Feasibility Report

Hypervelocity Particle Breakup Analysis and Experiment

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Hypervelocity Particle Breakup Analysis and Experiment

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For
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FOREWORD

This document was prepared, by the Martin Company, to describe a portion of the work accomplished under the Strontium-90 Fuel Development program Contract AT(30-1)-3062, for the Division of Isotope Development, Atomic Energy Commission. In the first part, a theoretical model is developed to predict the debris size distribution from the breakup of molten particles under the action of aerodynamic re-entry forces. The second section describes an experiment which proved the feasibility of using a light gas gun to accelerate micron-size particles into a simulated altitude chamber at re-entry velocities. The experiments were conducted by the Ballistic Research Laboratories at Aberdeen Proving Ground, Aberdeen, Maryland.

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SUMMARY

The statistical mechanical approach for describing molten droplet breakup appears to be an effective analytical tool. However, the equations presented herein require revision, perhaps by expanding the energy partitioning functions so they agree with subsonic and near-sonic experimental data. The feasibility of launching and observing particle behavior at hypersonic speeds has been demonstrated. As a result, the light gas gun facility can be used to exactly duplicate the dynamics of particle re-entry and provide breakup data in support of the analysis.

I. INTRODUCTION

During the re-entry destruction of an isotopic generator, the mechanisms of fuel form ablation must be predictable to properly assess the nuclear hazard associated with the event. Ultimate land deposition patterns and contaminant densities are directly a function of the final ablative particle size. One mechanism of fuel form ablation is the mechanical breakup of molten material by aerodynamic forces created during hypervelocity re-entry. The object of this study was to determine the feasibility of describing the breakup phenomenon by statistical mechanical analytic techniques, and to determine the applicability of employing a light gas gun and a controlled environmental range to experimentally observe the breakup phenomenon.

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II. STATISTICAL MECHANICAL APPROACH

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The breakup of liquid droplets is discussed extensively in the literature, but only for the case of low Mach numbers. Most of the work is empirical. Theoretical approaches to quantitative description range from restricted solutions of the Navier-Stokes equation of fluid dynamics to approximating droplet size with a critical Weber radius (above which shear force exceeds surface tension). Unfortunately, these methods do not give a distribution of particle sizes necessary for determining atmospheric residence time and the ground dispersion pattern.

High-speed photographs of the breakup process for water and other liquids reveal that it is extremely chaotic, even at low Mach numbers. Initial droplets of equal size each break up differently in a random manner. The only constraints on the process are the total mass and energy, which must be conserved. Thus, the general problem really concerns a system of many molecules, contained in the original droplet, subject to overall, decisive physical constraints. This implies statistical behavior and suggests using the methods of statistical mechanics.

Most applications of statistical mechanics are to gas dynamics, thermodynamics, solid state physics, quantum behavior and, in general, to problems involving atomic and nuclear particles. But there is no fundamental restriction to such relatively small objects. It is sufficient that the subject system be many-bodied. Thus, one notable application is determination of the planetary distribution in our solar system, starting with known total angular momentum and mass. (Hart, R. W. and Guier, W. H.; "Statistical Treatment of Weakly Interacting Particles in a Newtonian Potential," *Phy. Rev.* 97, 4, 841 (February 15, 1955).) The present application to droplet breakup is similar but relatively simple.

A. FORMULATION

Consider the set of particles resulting from breakup of a liquid droplet. The particles have various sizes and speeds, with the original droplet volume distributed over the particle volumes, and the original droplet energy distributed over the particle kinetic, surface tension and viscous energies. Assuming that the droplet breakup is indeed chaotic, so that statistical mechanical principles do apply, the most probable distribution of particle sizes will be found.

To make the statistical approach valid, a many-bodied system is needed. Consequently, work is done with the individual molecules in the original droplet and the number of ways these N molecules may be assorted into particles, with m_1 particles of ℓ molecules each, m_2 particles of $\ell + 1$ molecules each, ..., and m_k particles of $\ell + k - 1$ molecules each considered. (See Table 1 for symbol definitions.)

$$W = \frac{N!}{\prod_{k=1}^{\infty} m_k! (\ell + k - 1)!^{m_k}} \quad (1)$$

The lower limit on the number of molecules per article is necessary, in general, since the surface energy density increases with decreasing particle size and the total system energy is finite.

The $N!$ in Eq (1) gives the maximum number of ways of assigning the N particles: N choices for the first one, $N-1$ for the second, etc. In each particle with $\ell + k - 1$ molecules, however, the $\ell + k - 1$ choices can be made in any order without affecting the distribution, since all molecules are identical. Therefore, W must be reduced by $(\ell + k - 1)!$ for each particle. There are m_k particles of this size so that W must be reduced by $(\ell + k - 1)!^{m_k}$ times. Furthermore, each of these m_k particles is identical and the $m_k!$ ways of choosing an assembly sequence all result in the same distribution. These two corrections, one at the molecule level and one at the particle level, must be made for all particle sizes; hence, the product over k in the denominator.

