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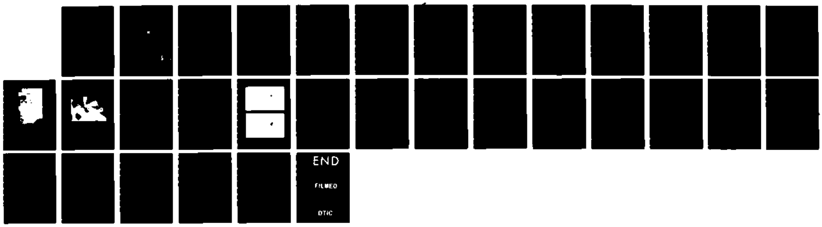

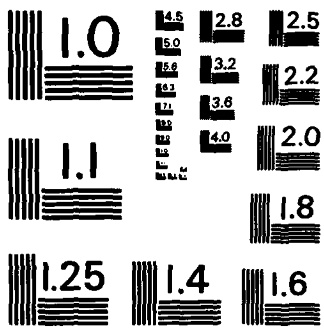

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CONTRACTOR REPORT

PRELIMINARY RESULTS OF VELOCITIES

AND DECELERATION OF ALUMINUM, MAGNESIUM,

ZIRCONIUM, TANTALUM, PYROFUZE AND TITANUIM PARTICLES

BURNING IN STEAM

Jacob Kol, Yair Chozev and Mati Berger

July 1985

Approved for public release; distribution unlimited.

Prepared for: Naval Surface Weapons Center
White Oak Laboratories
Silver Springs, MD 20910

NAVAL POSTGRADUATE SCHOOL
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The work reported herein was carried out for the Naval Postgraduate School by Mr. Jacob Kol under Contract N62271-84-M-3357 and Mr. Yair Chozev under Contract N62271-84-M-3055. The work presented in this report is in support of "Underwater Shaped Charges" sponsored by the Naval Surface Weapons Center. The work provides preliminary experimental results of velocities and decelerations of aluminum, magnesium, zirconium, tantalum, pyrofuze and titanium particles burning in steam. The project at the Naval Postgraduate School is under the cognizance of Distinguished Professor A. E. Fuhs who is principal investigator.

Prepared by:

MR. YAIR CHOZEV
Research Contractor

MR. JACOB KOL
Research Contractor

Reviewed by:

ALLEN E. FUHS
Distinguished Professor

M. F. PLATZER
Chairman, Department of Aeronautics

Released by:

J. N. DYER
Dean of Science and Engineering

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wires of various metals were exploded in a steam atmosphere. The metals investigated were aluminum, magnesium, tantalum, zirconium, pyrofuze, and titanium. Exploding wires generated numerous hot, small particles. Using high speed photography, velocities and decelerations were measured. Typical results are as follows: aluminum particles initial velocity 26 ± 0.74 m/s and deceleration of 8075 m/s^2; zirconium (ejected from 1 mm diameter wire) particles initial velocity is from 5 to 11 ± 0.47 m/s and deceleration is from

200 to 635 m/s^2; zirconium (ejected from 0.127 mm diameter wire) particles initial velocity is from 1.25 to 1.6 ± 0.47 m/s and acceleration 16 m/s^2; magnesium particles initial velocity from 27 to 34 ± 0.43 m/s and deceleration from 3300 to 6750 m/s^2; tantalum (ejected from 1 mm diameter wire) particles initial velocity is 5.9 ± 0.74 m/s; pyrofuze (ejected from 0.5 mm diameter wire) particles initial velocity is from 1.25 to 1.6 ± 0.74 m/s and deceleration from 3700 to acceleration of 200 m/s^2; titanium (ejected from 0.127 mm diameter wire) particles initial velocity is 0.6 ± 0.43 m/s and acceleration of 15 m/s^2.

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ABSTRACT

Wires of various metals were exploded in a steam atmosphere. The metals investigated were aluminum, magnesium, tantalum, zirconium, pyrofuze, and titanium. Exploding wires generated numerous hot, small particles. Using high speed photography, velocities and decelerations were measured. Typical results are as follows: aluminum particles initial velocity 26 ± 0.74 m/s and deceleration of 8075 m/s^2; zirconium (ejected from 1 mm diameter wire) particles initial velocity is from 5 to 11 ± 0.47 m/s and deceleration is from 200 to 635 m/s^2; zirconium (ejected from 0.127 mm diameter wire) particles initial velocity is from 1.25 to 1.6 ± 0.47 m/s and acceleration 16 m/s^2; magnesium particles initial velocity from 27 to 34 ± 0.43 m/s and deceleration from 3300 to 6750 m/s^2; tantalum (ejected from 1 mm diameter wire) particles initial velocity is 5.9 ± 0.74 m/s; pyrofuze (ejected from 0.5 mm diameter wire) particles initial velocity is from 1.25 to 1.6 ± 0.74 m/s and deceleration from 3700 to acceleration of 200 m/s^2; titanium (ejected from 0.127 mm diameter wire) particles initial velocity is 0.6 ± 0.43 m/s and acceleration of 15 m/s^2.

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The authors acknowledge the valuable help, cooperation and guidance of Professor Allen E. Fuhs during this work.

I. INTRODUCTION

The energy released by metals burning in steam has several important applications including torpedo propulsion, nuclear reactor safety, underwater vehicles, underwater ordnance, etc.

This report continues the studies that were performed by Hallenbeck [1] and Kol, et. al., [2] which are related to underwater shaped charge investigations. Investigation of velocities and decelerations of aluminum, magnesium, zirconium, tantalum, pyrofuze and titanium were rarely found in the literature. Hallenbeck [1] measured the velocity of aluminum particles burning in steam and in air by using high speed motion picture camera. The velocity in steam was from 2 to 4 m/s and in air from 7 to 11 m/s. No additional data was found in literature. For investigation of shaped charge performance, velocities and decelerations of the burning particles are important parameters that can be used for aerodynamic drag studies as well as for studies of different burning mechanisms.

