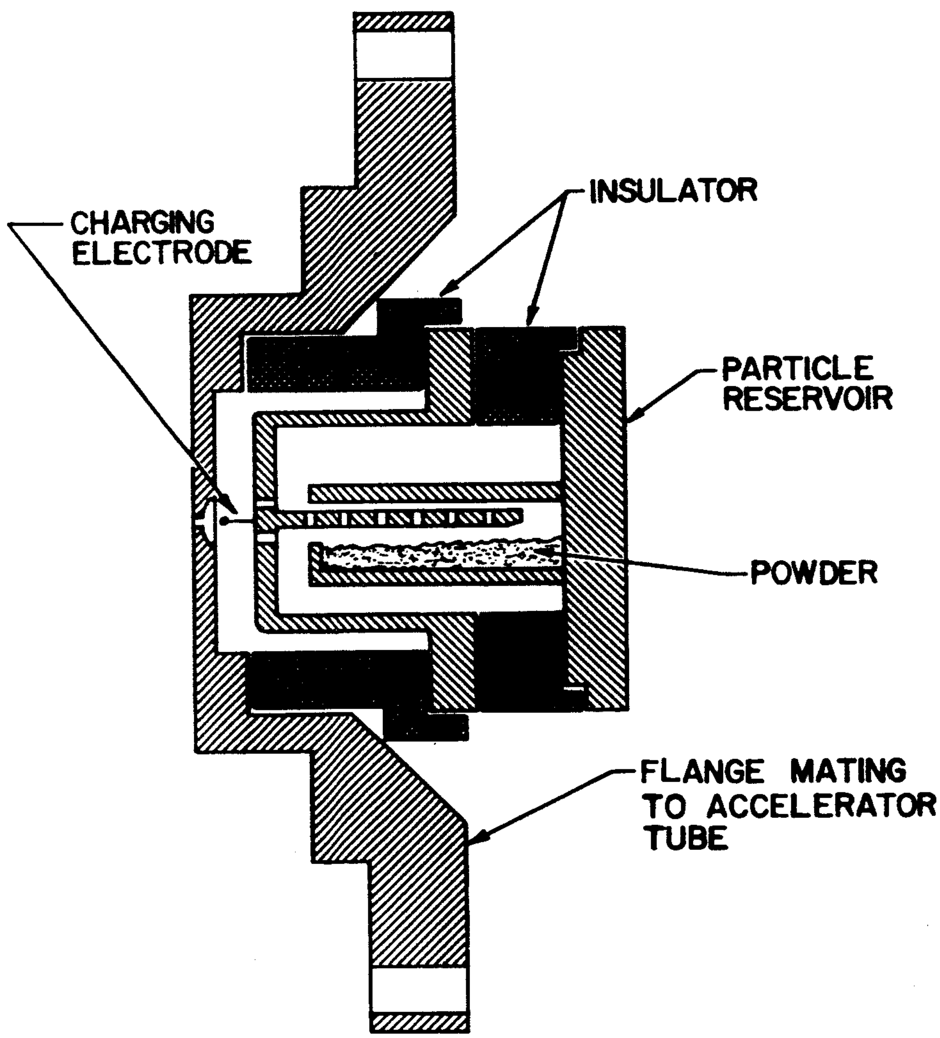


Figure 1. The Charged Particle Injector

thus to put some of the particles into a motion that resembles the behavior of molecules in a gas, and as a result of collisions with walls and other particles, some of the particles effuse out of the small hole and enter the region occupied by the charging electrode.

In this region, each time a particle comes into contact with a surface it acquires a charge of the same polarity as that of the surface and is repelled by it. Thus, particles injected into this region are bounced back and forth because of the potential difference between the surfaces. During this random motion some of the particles come into contact with the small charging electrode and acquire a much larger charge, because the electric field at the surface of the electrode is much greater than the field on other surfaces within the cavity. Some of these highly charged particles escape through a small aperture into the Van de Graaff accelerator tube, where they are subsequently accelerated through the full potential difference of the accelerator.

Detectors.

Electronic detectors are used to measure the velocity, charge, and mass of a particle as it passes from the accelerator. A detector consists of an insulated drift tube mounted coaxially with the beam of particles from the Van de Graaff. The passage of a charged particle through the detector induces a voltage pulse that is proportional to the charge on the particle and inversely proportional to the capacitance of the detector to ground. Hence the amplitude of the detector signal is proportional to the particle charge. The duration of the signal is the transit time of the particle through the detector. This signal is either amplified and displayed on an oscilloscope and photographed for later analysis or fed to an electronic data-plotting system.

The velocity attained by a charged particle is given by

$$v = (2V_a q/m)^{1/2} \quad , \tag{1}$$

where V_a is the accelerating voltage, q is the charge on the particle, and m is the particle mass. Since the accelerating voltage is known, the measurements obtained with the detector allow the mass of the particle to be computed.

Mass and velocity ranges.

As shown by Eq. (1), the final velocity is limited only by the magnitude of the accelerating voltage and the charge-to-mass ratio of the particles. Economic considerations usually limit maximum voltage, whereas the maximum charge-to-mass ratio is a more fundamental limitation.

The charge-to-mass ratio of the particle can be expressed in terms of the electric field at the surface of the particle by

$$\frac{q}{m} = \frac{3\epsilon_o E}{\rho r} \quad , \tag{2}$$

where ϵ_o is the permittivity of free space, ρ is the density, and r is the radius of the particle. It can also be shown that the field at the particle surface after separation and charge redistribution is proportional to the field on the charging electrode. The charge-to-mass ratio obtainable is determined by the maximum field that a particle can sustain while contact with the charging electrode (which is the maximum field to which it is subjected). Good and Mueller[3] report that most metals are able to support positive fields in excess of 10^{10} volts/meter, beyond which appreciable ion evaporation occurs. Because of geometrical factors, sputtering, and other effects, this upper limit is generally not achieved, but we have been able to consistently charge particles to the point that the surface electric field is about 2.5×10^9 volts/meter.