TABLE 1
Symbol Definitions

A	=	molecular mass
$b = \frac{A}{\rho N_a}$	=	molecular unit volume; N_a = Avagadro's number
$C = Ne^{-\alpha}$	=	normalized number of molecules
E	=	kinetic energy of original droplet
g_k, g_v	=	molecular and volume distribution function, respectively
m_k	=	number of particles of k molecules each
N	=	total molecules in original droplet

TABLE 1 (continued)

v, V	=	particle volume and original droplet volume, respectively,
W	=	system disorder (number of ways of arranging the molecules)
α	=	normalizing multiplier
ϵ_k	=	energy in particle of k molecules
$\gamma = E/V$	=	energy density
η	=	viscosity
ρ	=	density
σ	=	surface tension
τ	=	breakup time
ℓ	=	lower limit on number of molecules per particle

Note that Eq (1) contains no energy partitioning. In most statistical mechanical problems, a set of energy levels is also considered, since the system particles are free to collide and exchange energy. In a mixture of light and heavy gases, for example, the heavy molecules have the same mean energy as the light molecules, and their average speed is slower. In the present case, it is experimentally known that the smaller particles are moving more slowly than the larger particles, immediately after breakup. This is apparent from photographs of the breakup process, which show the smaller particles forming at the rear (bag-shape deformation at low Mach numbers) or trailing edges (hemisphere deformation at high Mach numbers). Furthermore, all molecules in the initial droplet are moving together uniformly, at the same speed (discounting their random vibrational energy), and are suddenly separated, with no subsequent energy exchange. Thus, it is expected that the actual particle energy distribution will be approximated by a constant volume density. The energy variable can be disposed of with the equations:

$$\begin{aligned} \epsilon'_k/k &= \text{constant} = E/N = \gamma b \\ \epsilon'_k &= b_k = \gamma v_k \end{aligned} \tag{2}$$

where ϵ'_k is the total energy of a particle of k molecules. This is the only constraint on energy considered. It implies that the smaller particles have lower speed, since a larger fraction of their fixed energy density appears as surface energy. This will be discussed quantitatively after formulating the particle size distribution.

In a truly chaotic breakup, the degree of disorder given by Eq (1) will be a maximum. $\ln W$ will be maximized, since N is a large number. Using Stirling's approximation,

$$N! \approx N^N e^{-N} (2\pi N)^{1/2} \quad (3)$$

and neglecting terms in $(2\pi N)^{1/2}$,

$$\ln W = \ln \frac{N^N e^{-N}}{\prod_k \left(m_k^{m_k} e^{-m_k} \right) \left(k^k e^{-k} \right)^{m_k}} \quad (4)$$

where $k = \ell + k' - 1$ has been substituted for simplicity. Equation (4) becomes

$$\ln W = N \ln N - \sum m_k \left[(\ln m_k - 1) + k \ln k \right] \quad (5)$$

$$= \sum m_k \left[k \ln N - (\ln m_k - 1) - k \ln k \right] \quad (6)$$

since the constraint

$$N = \sum k m_k \quad (7)$$

allows canceling the exponentials in N and k , in Eq (4), and replaces the coefficient of the $\ln N$ term in Eq (5).

The necessary condition for maximum W is that the m_k have such values that small variations in them do not affect W :

$$\sum \frac{\partial}{\partial m_k} \left[\ln W \right] \delta m_k = 0 \quad (8)$$

or

$$\sum (k \ln N/k - \ln m_k) \delta m_k = 0 \quad (9)$$

and since the δm_k are arbitrary, it is necessary to have

$$m_k = \left(\frac{N}{k} \right)^k. \quad (10)$$

But these m_k are obviously not normalized properly since Eq (10) indicates that one of the many particles produced in the breakup ($k = N$) is as large as the original droplet. Thus, $m_N \ll 1$ is required for proper normalization.

The m_k is constrained by maximizing W subject to Eq (7). Using the method of undetermined coefficients, multiply Eq (7) by a constant, α , subtract from $\ln W$ and again consider small variations about the m_k :

$$\sum \frac{\partial}{\partial m_k} [\ln W - \alpha (\sum k m_k - N)] \delta m_k = 0 \quad (11)$$

$$\sum \frac{\partial}{\partial m_k} m_k [k \ln (N/k) - (\ln m_k - 1) - \alpha k] \delta m_k = 0 \quad (12)$$

where summation signs have been dropped from Eqs (6) and (7) since only terms in m_k contribute to the derivative. Differentiating,

$$\sum \left[m_k \left(-\frac{1}{m_k} \right) + k \ln (N/k) - (\ln m_k - 1) - \alpha k \right] \delta m_k = 0 \quad (13)$$

and since the δm_k are arbitrary,

$$m_k = \left(\frac{N}{k} \right)^k e^{-\alpha k} = \left(\frac{C}{k} \right)^k \quad C = N e^{-\alpha} \quad (14)$$

is the condition necessary for maximum W . The functional relationship is perhaps clearer if Eq (14) is rewritten as

$$k \cdot \sqrt[k]{m_k} = C. \quad (15)$$

Equation (14) has the exponential character of statistical mechanical partition functions, since the total number of particles is fixed, but the $(N/k)^k$ factor makes the function drop off toward zero as k approaches one. The maximum occurs for