In this report the velocity and deceleration characteristics for aluminum, zirconium, tantalum, magnesium, pyrofuze and titanium particles burning in steam are summarized. The measurements were performed using Hycam 2004-E and K1001 high speed motion picture cameras operated at 3850 FPS and 1500 FPS respectively. The cameras were equipped with stroboscopic markers for precise time measurements. The Kodak 4-X reversal film 400 ASA 7277 was used for combustion photography, and various f-numbers were used during the experiments due to different radiant energy emitted by the burning particles.

II. EXPERIMENTAL

The experiments were conducted in pressure vessel which consisted of a twelve inch high stainless steel cylinder, 10.75 inches diameter with four evenly spaced, 5 inch diameter observation ports welded into its circumference. One inch thick, Schlieren quality, Borosicalate crown glass (BK-7) was installed in each port. See Figure 1. Two Watlow Band Heaters were used to heat the apparatus to operating temperature and four additional Watlow Heaters were mounted on observation ports in order to prevent steam condensation during experiments. An Omega model 157 Digital Controller was used for temperature stabilization. The experiments were conducted in pressure range of 20 to 38 psi and steam temperature range of 354 to 382°F. Thermocouples were mounted in different locations inside the chamber to measure the internal temperature.

The metal particles were generated by the exploding wire technique. The 5 cm length wire was mounted between two holders and the electrical energy transfered to the various wires was 10 to 100 Joules. See Figure 2. Measurements of particle velocity were performed by using high speed movies from Hycam 2004-E and K1001 high speed motion picture cameras. The cameras were equipped with stroboscopic lights which mark the frames at a precise frequency. The test conditions for different metals burning in steam are summarized in Table 1.

METAL*	AMBIENT TEMP °F	PRESSURE psia	DISTANCE** inch	f-number	FILM SPEED FPS
Aℓ (1 mm)	374	38	46	4	3850
Ta (1 mm)	354	22	46	22	3850
Ta (0.127 mm)	382	23	46	8	3850
Pyrofuze (0.5 mm)	380	20	46	11	3850
Zr (1 mm)	381	24	36	8	1500
Zr (0.127 mm)	371	21	36	5.6	1500
Mg (1 mm)	374	22	36	4	1500
Ti (0.127 mm)	372	20	36	5.6	1500

* Metal Identification (Wire Diameters)

** Distance from Lens to Wire

Table 1. Test Conditions for Metals Burning in Steam (Focal Length of Lens = 75 mm)

IV. DISCUSSION AND RECOMMENDATIONS

A. Particles of aluminum and magnesium which are burning in vapor phase (see Brzustowski and Glassman [5] and Markstein [6]) have higher velocities and decelerations and shorter burning times compared to other metals such as zirconium and titanium and even pyrofuze.

B. All the decelerations of particles that were ejected from 1 mm diameter wires were relatively high (aluminum, zirconium and magnesium). The particles from 0.127 mm diameter wires accelerated during their burning time (titanium and zirconium). The pyrofuze particles were ejected from 0.5 mm diameter wire, and one can see large distribution of decelerations as well as accelerations.

C. Recommendations

a. In this report preliminary results of single experiments for each metal burning in steam are summarized. To confirm the statistical results for velocity and deceleration measurements, more experiments are needed.

b. Due to limited field of view through the lens, the precise burning time of part of the metals was impossible to measure. Therefore use of wide angle lens for high speed movie camera and changes in size of combustion chamber are recommended.

c. The experimental set up for velocity and deceleration should consist of additional perpendicular still camera for inclination angle measurements.

J. Summary of Results

The results based on film from the high speed motion picture camera are summarized in Table 3.

Metal	Initial Velocity [m/s]	Deceleration* [m/s^2]	Burning Time [ms]
Aℓ [1 mm]	26	8075	4
Zr [1 mm]	5-11	200-635	11
Ta [1 mm]	5.9		1
Mg [1 mm]	27-34	3300-6750	2
Pyrofuze [.5 mm]	2-18	3700- (-)200	>26**
Zr [0.127 mm]	1.25-1.6	-16	>40**
Ta [0.127 mm]			
Ti [0.127 mm]	0.6	-15	>63**

* Note that minus deceleration is acceleration.

** Due to limitation of field of view, burning time may exceed value shown.

Table 3. Summary of Results of Velocity, Deceleration, and Burning Time.