From Eq. (2) it can be seen that higher charge-to-mass ratios are obtained for smaller particles and also for low-density materials. For most of our work we have used carbonyl iron spheres, which are readily available in the correct size range. A more limited amount of work has been done with carbon black particles, which because of their lower density obtain considerably higher velocities. The performance of the TRW electrostatic accelerator under nominal operating conditions is illustrated in Fig. 2. (Not shown on this graph are recently acquired data points giving velocities in excess of 30 km/sec for ~0.1 micron radius particles.) While the velocity and mass ranges available do not match the natural meteoroid spectrum, the area of overlap is sufficient to allow useful experimentation.

Particle detector preamplifiers.

As described briefly in the previous section, the parameters of an accelerated particle are derived from analysis of a voltage signal induced on the capacitance of a detector as the particle passes through it.[1,2] The amplitude of the signal V in volts is given by $V = q/C_d$, where q is the particle charge in coulombs and C_d is the effective capacitance of the detector. In order to obtain a true measurement of pulse height, the decay time constant of the signal must be long compared to the signal rise time. This requirement implies that the preamplifier input circuit must provide a high input impedance to ground. With these considerations in mind, we first used conventional cathode-follower input circuits, as illustrated in Fig. 3a. The cathode follower was followed by several RC coupled amplification stages. With this type of circuit the minimum input capacitance obtainable was of the order of 10 picofarads or so, the grid-to-cathode

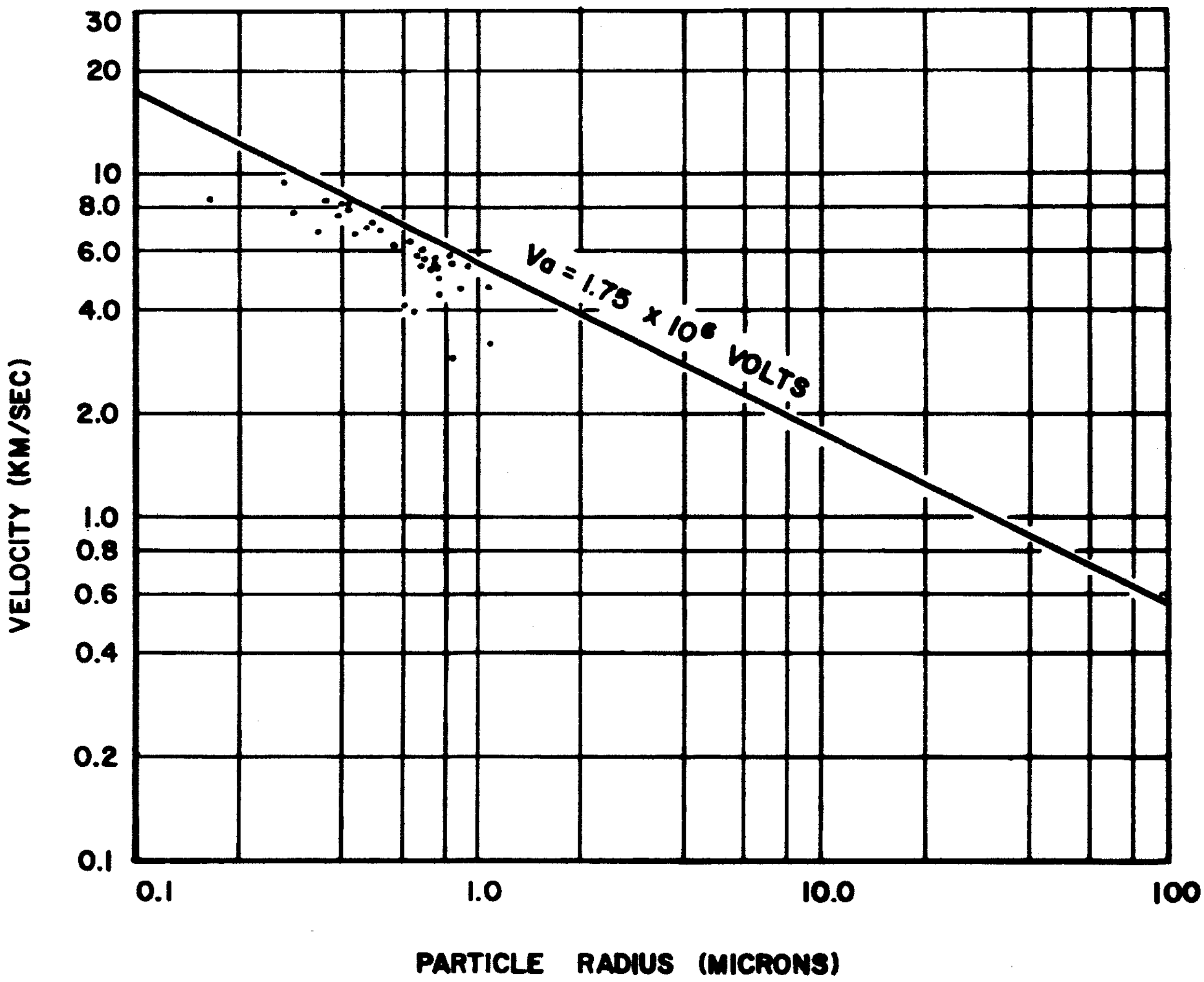
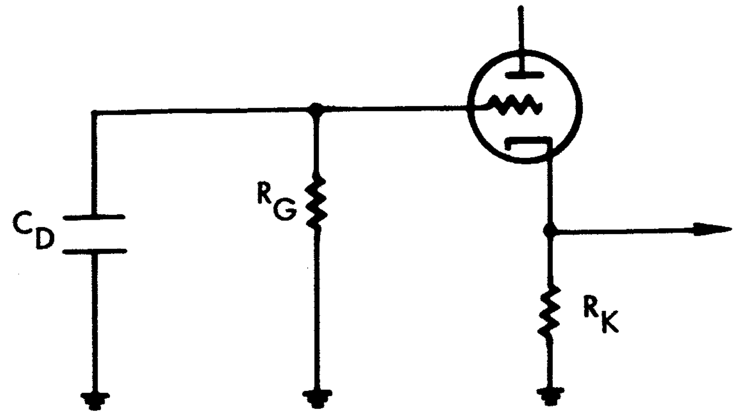
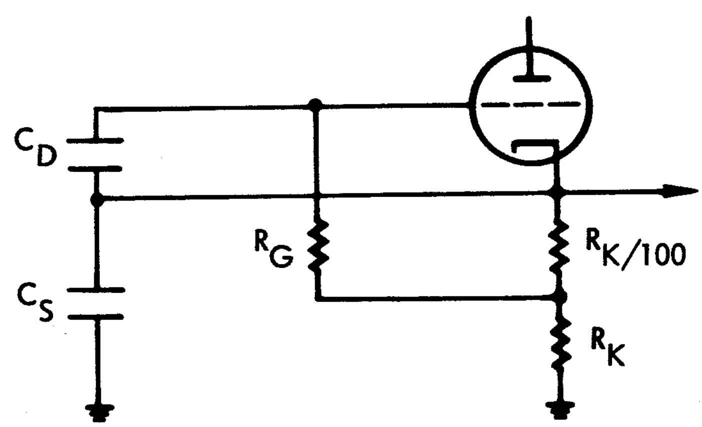