$$\frac{d m_k}{d k} = 0 = \frac{d}{d k} \left(\frac{C}{k} \right)^k = \frac{k^k (C^k \ln C) - C^k k^k (1 + \ln k)}{k^{2k}} \quad (16)$$

$$= - \left(\frac{C}{k} \right)^k [1 + \ln (k/C)] = 0 \quad (17)$$

or when

$$k = C/e. \quad (18)$$

A more useful form of the condition for maximum W is in terms of the fraction of molecules contained in particles of k molecules each:

$$g_k = \frac{k m_k}{N} = e^{-\alpha} \left(\frac{C}{k} \right)^{k-1} \quad (19)$$

Multiplying the numerator and denominator of Eq (19) by b gives the fraction of original droplet volume contained in particles of volume, v:

$$g_v = \frac{v m_v}{V} = e^{-\alpha} \left(\frac{b C}{v} \right)^{(v-b)/b} \quad (20)$$

Differentiating Eq (19) or (20) shows that these two functions have their maximum where k equals the special value $\hat{k}$, satisfying the equation

$$C = \hat{k} e^{(\hat{k}-1)/\hat{k}}.$$

A Newton-Raphson expression yielding $\hat{k}$ iteratively is

$$\hat{k}' = \hat{k} + \left(\frac{\hat{k}}{\hat{k}+1} \right) \left[C e^{-(\hat{k}-1)/\hat{k}} - k \right].$$

An expression leading to a numerical value of α is obtained by summing Eq (19) over all particles, corresponding to Eq (7):

$$1 = \sum g_k = \sum \frac{k m_k}{N} = e^{-\alpha} \sum_{k=\ell}^N \left(\frac{C}{k} \right)^{k-1} \quad (21)$$

where $k = \ell + k' - 1$ has been written from Eq (1) to emphasize the actual limits of summation.

It is not possible to sum analytically since the general term

$$a_{k+1} = a_k \left[\frac{C}{k} \left(\frac{k}{k+1} \right)^k \right] = \prod_{j=1}^k \frac{C}{j} \left(\frac{j}{j+1} \right)^j \quad (22)$$

does not progress arithmetically or geometrically. It diverges in the range of interest, $k < c$, but since this range is finite, the sum is finite also.

The summation in Eq (21) can be done numerically with an estimated α , even for molar magnitude values of N , and an improved α can be obtained to any desired accuracy by iteration:

$$\alpha' = \alpha - \frac{1 - e^{-\alpha} \sum_{\ell}^N \left(\frac{C}{k}\right)^{k-1}}{e^{-\alpha} \sum_{\ell}^N \left(\frac{C}{k}\right)^{k-1}}$$

where, as in the expression for k above, a Newton-Raphson form has again been used.

The particle speeds after breakup are determined after considering Eq (2) in greater detail. Substituting the surface tension and viscous energy terms in Eq (2) and solving for the kinetic energy give

$$\epsilon = \gamma_v - \sigma' v^{2/3} - 32 \eta v / \tau \quad (23)$$

where $\sigma' = (36 \pi)^{1/3} \sigma$. The viscous term is an approximation based on Poiseuille's law, assuming (per Gordon) that a cylindrical plug of length and diameter equal to the particle diameter is extracted from the original droplet:

$$\begin{aligned} Q \text{ (flow rate)} &= \frac{\pi R^4}{8 \eta L} \Delta P \\ &= \frac{R^2 \cdot \Delta F}{8 \eta L} \left(\Delta P = \frac{\Delta F}{\pi R^2} \right) \\ &= \frac{\frac{1}{4} L^2 \cdot \Delta F}{8 \eta L} \left(R = \frac{1}{2} L \right) \\ &= \frac{L \Delta F}{32 \eta} \\ &= v / \epsilon \end{aligned} \quad (24)$$

so that the last term in Eq (23) is for the viscous energy, $L \Delta F$.

The particle speed immediately after breakup is therefore

$$\dot{s} = \sqrt{\frac{2}{\rho} (\gamma - \sigma' v^{-1/3} - 32 \eta/\epsilon)} \quad (25)$$

and corresponding to $\dot{s} = 0$, there is a minimum possible particle size

$$v_0 = \left(\frac{\sigma'}{\gamma - 32 \eta/\epsilon} \right)^3 \quad (26)$$

and corresponding lower limit on the summation in Eq (21):

$$\ell = \frac{1}{b} \left(\frac{\sigma'}{\gamma - 32 \eta/\epsilon} \right)^3 \quad (27)$$

Note that according to the very approximate treatment of the viscous effects, the original droplet will not break up if

$$\tau \leq \frac{32 \eta}{\gamma} . \quad (28)$$

The burden of accounting for viscosity in these equations obviously rests on the breakup time, which must be estimated or obtained independently. In lieu of a model for hypersonic breakup time, Gordon's subsonic model may be used as an approximation. It gives as an approximate solution for breakup time:

$$\tau = \frac{2d \sqrt{\rho \xi}}{\sqrt{W_e - W_{eC}}} + \frac{32 \xi \eta}{W_e - W_{eC}}$$

where $\xi = \frac{d}{2\sigma}$ and W_{eC} is the critical Weber number.