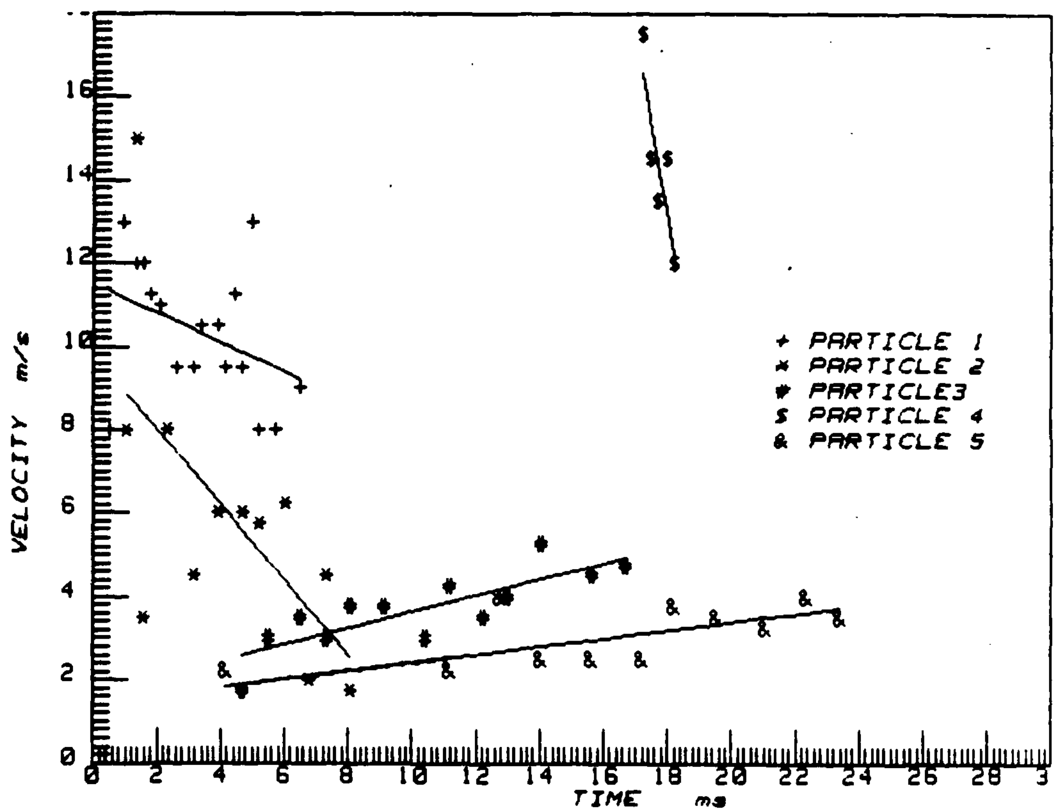


Figure 9. Velocities of Five Representative Pyrofuze Particles Combustion in Steam Versus Time.

3. After 11 ms the plasma separated into two parts. One part of plasma was burning and has constant velocity of 3.3 m/s. Its period of illumination (burning time) of 26 ms was not completed due to limitation of the field of view. The second part of the plasma was ejecting particles. One representative particle (particle 4 in Figure 9) has initial velocity of 18 m/s, and the calculated deceleration is 3700 m/s^2. The total burning time was longer than 26 ms.

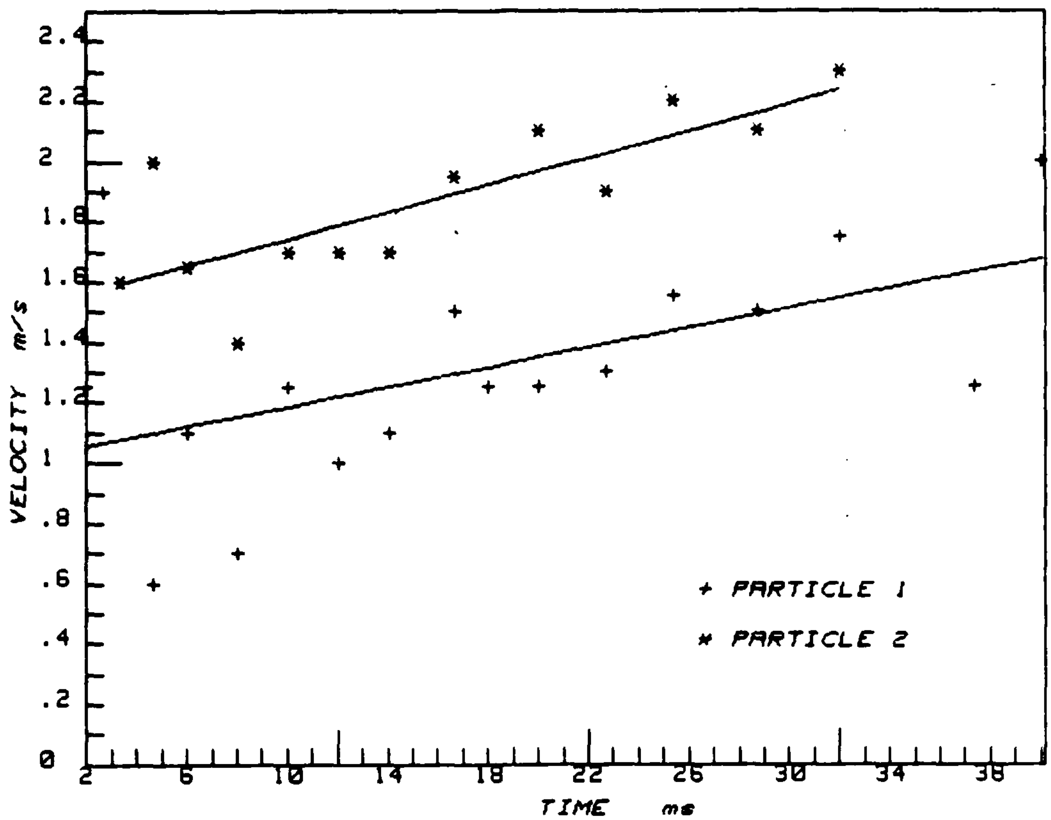


Figure 8. Velocity of Two Representative Titanium Particles Combustion in Steam Versus Time.

1. After the ignition of the wire, for the first 4.0 ms, a bright background was observed. The plasma was deflected down while ejecting particles. The initial velocities for two representative particles in the period were 8 m/s. By using the same analysis of polynomial regression the calculated decelerations are from 360 m/s^2 to 900 m/s^2.

2. After 40 ms, the bright background disappeared and the center of the plasma moved gradually down while ejecting particles. Two representative velocity profiles (particles 3 & 5 in Figure 9) were observed with initial velocities from 1.75 to 2.25 m/s. The calculated accelerations (using the analysis of polynomial regression) were from 100 to 200 m/s^2.