Figure 2. Performance Curve for an Electrostatic Accelerator. The solid line is the expected performance for particles charged to a value that results in an electric field of 2.5 x 10^9 volts/meter at the surface of the particle. The points are the result of actual measurements under nominal conditions.



A



B

Figure 3. Circuit Diagrams of a Conventional Cathode Follower (A) and a Cathode Follower in the Bootstrapped Configuration (B).

capacitance of the tube accounting for about 1 or 2 picofarads and the detector structure accounting for the remainder.

It is obvious that decreasing the input capacitance results in increased signal amplitude. A further consideration, however, is that of signal-to-noise ratio. The chief source of electrical noise is the thermal noise generated in the grid resistor. The value of the mean-squared thermal noise voltage produced in a resistor is given by

$$E_n^2 = 4kTR\Delta f \quad , \tag{3}$$

where k is Boltzmann's constant, T is the temperature in degrees Kelvin, R is the resistance in ohms, and Δf is the effective bandwidth. For an RC circuit such as that shown in Fig. 3a, it can be shown that $\Delta f = 1/4RC_d$. Substitution into Eq. (3) gives

$$E_n^2 = \frac{kT}{C_d} \quad . \tag{4}$$

Thus the signal-to-noise ratio is proportional to $1/\sqrt{C_d}$ and is improved by decreasing the capacitance.

Unfortunately, the input capacitance of conventional cathode followers cannot be reduced much further. To overcome this limitation, preamplifiers utilizing a bootstrapping, or feedback technique to decrease the effective input capacitance have been developed. The input circuit of a bootstrapped cathode-follower input stage is illustrated in Fig. 3b. In this arrangement the detector element is enclosed within a shield that is connected to the cathode of the tube. The capacitance between the detector element and the shield is denoted by C_d, while C_s is the capacitance of the shield to ground. A particle passing through the detector induces a voltage across C_d given by $V = q/C_d$. The grid voltage V_g is the sum of the voltages across C_d and C_s. The voltage across C_s is the output voltage of the cathode follower and is simply GV_g where G is the cathode follower gain. From this we obtain

$$V_g = q/C_d + GV_g \quad , \tag{5}$$

or

$$V_g = \frac{q}{(1-G)C_d} \quad . \tag{6}$$

This can be interpreted as a decrease of the effective input capacitance by the factor of (1-G). A well-designed cathode follower has a gain of 0.9 or better, so the input capacitance is reduced by a factor of about 10.

A further comment about the signal-to-noise ratio is in order. Equation (4) gives the total mean-squared thermal noise voltage in the bandwidth Δf. It can be seen that for a given value of C_d, increasing R increases E_n^2, but the bandwidth Δf is simultaneously decreased. In practice, we attempt to choose R and C_d so that Δf is on the order of 1000/cps or less, thus confining most of the noise to low frequencies. High-pass filters in the succeeding amplification sections then reject the low-frequency components. In most cases little information is lost from the particle signal as a consequence of low-frequency rejection.

In conventional cathode-follower input circuits no difficulty is encountered with this system of noise rejection. However, as the input capacitance is reduced by bootstrapping, larger values of R are required to reduce the noise bandwidth, and unfortunately, the resistance cannot be increased without limit in conventional cathode followers because of grid current effects. Despite this problem significant improvements have been made over the unbootstrapped type of detector.

Further advances have been realized by conversion from electron tube to solid state electronics. Ordinary transistors are quite adequate for the amplification stages of the preamplifiers, and hybrid types, utilizing a vacuum tube input stage and solid state amplification stages, have been used for some time. More recently, field effect transistors having extremely high input impedance and small junction capacitance have become available. These are currently being used in the input stages of the preamplifiers. With this type of input stage the full benefits of the bootstrapping technique are obtained. Furthermore, their small size and lack of filament-power requirements make them particularly useful, since they can be located physically within the vacuum system. This reduces stray wiring capacitances and minimizing electrical pickup, which is another source of noise.