B. COMPUTATION STRATEGY

To predict the particle distribution for specified initial conditions, Eqs (27), (21) and (20) must be applied, in that order. Equation (27) determines the lower limit on the summation in Eq (21), which must be solved iteratively for α . The size distribution is then available from Eq (20). Typical results from an appropriate FORTRAN IV program are shown in Fig. 1.

Fig. 1. Size Distribution of Debris from Breakup of Molten Plutonium Fuel Droplet

Fig. 2. Strontium Particles and Five 1/32-Inch Steel Balls Loaded on 0.3-Inch Diameter Lexan Sabot

C. DISCUSSION OF RESULTS

The results in Fig. 1 are for a plutonium compound fuel but, as explained in the next paragraph, a similar absolute mean size, i. e., millimicron mean diameters, would be obtained for a strontium compound fuel droplet. Note that the size distribution is essentially a delta function, the diameter scale being greatly expanded. The general characteristics of this result are plausible, although no experimental data exist to be used as an explicit check. The SNAP 9A debris appears to be of submicron size (Ref. 1), but it is probably so because of evaporative ablation. Also, it is not clear whether breakup would occur before or after oxidation. Note that natural aerosols are frequently of submicron size (Ref. 2).

Unfortunately, while the results in Fig. 1 are plausible for re-entry conditions, the same model does not agree with the experiments for subsonic and near-sonic conditions. The experiments of Bitron (Ref. 3), for example, give micron-size debris while the model herein predicts millimicron-size debris. Essentially, the present model is relatively insensitive to the various physical parameters concerned: velocity, surface tension, density, viscosity, etc. These enter as constraints on the minimum possible particle size consistent with total initial energy conservation (Eq 27), but have little effect. Attempts to arbitrarily constrain the breakup to some larger minimum debris size result in an even more strongly peaked delta function at that specified minimum size.

D. CONCLUSIONS

The initial assumption of a uniform volume distribution of total particle energy after breakup, Eq (2), is evidently not consistent with actual chaotic conditions, at least for subsonic and near-sonic droplet speeds. The objective of this assumption was to make the debris particle speeds after breakup agree qualitatively with the experimental observation, i. e., that smaller debris moves more slowly than larger. That is, Eq (25), which follows from Eq (2), should yield an $\dot{s}$ which diminishes with decreasing particle volume, v . This is true functionally, but on substituting actual numerical values, the surface tension and viscous terms under the root sign are relatively insignificant compared to the KE term, γ , so that $\dot{s}$ tends to be independent of debris size--all debris having the same speed as the initial droplet. Thus, the objective of assuming Eq (2) is not achieved.

Evidently then, Eq (2) must be revised to allow the energy density, γ , to depend on final particle size, i. e., $\gamma = \gamma(v)$, although the appropriate functional form is not immediately apparent. It may be deducible, however, by rewriting Eq (1) to include partitioning on energy, i. e., by including an ϵ_k , in addition to the present m_k . This generalization should be the object of further study.

III. EXPERIMENTAL PROGRAM

Author: Walter Braun; BRL, APG

The experimental investigations were designed:

- (1) To develop techniques for accelerating fuel particles to hypersonic velocities from a light gas gun into a simulated high altitude environment.
- (2) To evaluate some photographic methods for obtaining proof of launch.
- (3) To make observations on the physical condition of the particles during flight.

This phase of the investigation was conducted in a range facility at the Ballistic Research Laboratory, Aberdeen Proving Ground, under a contract with the Atomic Energy Commission.

A. GENERAL DESCRIPTION OF THE EXPERIMENT

The experiment involved extending and defining the limitations of the present techniques of ballistic model testing (Ref. 4) in supersonic and hypersonic ranges to include spherical micron-size particles. The initial step in the experiment was, necessarily, the development of methods of launching the particles at the required velocities. Concurrent with this effort was the requirement for obtaining proof of launch conditions. Three types of observations were used to obtain this evidence: the spark shadowgraph, the streak camera and a target.

The ballistic models were spheroidal particles of a strontium compound with diameter ranges varying from 100 to 150 microns. Other particles that were available for control observations were: steel balls with 1/32-inch diameters (794 microns); steel shot with a range of diameters from 125 to 400 microns; glass spheres with 33- and 100-micron diameters. Figure 2 shows five steel balls with 1/32-inch diameters and about a hundred strontium particles on the sabot. Figure 3 shows a couple of hundred steel shot on the sabot. One variance from normal ballistic testing is the large number of models or particles fired with each round.

The sabot and particles were fired from a typical light gas gun as shown in Figs. 4 and 5. This type of gun is capable of launching models in the velocity range of 10,000 to 20,000 fps. Appendix A tabulates the flight and photographic observations for the 40 rounds which were fired.

—→ | ← 0.1 in.