G. Velocity and Deceleration Measurement of Magnesium Combustion in Steam (1 mm Diameter Wire)

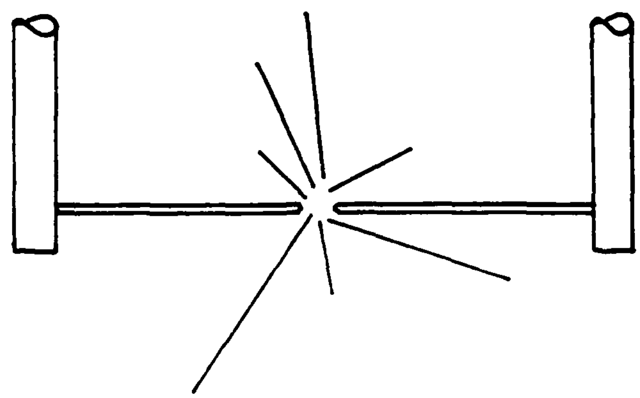
A cloud of small particles was ejected. Two particles were observed with initial velocities from 27 to 34 m/s for three frames (about 2 ms). The calculated decelerations were from 3300 to 6750 m/s^2.

H. Velocity and Deceleration Measurement of Titanium Combustion in Steam (0.127 mm Diameter Wire)

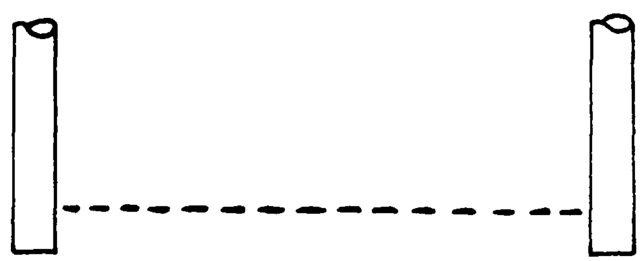
Six particles were ejected downward. Particle fragmentation was not observed. The velocities and the decelerations for two representative particles are summarized in Figure 8. The initial velocities were 0.6 m/s. Using the analysis of polynomial regression, the best results were for linear functions which are shown in Figure 8. The calculated accelerations are about 15 m/s^2. The precise burning time is not known since the field of view through the observation windows was limited.

I. Velocity and Deceleration Measurement of Pyrofuze Combustion in Steam (0.5 mm Diameter Wire)

Pyrofuze particle velocity and deceleration was measured by using high speed movies from Hycam 2004-E high speed motion picture camera operated at 3850 FPS. More than 50 burning particles were ejected from the exploding wire. The random ejection time characterized the pyrofuze combustion during the period of the first 17 ms. The pyrofuze combustion could be summarized as follows (see Figure 9):



(a) Rupture of Tantalum 1.0 mm Diameter Wire.



(b) Mechanical Failure of Tantalum 0.127 mm Diameter Wire.

Figure 7. Behavior of Different Diameter Exploding Wires of Tantalum.

E. Velocity and Deceleration Measurement of Tantalum Particles Combustion in Steam (1 mm Diameter Wire)

Tantalum particle velocity and deceleration were measured by high speed movies from Hycam 2004-E high speed motion picture camera operated at 3850 FPS. Few small particles were observed at wire rupture while a cloud of particles were ejected. The cloud vanished after 0.26 to 0.52 ms. The initial velocity was 5.9 m/s. Deceleration was not measured due to small number of frames. The particles were masked by high intensity radiation from the plasma.

F. Velocity and Deceleration Measurement of Tantalum Combustion in Steam (0.127 mm Diameter Wire)

Depending on wire diameter and electrical energy input, the wire ruptures in a significantly different manner. Figure 7(a) shows the rupture of a 1.0 mm diameter wire and is characteristic of the case reported in Section E above for tantalum. Figure 7(b) illustrates the rupture for small diameter wire; tantalum wire of 0.127 mm diameter breaks as shown in Figure 7(b).

For large diameter wire, the wire ruptures and leaves a small gap. The metal within the gap is ejected at high temperature. For small diameter wire, the complete span of the wire breaks into small particles or, if molten, into small droplets. All particles fall under the action of gravity; particles are not ejected upward.

Similar observations were made by Merzhanov et. al., [4].