The use of bootstrapped detectors makes the detection of smaller charges possible. In an electrostatic accelerator, the smaller, higher-velocity particles carry the least net charge, hence the ability to detect small particles increases the effective velocity range attainable. In fact, the increase in maximum velocity from 10 km/sec to upwards of 30 km/sec is due primarily to the improved detection techniques. A complete description of the latest preamplifier developed for this use is given in Appendix A.

High-Repetition-Rate Particle Injection

Certain classes of experiments, particularly those intended to simulate long-term micrometeoroid bombardment, require a large number of particle impacts. An automatic particle-injection system capable of satisfying this requirement has been developed and is currently in use on the accelerator.

A large negative voltage pulse is needed to eject particles from the injector into the accelerator, as described in the section entitled "Description of Electrostatic Accelerator." This pulse was initiated in the original system by the manual closure of a switch, which discharged a capacitor through a pulse-forming network. The pulse from the network was fed to the grid of the high-voltage pulse tube, whose output was applied to the particle injector. Solenoid-driven control rods that are an integral part of the Van de Graaff accelerator were used to operate the switch and make voltage adjustments from the operator's console. This manual mode has been incorporated into the new system.

In the automatic system an electronic subassembly generates triggering pulses at a predetermined rate. The automatic pulsing system contains two major units, one located in the operator's console and the other in the high-voltage terminal of the accelerator. Pushing a pulse-control button on the operator's console advances a stepping switch, whose position corresponds to that of a stepping switch within the terminal. Manual operation or automatic pulses at one of a number of discrete frequencies from 10 to 600 pulses/minute may be selected. Indicator lamps on the control panel show the position of the stepping switch. A time delay ensures that the solenoid is actuated long enough to allow the terminal stepping switch to step and to prevent the stepping motor from being on more than 2 seconds to prevent overheating.

The unit within the Van de Graaff high-voltage terminal applies the proper voltages to the particle injector for the desired speed and mode of operation. Details on the operation of this unit are given in Appendix B.

The number of particles injected per pulse is a function of pulse amplitude and duration, which are normally adjusted so that the average injection rate is about one particle per pulse. The injector has been operated under these conditions at the rate of 10 particles per second for periods of over 100 hours with no noticeable deterioration in performance.

Velocity Selector

Carbonyl iron spheres have been used as a source of particles for most of our work. This material is available in the form of a fine powder with a mean particle diameter of about 1.5 microns. However, there is a considerable spread in particle size about this mean value - typically, from about 0.1 to 3.0 microns. As described in Refs. 1 and 2, the particle charge-to-mass ratio is a function of the size of the particle. Hence, a large spread in particle velocities occurs. Since the particle velocity is one of the most important parameters in the type of experiments we have conducted, it is often desirable to select the particle velocity in advance. A system for accomplishing this has been developed and is described briefly below and in more detail in Appendix C.

The velocity selection is made on the basis of time-of-flight measurements between two fixed particle detectors. The signals from both of the detectors are amplified and presented to voltage discriminators, where standard pulses are generated. The output pulse from the first discriminator triggers a one-shot multivibrator with an output pulse of adjustable length. The trailing edge of the output pulse from the first multivibrator triggers a second one-shot multivibrator of variable, but preset duration. This pulse opens the gate of an electronic gating circuit for the duration of the pulse. The output pulse from the second discriminator is fed to the gate, and if it appears while the gate is open, a coincidence pulse is generated by the gating circuit.

It can be seen that the duration of the first multivibrator pulse determines the upper velocity limit of the system, while the length of the second multivibrator pulse determines the velocity interval over which output pulses are generated. The lengths of both of these pulses are adjusted over wide ranges by selection of the multivibrator coupling capacitors.

The output pulse can be utilized in several ways. In the most common mode, it has been used to trigger an oscilloscope in order to display selected signals while ignoring all others. It also performs the velocity selection function utilized in the particle-parameter selection system described in the following section.

Particle-Parameter Selection System

A particle-parameter selection system that aids materially in the acquisition of data from the accelerator has been developed. The main elements of the system are an electrostatic deflector, gating circuits, and a high-voltage pulse circuit. The deflector consists of a pair of parallel plates with a potential difference between them. Upon entering the region between the plates, particles from the accelerator experience an electrostatic force perpendicular to their original direction of motion and are deflected from their initial trajectory. The magnitude of the deflection, which is independent of the particle charge-to-mass ratio, is great enough to prevent particles from entering the target chamber complex.

The particle parameters selected are velocity and charge (which is proportional to the size of the particle). The velocity selection is accomplished by the system described in the preceding section. The signal from the second detector (or a third detector, if more convenient) is fed to a single-channel window discriminator, and if the amplitude of the signal (which is proportional to particle charge) lies within the window, an output pulse is generated. This pulse and the output pulse from the velocity selector are fed to a coincidence circuit. If the two signals appear simultaneously, a coincidence output signal is generated, indicating that both the velocity and charge of the particle are within the desired range. (In practice, windows of finite width must be used in both legs of the circuit. There are, therefore, slight spreads in the ranges, but this is monitored by means of another particle detector located within the target chamber.)

Finally, the coincidence pulse is used to trigger the high-voltage pulse circuit. Normally, the high-voltage pulse tube is biased off so that its plate is at a positive high voltage. One of the deflection plates is connected directly to the plate of the tube while the other plate is grounded. The input signal drives the tube into saturation, which drives the plate to ground. The signal is long enough to allow the particle to pass through the deflection plates and on toward the target chamber before the bias is re-established.