Fig. 3. Steel Shot Size 125 to 400 Microns Loaded on 0.3-Inch Diameter Lexan Sabot

Fig. 4. The Light Gas Gun with 37-mm Pump Tube and 0.30-Inch Launch Tube

Fig. 5. Drawing of Light Gas Gun

Fig. 6. High Altitude Simulation Range

Fig. 7. Spark Shadowgraph Station in the Range

The gun was mounted in an available High Altitude Simulation Range Facility as shown in Fig. 6. The gun is located in the eight-foot diameter tank at the left. The 10-foot diameter tank at the right was used as the instrumented range area. Spark stations, streak cameras and target or recovery are located here. These are shown in Figs. 7, 8 and 9 of the interior of the range. This range facility can be evacuated to an absolute pressure of less than 0.1 mm.

One problem is separating the small particles from the sabot. Because of the differences in size, and notwithstanding the advantages of specific gravity and of shape, the small spherical particles will decelerate faster than the sabot and (assuming separation was achieved) unless the sabot is deflected promptly from the trajectory, it will plunge through the field of small particles, disrupting their trajectory.

A sabot retarding technique is used to separate the micron particles from the sabot (Ref. 5). A deceleration tube on the end of the gun slows the sabot but not the particles. At the end of the deceleration tube a one-degree ramp causes the sabot to deflect from the normal trajectory. At 12 feet from the gun muzzle, a steel baffle wall with an orifice made from a two-inch pipe nipple six inches long prevents the sabot from entering the range area but permits particles to enter the range area.

The usual procedure in ballistic model testing is to use a photoelectric screen to trigger the spark station and take the pictures of the model. Typical equipment for nonluminous missiles can work on a decrease in light of approximately 1% falling on the phototubes. Since a 100-micron diameter would cause a change in light level of less than 0.01%, another scheme for triggering the spark station was devised.

The small strontium particles decelerate rapidly even at reduced pressure in the range. Steel balls with 1/32-inch diameters do not lose velocity as fast. If both types of particles are loaded on the sabot, their muzzle velocities should be the same. The steel balls will enter the range area first and can initiate a trigger screen which in turn starts four time delay circuits. At the end of the preset times, the various spark gaps are triggered. Velocity versus distance from the muzzle and time versus distance from the muzzle were computed for four sizes of strontium particles and the steel balls at several range pressures and muzzle velocities. These data are shown in the graphs of Figs. 10 through 14. The assumption was made that the particles were spheres and constant value, $C_D = 0.9$, was used in the computation. Mass was obtained from specific gravity and volume computations. The vertical bands on the graph marked Station 1, etc., represent the field of view along the trajectory covered by the four orthogonal spark shadowgraph stations. A mylar trigger screen was located

Fig. 8. Streak Cameras Focused on the Trajectory

Fig. 9. Streak Cameras and Spark Gap Location in Range

Fig. 1. Velocity and Time vs. Distance from Gun Muzzle

Fig. 11. Velocity and Time Versus Distance from Gun Muzzle

Fig. 12. Velocity and Time Versus Distance from Gun Muzzle

Fig. 10. Velocity and Time Versus Distance from Gun Muzzle

Fig. 11. Velocity and Time Versus Distance for 1/32 in. Steel

between Stations 3 and 4. From the graph, the time the steel spheres would penetrate the trigger screen is known. The time delay for Station 4 is selected so that the steel balls would be in the center of the station if the muzzle velocity and the drag are as predicted. The large width of the station allows for wide dispersion in muzzle velocity. Measurements of the plates will give the average velocity between the trigger screen and the photograph. By reading the charts, one can predict what is in the field of view of the other three stations at various times related to the trigger time. The technique of operation is to predict the velocity history of the particles and the steel balls, to select the proper time delays, to fire the round, and then to search the photographic plates for evidence of strontium particles.

Streak cameras were focused on the trajectory to record any luminous particles that were launched. These are shown set up in the range in Figs. 8 and 9.

Two types of targets were used. Both are associated with the trigger screen. Initially, the trigger screen served to both trigger the station and provide evidence of impacting hypervelocity particles. Two objections were in evidence after a few rounds. First, the aluminized trigger screen generated light (electric arcs when the missile shorted the screen) and reflected muzzle flash to fog the spark station plates. Second, it is difficult to differentiate between holes in the screen and imperfections in the aluminum coating. After a limited search for a dark opaque target material, a plastic sheet film was used ahead of and after the mylar trigger. This prevented fogging the plate and the material could be examined with transmitted light from a film viewer. However, on several rounds there is evidence that the particles ricocheted off the film and did not penetrate the screen. The steel spheres always penetrated the plastic screen.

In addition to the firings conducted in the High Altitude Simulation Range, a limited number of rounds were fired at ambient atmospheric pressure conditions. Procedures and equipment were the same as described herein. Some changes in working distances were necessary because of the extreme deceleration of the particles.