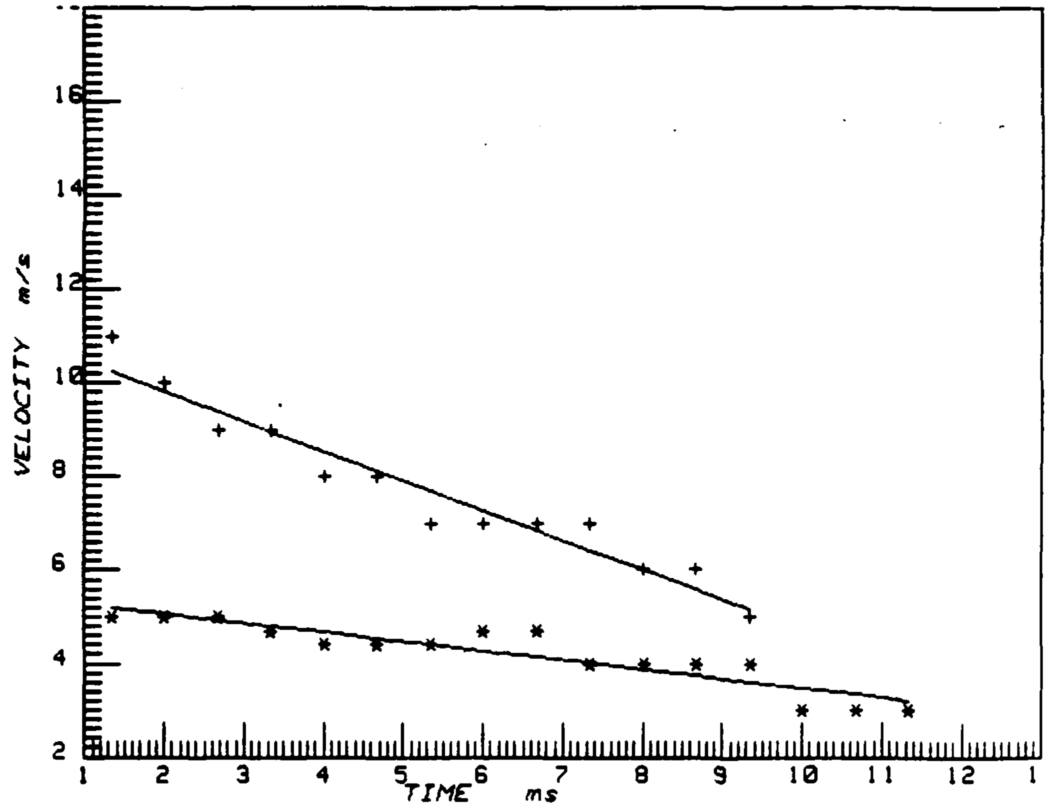


Figure 5. Velocities of Two Representative Zirconium Particles (1 mm Diameter Wire) Combustion in Steam Versus Time.

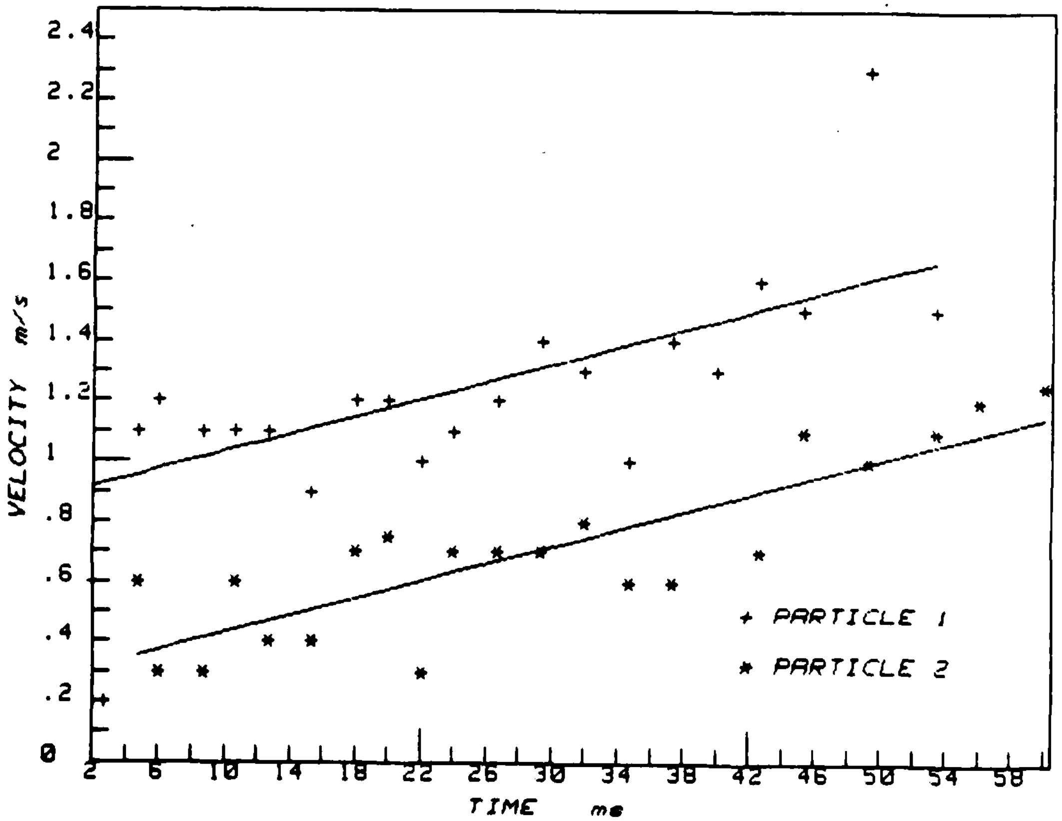


Figure 6. Velocity for Two Representative Zirconium Particles (0.127 mm Diameter Wire) Combustion in Steam Versus Time.