A more complete description of the particle-parameter selection system is given in Appendix D. An all-solid-state pulse generator which was developed to drive the high-voltage pulse tube is described in Appendix E, while Appendix F contains a discussion of the complete high-voltage section of the particle-parameter selection system.

Data Analysis

The improvements that have been incorporated into the accelerator have resulted in a faster rate of data acquisition, with a consequent need for more complex computational procedures than those originally used. To meet this need, semi-automatic and automatic particle-analyzing techniques have been developed.

Semi-automatic method of data analysis.

The semi-automatic method differs from manual data reduction primarily in that a high-speed electronic computer performs the routine calculations to determine the characteristics of particles from the accelerator. The detector signal produced by a given particle is recorded photographically, as in the manual mode, but then a Telereader is used to read the desired information from the recorded traces. This information is punched automatically onto computer cards by a companion IBM key punch machine. The data cards, together with cards carrying the values of the other system variables, are fed into an IBM 7094 computer, which performs the calculations.

Particle radius, velocity, mass, energy, and momentum are determined in this manner. An additional experimental quantity may also simultaneously be measured and recorded by this process; usually the output signal of the experiment is selected.

The use of the semi-automatic system, in addition to shortening computational time, also generally results in more accurate measurements than those obtained by the manual mode of data reduction. The semi-automatic system is used for nearly all data reduction on experiments where a number of data points are required, and it is also particularly useful for experiments where correlation of particle parameters with a third quantity (in addition to the amplitude and duration of the detector signal) is needed. It is also used for sampling particle-parameter distributions in experiments involving too many particles to make measurements of each particle practical.

Automatic data analysis.

In the automatic mode of data reduction, the amplitude and duration of the detector signal are electronically plotted as a point on a two-dimensional display, rather than as a rectangular pulse. Displacement of a point in the Y direction on the display is proportional to the charge on the particle, while displacement in the X direction is proportional to its transit time through the detector.

Because each particle is represented by a single point, a large number of data points can be placed on a single display. The method of display also makes it possible to estimate the radius and velocity of a particle fairly accurately by inspection alone. An additional feature of the system is that information on the effect of particle impact after the particle has passed through the detector can also be indicated.

Visual estimation of the radius and velocity of a particle from its position on the display produced by the electronic X-Y plotter is made possible by the use of equal-radius curves. It can be shown (the derivation is given in Appendix G) that when the system variables are specified, the radius of a particle is defined by

$$\frac{r^3}{K} = yx^2 \quad , \qquad (7)$$

where K is dependent on the system variables. Lines of equal radius could therefore be plotted from yx^2 = a constant determined by K and the value chosen for r.

To avoid generating and plotting new sets of curves each time K is changed, a parametric radius R and an arbitrary constant K_1 are defined to have the relationship

$$\frac{R^3}{K_1} = yx^2 \quad . \tag{8}$$

Using an arbitrary value of K_1 and letting R take on different values, a family of equal-R curves can be plotted (see Fig. 4). From Eqs. (7) and (8),

$$\frac{R^3}{K_1} = \frac{r^3}{K}, \text{ or } r = \left[\frac{K}{K_1}\right]^{1/3} R \quad . \tag{9}$$

The curves generated for R are universal. Once a specified value for K is determined, the equal-R curves may be relabeled to reflect actual radii by use of Eq. (9).

Since the displacement of a point in the X direction is proportional to the reciprocal velocity of a particle, both particle velocity and radius can be determined fairly accurately by noting the position of the point with respect to the adjacent equal-radius curves and its X coordinate. The velocity and radius of a particle can be determined more accurately by interpolation along a line from the origin of the graph to the point. Substituting the equation of such a line, $y = Cx$, into Eq. (7) yields $r = (CK)^{1/3}x$; hence measurement of the slope C and the X displacement yields r precisely.

To facilitate measurements, an oscilloscope graticule with equal-R curves etched on it has been prepared. Since the data may be read directly from photographs of the display, the necessity of transposing data points has been eliminated.

Information on particle impact following passage through the accelerator is presented as a "yes-no" type of response, wherein short lines are recorded for "yes" events and points are plotted for "no" events. Details on this feature and on other aspects of the electronic X-Y plotter are given in Appendix G.

APPLICATIONS AND EXPERIMENTS

The accelerator facility described in the previous section has been used in a variety of experiments on hypervelocity impact phenomena. Most of the experimental work has been described either in published papers or in the form of technical reports submitted under the various contracts. Copies of these documents, which give detailed accounts of the various experiments, are appended to this report. For purposes of reviewing the experiments, they have been placed in the somewhat arbitrary categories under which they are described below. A previously published review article incorporating a similar discussion is included as Appendix H.

Transient Effects of High-Speed Impact

This terminology refers to effects observable only during the actual cratering, or impact process. The major items covered in this area are experiments on ionization processes, light flash, and momentum transfer upon impact.

From our experimental observations we have concluded that a quantity of material near the impact site of a high-velocity particle is vaporized by the large energy release associated with the impact, and that the temperature of the vapor is apparently high enough to result in ionization of some of the atoms. The vapor cloud must initially be very dense, but it expands rapidly because of high internal pressure. Since the expansion time of the cloud is short in comparison with the recombination time of the ions, weakly bound charges of both signs exist in the region near the impact site for a time following impact. The application of modest electric fields (on the order of 10^4 volts/meter) is sufficient to separate the charged particles from the vapor cloud, and the charge collected can be measured by straightforward techniques and examined as a function of particle impact parameters. Measurements of this kind using a variety of particle and target materials are discussed in Appendices I and J. The results of these experiments led to the conclusion that ions formed from atoms of the particle material were the predominant positive charge carriers. However, recent experiments (conducted under the TRW Systems Independent Research Program) suggest a much more complicated effect. In particular, easily ionized impurities (e.g., Na and K) may contribute to the measured effect.