1. Range Environment

The gun and shadowgraph stations were set up in an available High Altitude Simulation Range, Fig. 6. The tanks were, respectively, 8 and 10 feet in diameter and both were 30 feet long. Vacuum pumps were available to evacuate the range to an absolute pressure of 19 mm in approximately one hour. The ultimate operating pressure in the tank was 10 microns. The gun was set up in the tank having an eight-foot diameter and the station equipment was placed in the 10-foot diameter tank. Time interval counters, power supplies, time delays units and firing circuits were located in the trailer.

2. Light Gas Gun

The light gas gun used to accelerate the particles was a 37 mm/0.30 caliber gun. The essential dimensions are shown in Figs. 4 and 5. Operational conditions such as powder charges and helium gas charges were established for the range of velocities between 10,000 and 20,000 fps. These are tabulated as follows:

<u>Weight Missile-Sabot</u> <u>(gm)</u>	<u>Powder Charge</u> <u>(grains)</u>	<u>Helium Pressure</u> <u>(psi)</u>	<u>Velocity</u> <u>(fps)</u>
0.45	800	150	12,500
0.45	950	150	15,000
0.45	1300	110	17,500

Several comprehensive reports on the operation of light gas guns are available (Ref. 6), thus, only a very brief description of its operation will be given. The burning powder charges accelerate the piston to a supersonic velocity. The piston compresses the inert light gas.

At the prescribed pressure, a shear disk in back of the sabot breaks and the high temperature, high pressure helium accelerates the missile to the hypersonic velocity.

A device that was added to the launch tube is the deceleration tube and the deflection ramp. The function of these items is to separate the sabot from the model or particles and deflect the sabot so it does not enter the range area.

The deceleration tube is a two-foot extension added to the launch tube. A mylar diaphragm, 0.0005 inch thick at each end of the deceleration tube, separates it from the launch tube and the range. The launch tube is usually pumped to a low pressure. The range area is, of course, at the required test pressure. The sabot, upon entering the deceleration tube, generates a shock wave in the one-atmosphere air column, raising its pressure to a level greater than the driving pressure. This produces a decelerating force which acts on the forward face of the sabot, while the particles travel onward in the high pressure gas region and are not decelerated. Ideally, there should be no gas flow over the particles as they have the same velocity as the shock compressed gas and thus the pressure is uniform over their entire surface.

At the end of the deceleration tube, a deflection ramp with a one degree inclination diverts the sabot from its normal trajectory, causing it to impact on a baffle wall about 12 feet from the muzzle of the gun.

Geometry of Spark Photography Station
used to take photographs in Fig. 16

Particle Diameter (microns)	Distance (in.)		Image Diameter (microns)			Geometrically Projected Diameter
	Y	X	Central Dot	Gray Area Maximum Diameter	Fringe Ring	
33	50	4	100	300	500	36
100	50	4	100	300	500	107
33	46	8	100?	500	700	39
100	46	8	100	400	700	116
33	42	12	?	700	900	43
100	42	12	?	600	1000	128

Strontium Particles. Diameter = 100 to 150 microns

100-150	50	4	100	300	500	107-160
100-150	46	8	100	400	700	116-174
100-150	42	12	100?	600	1000	128-192

Fig. 15. Static Spark Shadowgraph of Small Particles

3. Sabot and Strontium Particles

The function of the sabot in all gun-launched missiles is to provide support for the model, to distribute the accelerating forces to the model and to obturate in the launch tube where the missile does not fill the bore of the gun completely. In this case, a simple sabot design was selected--a 0.2 inch length lexan cylinder a few thousandth inch over the bore diameter. The models or particles were five steel spheres each 1/32 inch and many spheroidized strontium particles ranging in size from 100 to 150 microns in diameter. The technique for loading the sabot is as follows: Five small dimples were made with a 1/32 inch drill on the front sabot face. These were less than a radius deep. A layer of vacuum grease was placed on the sabot and carefully wiped off with a paper towel. The remaining vacuum grease provided sufficient adhesion so that the five steel spheres and the micron particles would stick to the sabot face. About a hundred micron particles were placed in a random manner by sprinkling them on the sabot from an improvised salt shaker. Figures 2 and 3 show the sabot ready to be loaded in the gun.

4. Spark Photography Shadowgraph Station

In experience with spark photography techniques in supersonic ballistics, observations have been made of small particles in flight at high velocities. Since these particles had not been launched intentionally their size could not be adequately described. It was considered that the technique could be useful in identifying the strontium particles in free flight and, thus, it would be important to establish some of the limitations of the method.

The basic shadowgraph station is shown in Fig. 15. The sketch shows the location of the point light source, the trajectory and the photographic plates. The station is used in pairs at right angles to obtain an orthogonal projection of the missile. For normal operation, the light source of 0.3 μ sec duration is triggered when the missile is between the light source and the photographic plate, producing a silhouette of the object and the air disturbances. With this geometry, the source which has a 0.040 inch diameter is about 10 times larger than the particles. For this size the image formed by the stationary particle is the characteristic Fresnel diffraction pattern of a circular obstacle which produces a bright spot in the center of a gray shadow with several diffraction rings.

Since the light source is not monochromatic, but only essentially blue and since for the geometry the Fresnel half-zone radii is larger than the spheroid, the pattern is not distinct. Figure 16 shows the images of two sizes of spheres, 33- and 100-micron diameters at 4, 8

Glass Beads, 33 Microns in Diameter

Glass Beads, 100 Microns in Diameter

4 in.