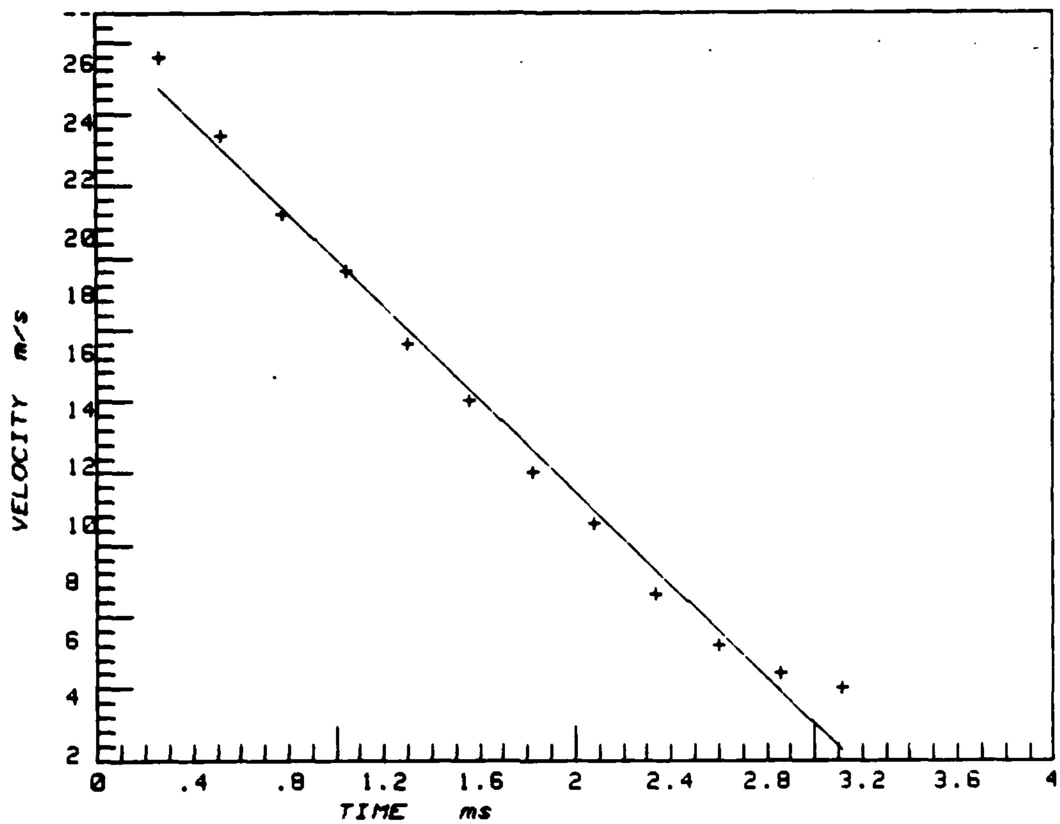


Figure 4. Velocity of Typical Aluminum Particle Combustion in Steam.

above) the best curve fits were again linear functions. The initial velocities were from 5 m/s to 11 m/s. The calculated decelerations were from 200 m/s^2 to 635 m/s^2.

D. Velocity and Deceleration of Zirconium Combustion in Steam (0.127 mm Diameter Wire).

Particle velocity and deceleration were measured using high speed movies from an Hycam K1001 high speed motion picture camera operated at 1500 FPS. Nine particles were ejected. The initial velocities of two representative particles versus time are shown in Figure 6. By using the analysis of polynomial regression (see for details in paragraph A) the best results were for linear functions. These functions are shown in Figure 6. Accelerations were about 16 m/s^2.

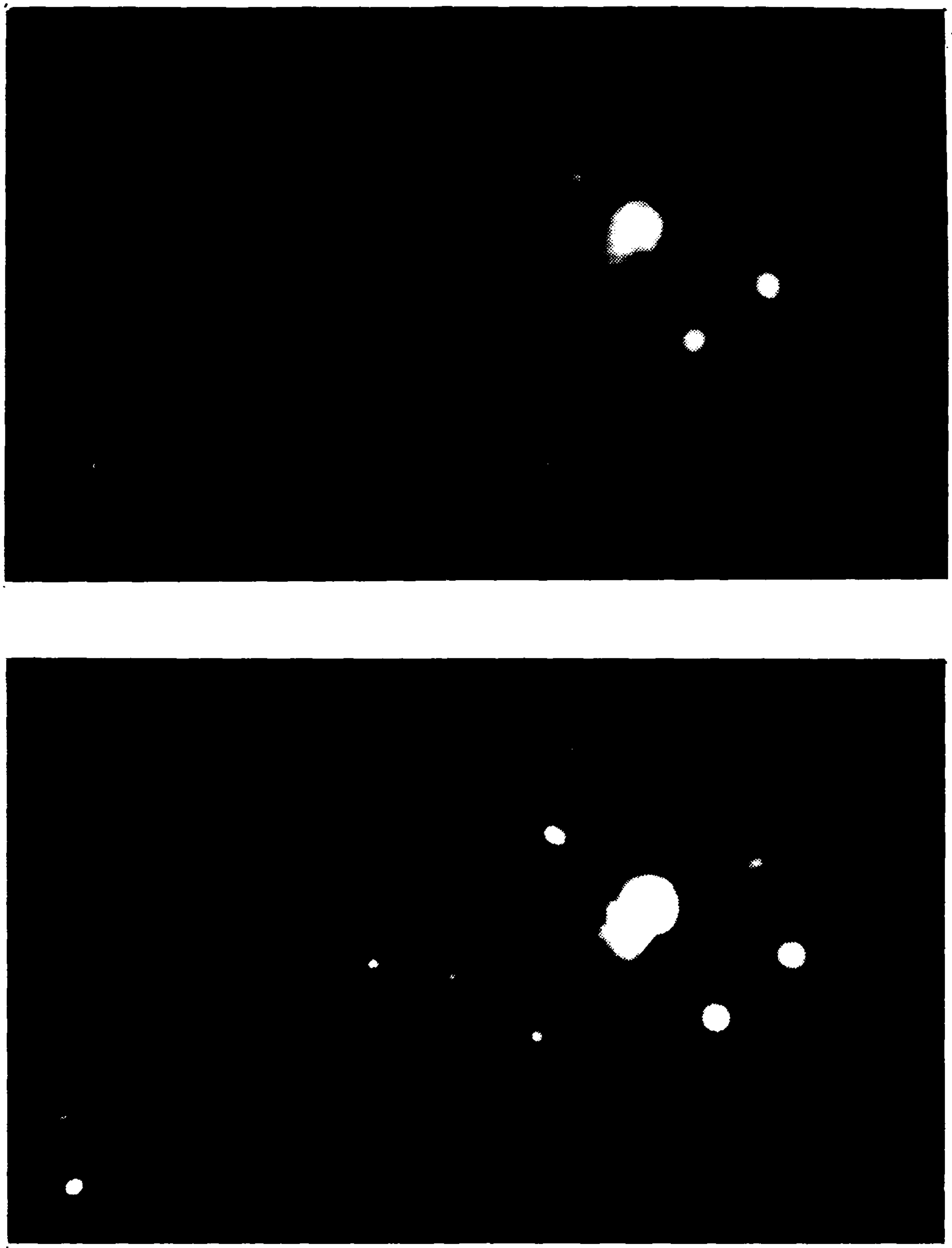


Figure 3. Two Typical Successive Frames of High Speed Motion Picture Camera Used for Velocity Measurement in the Experiments.

accuracy of distance measurement of actual distance of the different metals are given in Table 2.