Closely related to the impact ionization effect is the impact light flash from solid targets. In this phenomena a portion of the kinetic energy of the impacting particle manifests itself in the form of radiant energy that can be detected by the use of photomultiplier tubes. It should be emphasized that all of our experiments have been conducted in high vacuum so that only particles and target materials are involved in the emission process, whereas in experiments using large projectiles the main source of visible light would be the interaction of material ejected from the target with residual gas surrounding the target. In our tests, the radiant energy can derive from two sources: namely, blackbody radiation from material heated by the impact process, and emission from excited atoms in the vapor cloud near the impact site. No attempt has been made to assess the relative importance of the two possible light sources; however, radiation from the high-temperature vapor cloud is probably dominant. The experiments on impact light flash are discussed more thoroughly in Appendix K.

The impulse delivered to solid targets by the impact of high-speed particles is of interest both to studies of basic hypervelocity impact phenomena and development of micrometeoroid detection techniques. In studies concerned with the partitioning of energy upon particle impact, the kinetic energy of material ejected from the surface must be taken into account. Direct measurements of the mass and velocity distributions of ejecta have been relatively successful for large particle impacts, but much less is known about impacts by small particles. In principle, the mass-velocity product can be determined by determining the impulse delivered to the target by the departing material. One method of measuring impulse is to use a piezoelectric crystal transducer that is sensitive to impulsive loading. If the energetics of the impact process were firmly established experimentally, the inverse process could be employed to accurately calibrate the piezoelectric transducers that are used extensively as micrometeoroid detectors. The experiment described in Appendix L yields the over-all response of a piezoelectric crystal to the impact of a high-speed particle as a function of particle parameters for a rather specialized configuration. The experiment does not yield unambiguous results, but it does provide useful information.

Meteor Simulation

Much of what is known about the properties of natural meteoroids has been derived from observations of photographic and radio meteors. From this type of observation the velocity, acceleration, light intensity, ionization density, altitude of occurrence, and length of a meteor trail can be determined. To obtain values for the meteoroid mass and density, certain assumptions regarding the physical processes involved must be made. In particular, values for the drag and heat transfer coefficients and for the luminous and ionization efficiencies must be assumed.

Experimental verification of the values assumed for these quantities has been hampered by the difficulty of simulating the free-molecular-flow conditions under which most meteors are observed. Free molecular flow requires that the mean free path of air molecules be large compared to body dimensions. It is easily recognized that macroscopic bodies require very low-pressure gas targets to satisfy these conditions and that the interaction distances become impossibly long for laboratory simulation. If small particles, are used, however, the gas pressure can be increased to the point where experiments satisfying the aerodynamic requirements can be performed within a meter or so.

The experiments performed to data have been restricted to the measurement of heat transfer and drag coefficients for the special case of a solid particle. These measurements are described in some detail in Appendix M. The techniques developed in these experiments are directly applicable to the more general case of ablating meteors, and it is anticipated that measurements of this kind will be conducted in the future.

Hypervelocity Impact Studies

Traditional hypervelocity cratering and penetration studies represent a relatively small fraction of our effort, even though the application of such information to determining the hazard to spacecraft posed by meteoroids appears to be obvious. This lack of emphasis stems from two reasons: (1) a major effort would be required to develop satisfactory measurement techniques, and (2) there is some question as to whether or not the results would be directly applicable. As mentioned earlier, the chief hazard posed to spacecraft by meteoroids is bombardment by meteoroids somewhat larger than those available from our accelerator. The hydrodynamic model of hypervelocity impact, which usually is taken as an estimator of penetration at very high velocities, ignores heat conductivity and viscosity. These quantities are size dependent, and for large particles they are relatively unimportant and may be neglected. However, this may not be the case for micron-size particles. Comprehensive measurements to investigate this possibility has been deferred until recently. Early in 1965 a program with the objective of conducting cratering measurements with microscopic particles was begun under NASA Contract No. NASw-1116, which is under the technical direction of the NASA Ames Research Center.

Some measurements on the penetration of thin films by high-speed particles were undertaken and are described in Appendix N. These measurements were planned for use in connection with the development of micrometeoroid detectors and consequently are not subject to the size-scaling reservations discussed above.

Micrometeoroid Detector Development

One of the chief applications of our work is in the development of micrometeoroid detectors for satellites. With the exception of exploratory tests of a solid-state meteorite detector we have not developed any such detectors ourselves, but we have assisted NASA personnel in the development of several such instruments. This assistance ranged from discussion of fundamental concepts to tests of flight units. Generally, all quantitative test results have been retained by NASA personnel. A brief narrative discussion of some of the tests is given below.

The penetration of thin films by meteoroids is the triggering mechanism in a micrometeoroid detector developed by H. E. LaGow and L. Secretan of Goddard Space Flight Center. In this device, which was flown on the Explorer VII Satellite, a transparent substrate is coated with a thin, opaque film. The amount of light passing through the film is measured by means of an external light source and a sensitive photomultiplier tube. Since there are usually pin holes in thin films, a low-level current flows continuously in the photomultiplier tube. A micrometeoroid impact produces a small hole in the film, which then transmits more light to the photomultiplier tube and thereby causes an increase of current. The size of the hole and the magnitude of the resulting increase in phototube current are functions of the velocity and mass of the impacting micrometeoroid. The laboratory tests we made of the instrument consisted of measuring hole diameters as functions of film thickness, substrate material, and particle velocity and mass. The data relating the various quantities were retained by NASA personnel.

The cosmic dust detector on Ranger I, which was instrumented by W. M. Alexander and O. E. Berg from Goddard Space Flight Center, was also tested at our facility. This device simultaneously measured the magnitudes of impact light flash and momentum transfer by means of a crystal transducer affixed directly to the envelope of the photomultiplier tube. Our contribution in this program consisted primarily of determining the sensitivity and detection thresholds of the device. As before, data concerning detector performance were retained by the NASA personnel involved.