8 in.

12 in.

Strontium Spheroids, 100 to 150 Microns in Diameter

Fig. 16. Static Spark Shadowgraph of Micron Size Particles
at 4, 8, and 12 Inches from the Photographic Plate

and 12 inches from the photographic plate. The nominal trajectory is eight inches from the plate. The other two distances represent the extremes of allowable dispersion of the particles at the station. The detail of the image of the particles is difficult to reproduce on the printed page. The images on the plates are described and the dimensions are tabulated (Fig. 15). The central bright spot is readily seen on the film and prints for the four-inch distance with both particle sizes. At eight inches, only the 100-micron particle has a clear central spot. For the 12-inch distance, the image is barely discernible. The diameters of the central bright spot, the outer diameter of the gray or dark area and of the first white fringe are tabulated. From these data, it can be seen that the formation of the photographic image depends more on the optical geometry than the size of the object.

The short duration of the spark light source is normally expected to freeze the motion of the hypersonic missile to obtain adequate coordinate data. Some blurring of the image is tolerated. However, with the small size particle at the velocities of interest, the sphere moves 10 to 15 diameters in the effective exposure time. This means that the image should be a streak 10 to 15 diameters long with an exposure $9/10$ to $14/15$ of the normal background exposure. Thus, it was felt that to observe the particles in free flight it would be necessary to infer their flight from the existence of the shock wave of the missile. This in turn prescribed the selection of test atmospheric pressures. It had been observed that shadowgraph photography was sufficiently sensitive to record the shock patterns at $1/10$ and $1/20$ of an atmosphere. Thus, it was felt that the shadowgraph station could be used to establish proof of launch conditions at the range pressures of 76, 38 and 19 mm Hg. Particles were identified at higher velocities and lower pressures than were originally anticipated.

One particular problem with the direct shadowgraph technique when used with velocities over 10,000 fps is that the luminosity associated with the high temperature shock will fog the photographic plates. Since the particles were small, this was no real problem unless the sabot entered the range area. In this case, the luminosity of the large high velocity sabot would increase the overall exposure of the whole photographic plate, obscuring the fine detail of the small particle silhouettes.

5. Streak Cameras

Four 4 by 5 Graphic View Cameras were located in the range, two on each side of the trajectory. The two located to the right of the range have seven-inch focal length lens, $f/2.5$. The magnification factor is approximately 0.2 (Fig. 8). On the opposite side of the trajectory, two cameras with 105 mm focal length lens are mounted as shown in Fig. 9. The high speed panchromatic film (Royal X Pan) used

Fig. 17. Contact Print of Target Holes Made by Steel Balls and Strontium Particles

Fig. 18. Streak Photograph of Strontium Particles. Muzzle Velocity = 17,500 fps, Range Pressure = 38 mm Hg

in the cameras has an ASA rating of 1250. The film was developed in Acufine developer; time and temperature were controlled to obtain a possible ASA speed of 3000. The operating procedure for this type of streak picture is to have the range completely dark, load the film and open the shutters. Any luminous event occurring in the field of view is recorded on the film. The shutters are closed after the round is fired.

B. DISCUSSION OF RESULTS

Rounds were fired to investigate the performance of the launch technique and the behavior of the particles at three velocities: 12, 500, 15, 000 and 17, 500 fps and at three range pressures: 76, 38 and 19 mm Hg. Descriptions of the observations at the various velocities and pressures are given.

1. Velocity 12, 500 fps, Range Pressure 19 mm

The velocity history for the strontium and the steel balls is given in Fig. 12. For Round 15, the trigger screen was moved between Station 2 and Station 3. Stations 1 and 2 were coupled together and triggered at a time 110 μ sec after the 1/32-inch steel balls broke the trigger screen. Stations 3 and 4 were triggered at 200 μ sec. Referring to Fig. 12, the steel balls broke the trigger screen at 4 msec. The pictures of the steel balls were on the front part of Station 4 and the 100- to 150-micron particles were spread completely over Station 2. Station 2 showed approximately 100 particles. This is in good agreement with the predicted history of the particle velocity. The spread of particles on Station 2 is wider than anticipated but this can be accounted for by the variation in roundness of the particles and thus a variation in the drag coefficient. The 4 by 5 streak camera films show only one uniform streak across the field. These particles were apparently not luminous for this velocity, range pressure and length of trajectory.

2. Velocity 12, 500 fps, Range Pressure 38 mm

For this round, the trigger screen was located between Stations 2 and 3, as seen in Fig. 11. The time delay setting for Stations 1 and 2 was 180 μ sec. Some particles were photographed on Station 1 and a couple on the front edge of Station 2. For Fig. 11, the predicted velocity history indicates that the particle regime would be in the 75-micron size. This is not conclusive evidence of size but may be due to a conservative estimate for deceleration. The 4 by 5 streak cameras did not indicate any luminosity. The target for this round is shown in Fig. 17. This is a contact print of the target material. The four large dots are the 1/32-inch spheres. Twenty-five or so smaller specks are micron particles which pierced the target material. The

Fig. 19. Streak Photograph of Particles. Muzzle Velocity = 12,500 fps,
Range Pressure = Ambient

photographic image of the hole is larger than the hole in the target. The four large black dots measure about 1.9 mm; the holes in the target are 0.85 mm, which is about a 100% increase in size. The other holes made by the strontium measure between 150 and 550 microns in diameter in the photograph.