METAL	CORRECTION FACTOR, r	ACCURACY m/s
Aluminum	0.385	± 0.74
Magnesium	0.5775	± 0.43
Zirconium	0.625	± 0.47
Tantalum	0.385	± 0.74
Pyrofuze	0.385	± 0.74
Titanium	0.5775	± 0.43

Table 2. Correction Factors for Converting Image Distance to Actual Distance and Accuracy of Velocity Measurement.

B. Velocity and Deceleration Measurement of Aluminum Combustion in Steam

Particle velocity and deceleration were measured using high speed movies from a Hycam 2004-E high speed motion picture camera operated at 3850 FPS. The following discussion applies to a typical particle in a single experiment.

The velocity of the particle was gradually decreasing from 26.6 m/s to 4 m/s. By using the analysis of polynomial regression, the best curve fit was found to be a linear function. These results are shown in Figure 4. The deceleration is determined according to the slope of the graph in Figure 4 which is 8075 m/s^2. The error of the velocity measurement will be given in the discussion (for aluminum and the other metals).

C. Velocity and Deceleration of Zirconium Combustion in Steam (1 mm Diameter Wire)

Particle velocity and deceleration were measured using high speed movies from an Hycam K1001 high speed motion picture camera operated at 1500 FPS. About 10 particles were ejected from the wire in the experiment. The velocities of two representative particles versus time are shown in Figure 5. By using the analysis of polynomial regression (see for details in paragraph A

III. RESULTS

A. Data Reduction Procedure

The projected distance on the screen was calibrated according to the known distance between the two holders which is 5.00 ± 0.05 cm. Two typical successive frames from the experiments is shown in Figure 3.

The particle velocity, V, at time t, was calculated as follows:

$$V(t) = \frac{R}{T} = \frac{d_n \cdot r}{T} \qquad (1)$$

where: R is the actual distance between particle locations in two successive frames.

d_n is the distance between the particle images on the film.

T is the period in seconds between two successive frames ($t = 1/FPS$, where FPS is Frame Per Second).

r is the distance correction factor between the actual and image distances

$$r = \frac{5.0}{s} \qquad (2)$$

where: s is the distance between images of the wire holders on the film.

The particle deceleration at time t, $D(t)$, is calculated by using analysis of polynomial regression for the velocity measurement. The polynomial regression program takes the data points (t, V) and calculates the coefficients of a polynomial up to sixth degree using a least squares fit discussed in Hewlett Packard book [3]. By derivation of the best polynomial one can calculate the deceleration. The distance correction factors and the