The micrometeoroid detector being used on the OGO series of spacecraft has been subjected to detailed experimental analysis in our laboratory. This unit, which was developed by W. M. Alexander of Goddard Space Flight Center, is designed to measure the direction, velocity, momentum, and possibly one other parameter of an impacting micrometeoroid. The detector consists of three separate cylindrical units mounted in a mutually orthogonal array. Each unit is collimated to accept particles incident within a relatively small solid angle. The direction of a micrometeoroid trajectory is specified by noting which of the units is activated by an event and the orientation of the spacecraft when it occurs. The velocity is determined from a time-of-flight measurement. Signals to initiate and terminate the time-of-flight measurement are derived from two capacitor-type elements, the first of which is edge-supported at the entrance aperture of the cylinder and the second of which is affixed to the "sounding board" of an acoustical detector. The momentum of the meteoroid is determined from pulse height analysis of the acoustical detector signal. The first capacitor is extremely thin to minimize the energy loss suffered by the meteoroid in passing through it, whereas the second capacitor element is not so critical and may be composed of thicker elements.

We have been involved with the OGO-type detector since its inception. Impact ionization detectors were originally proposed to generate the time-of-flight signals, but because tests indicated that signals from thin-foil ionization detectors were not compatible with the rest of the system, the capacitor type of detector was evaluated. NASA personnel developed a capacitor utilizing an aluminum-oxide dielectric and vapor-deposited aluminum plates with a total thickness as small as 1500 Å. In tests of these units no signals were observed when less than 5 volts was applied. In the range from 5 to 20 volts the signal amplitude was proportional to particle parameters, as it is in tests of the impact ionization effect. At slightly higher voltages, say 30 volts or so, each particle initiated a complete voltage breakdown of the capacitor, which then healed itself. It was proposed to operate the capacitors in the "proportional" 5 to 20 volt region, thus providing a redundant measurement of mass and velocity. In the final tests each component of a prototype unit was tested with complete success.

Our interpretation of the proportional region observed in the tests of penetration capacitor detectors led to the evaluation of conventional solid-state particle detectors for possible use as meteoroid detectors. We assumed that ion-electron pairs were produced in the space between the capacitor elements, but in an insufficient quantity to initiate capacitor discharge. If this interpretation is correct, the capacitor plates serve as collectors for the ions and electrons. Of course, the charged particles must possess sufficient mobility to reach the plates before recombination occurs. It is safe to assume that the dielectric near the impact point is vaporized so the mobility conditions are satisfied. This mechanism is very similar in operation to the semiconductor nuclear-particle detectors that have become widely used in recent years. Clearly, the charge production mechanism between nuclear particles and meteoroids would be different. However, the advantages offered by using conventional components, whose properties are well understood, is attractive. Accordingly, an n-type silicon surface-barrier diode with gold electrodes was tested. The results, although somewhat difficult to interpret and not very promising, are discussed in Appendix O. Further exploratory measurements appear desirable before the concept is abandoned.

A number of other isolated tests of components and concepts were also undertaken under NASA direction. Examples include tests of capacitor penetration detectors and cosmic-dust collection systems. As usual, test results were retained by the NASA personnel involved.

Miscellaneous Applications

In addition to its use in the experiments described in the preceding pages, the accelerator facility has been used for a variety of other applications. Some of this work was conducted under other NASA contracts and is mentioned here only to provide a comprehensive picture of our activities.

One such program is concerned with the effects of micrometeoroid bombardment on the radiation properties of highly reflecting metallic surfaces. The erosive effects of micrometeoroid bombardment produce a gradual change in the emissivity of the surface, which could cause a deterioration in the temperature-control function served by certain radiators. Experiments conducted under NASA Contracts NAS8-11149 and NAS8-20120 have demonstrated that a one-year exposure to the space environment would probably result in a measurable, but not necessarily serious change of radiative properties. At the present time we are conducting experiments designed to provide a basis for extrapolation from laboratory test results to the anticipated spatial environment.

For other types of components subjected to meteoroid bombardment, an impact could initiate transients that could affect the over-all performance of the component. For example, an ion propulsion engine utilizing the contact ionization concept exposes many vulnerable parts to micrometeoroid bombardment. Since ion engines operate close to the electrical breakdown point, an impact would be capable of initiating electrical breakdown between the ionizer and the accelerator grid. How damaging electrical breakdown might be would depend upon the particular circumstances and would be determined by factors such as the environment of ions and neutral atoms, field strengths and voltages, surface conditions, electrical circuitry, and location of the impact. These factors have been investigated and evaluated under the terms of NASA Contracts NAS3-3569 and NAS3-5755, which were under the technical direction of NASA Lewis Research Center.

As an outgrowth of the work on ion engines a general study of vacuum electrical breakdown initiated by particle impact was undertaken under the present series of contracts. This work is summarized in Appendix P. These experiments were restricted to higher voltages and fields than those used in the ion-engine simulation work and were designed to test the validity of the Cranberg hypothesis of vacuum electrical breakdown. This hypothesis, which was modified by Slivkov, suggests that electrical discharge between planar electrodes is initiated by the impact of a small clump of matter on one of the electrodes. The vapor produced by the impact raises the pressure locally to the point where a low-pressure arc is formed between the electrodes. The hypothesis predicts that micron-size particles are capable of initiating discharge and that fragments of this size are always present, even on clean electrodes. Our work was devoted to determining the parameters of particles capable of initiating discharge. Since the particles were obtained from the accelerator, the test results do not verify the existence of breakdown-initiating particles in the general case. However, the experiments have demonstrated that breakdown can be initiated in this manner and provide an independent means of determining the parameters of particles required to initiate discharge.