3. Velocity 12,500 fps, Range Pressure 76 mm

At 76 mm, few particles were seen on the photographic plates. On one round particles were found on Plate 1. The time delay setting was 470 μ sec after the steel balls broke the trigger screen. This would suggest that the particle size is about 75 microns. The velocity estimated from the shock waves is 3000 fps. This is in reasonable agreement with the predicted velocity history.

4. Velocities 17,500 and 15,000 fps, Range Pressure 38 mm

At these higher velocities, one or two particles were found on the plates. The 4 by 5 streak cameras show many streaks which indicate that the particles were luminous and in turn were ablating. At the lower velocities, it was difficult to find the images of the particles on the plates. As the velocity is increased and if the particle has ablated, this observation difficulty is compounded. Figure 18 shows the streaks recorded by the 4 by 5 camera. Practically all the streaks are of uniform intensity over the field of view. This type of reaction can be compared with a round fired at ambient pressure as seen in Fig. 19. Here the luminous streak appears to explode into many streamers. This type of chaotic disintegration was not observed at the lower pressures. However, the field of view was only 20 feet from the gun muzzle. A much longer flight time may be necessary to observe this type of breakup of the particles.

C. CONCLUSIONS

The techniques described in this report can be used to launch the 100- to 150-micron diameter particles at velocities between 10,000 and 18,000 fps.

For the steel particles, both the 790-micron steel balls and the steel shot, 125 to 400 microns, the evidence from the photographic plates indicates that an average of 50% of the particles on the sabot was launched satisfactorily. There is less evidence of the strontium particles on the shadowgraph plates, probably due to their lower density. One round in particular, 12,500 fps at a range pressure of 19 mm, showed the most evidence of particles in free flight--about 25% of the particles launched were found on the plates. With an increase in

velocity and range pressure, the number of particles found on the photographic plates is less. However, the streak cameras now begin to indicate the presence of luminous particles in flight. As the velocity is increased, it is more difficult to stop the motion of the particles by the shadowgraph technique. For the effective exposure time, at 2000 fps, a 100-micron particle moves two diameters. This increases to 20 diameters at 20,000 fps. The large diameter spheres, 790 microns, were identified by the spark shadowgraphs for all velocities. Thus, for the small particles, the evidence of a successful launch at the higher velocity is provided mainly by the streak camera. The films from these cameras show many streaks of relatively uniform luminosity across the field of view. Little evidence of what is described as chaotic disintegration of the particles was obtained. However, the field of view was located less than 20 feet from the gun muzzle. Longer flight times should be investigated to establish the essentials of the disintegration phenomena.

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APPENDIX A

Table of Rounds Fired

Round No.	Velocity (fps)	Verified	Range Pressure (mm)	Steel Spheres	Evidence of Particles			Notes
					Streak 4 x 5	Spark 11 x 14	Target	
1-10	Calibration runs							
11	12,500		76	--	S	N	--	
12	12,500		38	--	N	N	--	
13	12,500		38	--	N	N	--	
14	12,500		38	--	N	N	--	
15	12,500		19	4	N	N	--	
16	12,500		38	3	N	N	F	
17	12,500		38	--	N	F	--	
18	12,500		38	3	N	F	F	
19	--		--	--	--	--	--	No ramp on gun
20	12,500		76	--	S	N	--	
21	12,500		76	3	S	N	--	
22	12,500		75	4	S	N	--	
23	18,000		38	--	--	M	M }	Steel shot only
24	18,000		38	--	S	M	M }	Special target
25	18,000		39	2	S	N	F	
26	18,000		39	3	S	N	--	
27	8,000		76	5	N	F	F }	Low velocity rounds
28	9,500		76	2	S	N	N }	
29	12,500		76	3	S	M	N	
30	12,500		70	4	S	F	N	
31	12,500		38	4	N	N	--	
32	15,000		38	--	S	N	--	
33	12,500		38	2	N	N	N	
34	17,500		38	2	S	F	F	
35	17,500		38	--	S	N	--	
36	17,500		38	2	S	F	F	
37	12,500		38	3	S	N	F	
38	12,500		76	--	S	F	N	
39	12,500		76	--	S	N	N	
40	12,500		76	0	N	N	N	No particles. No steel

Legend:

Column

4 x 5 Streak Camera: S--some evidence of luminous particles
N--no evidence of luminous particles

11 x 14 Spark Plates: F--a few holes found on target:
M--many holes found on target
N--no evidence on target
Note target material was changed at round 20 to 5-mil black mylar
Previous material was 0.5-mil aluminized mylar. It may not have been possible to find micron holes in this material.