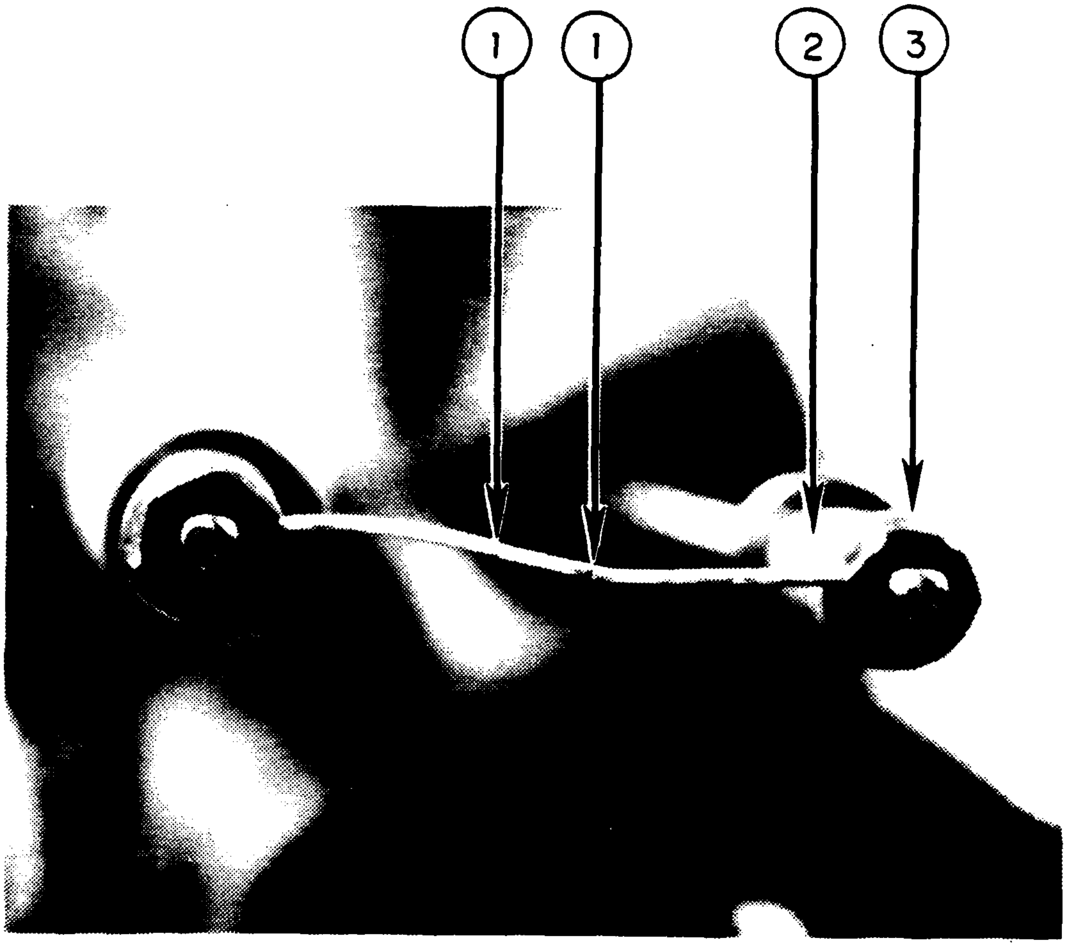


Figure 2. Metal Wire Under Test Positioned in Holder

(1) Notch in the metal test wires; test wires had diameter of 0.127 mm, 0.5 mm and 1 mm, (2) Spring (3) Washer in contact with end of test wire.

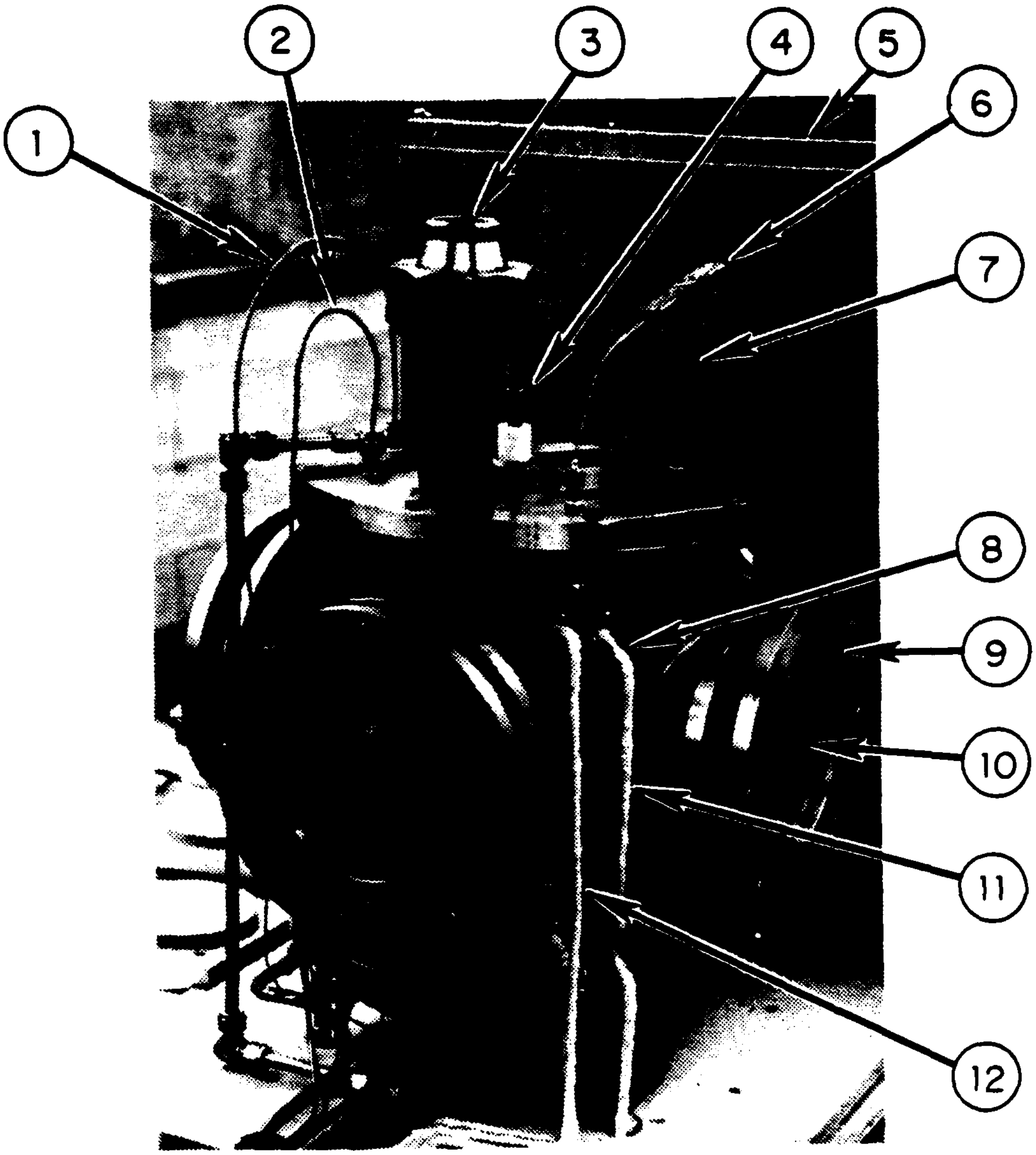


Figure 1. Pressure Vessel with Additional Parts Assembled

(1) Tubing for Heise Pressure Gauge, (2) Tubing for Pressure Transducer, (3) Pressure Relief Valve, (4) Positive Terminal for aluminum wire sample showing teflon insulator, (5) Side of wooden box with NCFR insulation, (6) Thermocouple #9, (7) Thermocouple #8, (8) Upper Watlow band heater, (9) Retaining ring for observation port, (10) Glass port, (11) Ground side of heater circuit, (12) "Hot" side of heater circuit

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Ministry of Defense
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Ministry of Defense
P.O. Box 2250
Haifa, Israel

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Department of Mechanical Engineering
University of California at Davis
Davis, CA 95616

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