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Abstracts of Formal Publications

1. H. Shelton, C. D. Hendricks, Jr., and R. F. Wuerker, "Electrostatic Acceleration of Microparticles to Hypervelocity", Journ. of Appl. Phys., Vol. 31, 1243, July 1960.

By electrostatic methods, μ-diam spheres of iron have been accelerated to hypervelocities. Techniques have been developed to give single impacts in vacuum of measured incident velocity, mass, and position.

2. J. F. Friichtenicht, "Two-Million-Volt Electrostatic Accelerator for Hypervelocity Research", Rev. of Sci. Inst., Vol. 33, 209, February 1962.

A 2,000,000-V Van de Graaff positive ion accelerator has been modified to accelerate micron-sized charged particles for studies of high speed impact and for micrometeor simulation. Modification was accomplished by replacing the ion source by a particle charging and injection system. The particles are contact charged to values resulting in electric field strengths at the surface of the particle of about 2.5×10^9 V/m. Using iron spheres, final velocities up to 14 km/sec have been observed. Techniques for measurement of particle parameters have been developed and measurements of the focusing properties of the modified accelerator are discussed.

3. J. F. Friichtenicht and J. C. Slattery, "Ionization Associated with Hypervelocity Impact", NASA TECHNICAL NOTE, TND-2091, August 1963.

Interest in the development of micrometeoroid detection systems has led to a program of research at Space Technology Laboratories, Inc., where efforts have been concentrated on phenomena associated with hypervelocity impact which have properties applicable to such systems. It has been found that electrically charged particles are emitted from the site of a hypervelocity impact. Presumably, the large energy release associated with the impact is sufficient to produce ionization and the ions or electrons can be extracted by means of electrical collector systems. The quantity of charge emitted from semi-infinite targets as a function of target material, projectile material, and particle velocity and mass was measured. The experiments were conducted with micron-sized iron and carbon black (graphite) particles from the STL electrostatic hypervelocity accelerator. Data were collected for velocities up to 16 km/sec. All of the data fits the empirical relationship $Q_c = K E_p \frac{v}{A}$, where Q_c is the charge collected, K a constant, E_p the particle energy, A the atomic weight of the particle material, and v the particle velocity. The quantity K contains target material parameters and has not been evaluated, as yet. Qualitative observations of ionization produced from thin foil impacts have also been made.

4. J. C. Slattery, J. F. Friichtenicht and B. Hamermesh, "Interaction of Micrometeorites with Gaseous Targets", AIAA Journ., Vol. 2, 543, March 1964.

Experiments have been conducted on the interaction of simulated micrometeoroids with gaseous targets. Iron spheres from 0.5 to 2.0 μ in diameter were accelerated to speeds up to 7 km/sec in the Space Technology Laboratories (STL) electrostatic accelerator. Oxygen, argon, and air were used as target gases. Gas pressures ranged from 1 to 2 mm Hg, which insured that conditions for free molecular flow were realized. Values of the drag coefficient Γ and the heat-transfer coefficient λ were determined. In this paper, λ is defined as the fraction of particle kinetic energy converted to internal energy and is applicable only for solid particles. The results are consistent with a value of Γ nearly equal to one for all of the gases. The values of λ depended upon the gas used and ranged from 0.8 to about 1.0.

5. J. F. Friichtenicht, "Micrometeoroid Simulation Using Nuclear Accelerator Techniques", Nuclear Inst. and Methods, Vol. 28, 70, June 1964.

A two-million volt Van de Graaff accelerator has been modified so as to accelerate microparticles (dimensions the order of microns) to high velocities for micrometeoroid simulation. The modification will be described and the program of research on the physics of high speed impact, which has been undertaken using the facility, is discussed.

6. J. C. Slattery, J. F. Friichtenicht, and D. O. Hansen, "High Voltage Breakdown Initiated by Particle Impact", Applied Physics Letters, Vol. 7, 23, July 1, 1965.

The high voltage electrical breakdown hypothesis of Cranberg suggests that the discharge arises from the impact of small particles on one of the electrodes. Under normal circumstances the existence or properties of such particles cannot be verified by direct observation. A technique whereby particles with known parameters are directed against one of the electrodes has been developed and measurements have been made. The results are somewhat qualitative, but some definite conclusions can be reached. The main conclusion is that particle impacts are capable of initiating discharge for wide ranges of voltages, electric fields, and particle parameters. For a given voltage and electric field, the existence of a low-energy limit for particles capable of initiating discharge has been verified. Significantly lower energy particles are required to initiate discharge when the impact point is the cathode rather than the anode. Although these measurements are preliminary in nature, it appears that continued work in this area could provide very useful information.

7. D. G. Becker, J. F. Friichtenicht, B. Hamermesh, and R. V. Langmuir, "Variable-Frequency Radially-Stable Micrometeoroid Accelerator", Rev. of Sci. Instr., Vol. 36, 1480, October, 1965.

A linear accelerator for micrometeoroids, employing a Wideröe-Sloan-Lawrence configuration, is described. The accelerator is operated in the radially-stable mode, and the frequency of the accelerating voltage is automatically adjusted to accept charged microspheres with q/m ~1-300 coul/kg. The waveform applied is a "drooping square wave" which allows focusing adjustments to be independent of frequency and phase. The change in phase over 93 gaps can be kept sufficiently small by proper selection of droop and other parameters so that acceleration occurs at all gaps. Injection is at 1.6 Mv from a modified Van de Graaff. The linac adds an additional 9.3 Mv. Speeds up to 70 km/sec should be reached with 0.1 μ diameter microspheres.