TEES

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HYPERVELOCITY IMPACT EFFECTS

SEMI-ANNUAL PROGRESS REPORT

to the

National Aeronautics and Space Administration

Manned Spacecraft Center

Research Performed Under NASA Grant NGR 44-001-106

by

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INTRODUCTION

This report describes the progress under NASA grant NGR 44-001-106, Hypervelocity Impact Effects for the period of 1 September 1970 to 28 February 1971. This grant was awarded by NASA to investigate the effects of target strength on the cratering process caused by the impact of hypervelocity projectiles. The majority of experimental studies in this area have been conducted using 1100-0 Al, which is a very soft, commercially pure, aluminum, as the target material. Unfortunately, this material exhibits a yield strength which is sensitive to the rate of loading. In order to correllate crater dimensions such as depth and volume with target material it was found necessary by Gehring[1] to use "dynamic hardness" values for the target material. These hardness values were obtained by measuring the hardness immediately adjacent to the crater formed in a target already subjected to a hypervelocity impact. It was noted by this investigator that the ratio of "dynamic" to "static" hardness reported by Gehring is equal to the ratio of the maximum "dynamic" to "static" yield stress reported from wave propagation experiments. Since the later tests are economically and quickly performed it would appear that penetration equations should be based on dynamic yield stress rather than dynamic hardness.

In order to demonstrate this effect a number of targets were made available by the Manned Spacecraft Center. These targets had been impacted by the NASA-MSC light gas gun by a variety of projectiles. The targets were selected on the basis of adequate documentation of projectile size, velocity and density, as well as target configuration and material properties.

PROCEDURE

The Aluminum targets were prepared by machining the crater lip and plastically deformed area adjacent to the crater down to the original surface. The targets considered were either finite or semi-infinite in thickness. The materials considered were either 1100-0 or 2024 Aluminum alloy.

After machining the targets, crater volumes were determined by metering alcohol injected into the crater until the level of the liquid reached the original surface of the target. Crater depths were determined by micrometer measurement from the undisturbed surface. This technique is similar to that employed by Howell and Whittrock[2].

These measurements are tabulated in Table 1. The target identification corresponds to the shot numbers used by NASA in recording each shot. In addition, the appropriate projectile data as provided by NASA is listed.

ANALYSIS

In order to develop confidence in these data and determine the effects of target strength, the data were compared with data obtained by other facilities and reported either in the literature or contract reports. In order to examine a wide variety of data, a penetration equation commonly employed by NASA-MSC was used. In particular:

$$p_d = K\, d_p^{1.06}\, \rho_p^{.5}\, \rho_t^{-.167} V^{.67}\, H_D^{-.25}$$

where

p_d = penetration depth

K = constant dependent on target material

d_p = projectile diameter

ρ_p = projectile density

ρ_t = target density

V = projectile velocity

H_D = dynamic hardness of target material

The effects of the target material may be separated by defining the quantities Q and K_T:

$$Q \equiv \frac{p_d}{d_p \sqrt{\rho_p}} \quad ; \quad K_T \equiv K\rho_T^{-.167}\, H_D^{-.25}$$

so that: $Q = K_T\, V^{2/3}$

The nonlinearity in size scaling due to projectile diameter will be ignored for the moment. With these definitions, a plot of Q as a function of V on log-log paper should appear as a straight line with a slope of 2/3. Different lines will represent different materials and the separation will be dependent on the parameter, K_T. When comparing 1100 and 2024 Aluminum alloy, since both have the same nominal density, the difference in the data are attributable only to strength effects. The data tabulated in Table 1 is plotted in Figure 1. The best straight line with a slope of 2/3 has been drawn through the data points. Although the data are severely scattered the straight lines agree quite well with the data published by

Harperson[3], Goodman[4], Sorensen[5], and Howell[2], (Figures 2 through 5). The NASA data agrees quite well with other reported data and the scatter of data may be attributed to the finite dimensions and resulting spall of most targets examined.

The separation of the two straight lines for 1100 and 2024 Aluminum alloys could not be related to the "static" strength of each material which resulted in Gehring's "dynamic hardness" values; however, if it is recognized that hardness numbers are directly proportional to yield stress, then, the dynamic hardness may be expressed as:

$$H_D = C\ \sigma_{Static}R$$

where C is a constant relating static harness to static yield stress and R is the ratio of dynamic to static yield stress. In this way, Q may be expressed in terms of the static yield stress and rate sensitivity R:

$$Q = K\ \sigma_{Static}^{-.25}\ R^{-.25}\ \rho_T^{-.167}\ V^{.67}$$

SUPPLEMENTARY ANALYSIS

In the process of removing the crater lip and adjacent area of plastic deformation, a distinct change in the surface appearance was noted, figure 6. This line of demarcation always appeared in the 1100 specimens and never in the 2024 specimens. Therefore, three targets were sectioned through the center of the crater and hardness readings obtained parallel to the surface (0^{o}), normal to the crater (90^{o}), and in between (45^{o}). Measurements were made on a Tukon hardness machine with a 500 gm force and Knoop hardness values read as a function of distance from the final crater surface. A plot of these hardness readings appears in figures 7 and 8. The third specimen evidenced a distinct region of hardness comparable to the most strain hardened region at some distance from the crater. Additional targets will be examined to determine if this effect is peculiar to that one target due to some predictable wave interaction phenomenon.

FUTURE WORK

It has been realized by several researchers that the hydrodynamic theory could predict very well the initial stages of crater formation when the pressure is of the order of megabars, but during the later stages where the pressures drop down to the values comparable to material strength, the hydrodynamic theory can not be applied.

Also it was observed, especially with small particle impacts, for a given target and projectile combination, $\frac{P_d}{d_p}$ is not found to be a function of velocity but $\frac{P_d}{d_p} = f(V_o)\, d^{1/18}$. Similar non-linear diameter size scaling effects were also observed with the target, projectile momentum ratio. To a first approximation, researchers felt that these non-linear size scaling effects are attributable to the strain-rate sensitivity of the target material.

Thus the importance of strength and strain-rate effects being realized, it is evident that such effects can come into hypervelocity impact calculations only through a constitutive equation. A purely hydrodynamic constitutive equation neglects the strength and strain-rate effects whereas the hydrodynamic-elastic-plastic constitutive equation neglects the strain-rate effects and thus fails to predict the non-linear effects. A hydrodynamic-elastic-viscoplastic constitutive equation in its most general form proposed by Perzyna[6] which takes into account the strength and strain-rate effects was applied to hypervelocity impact problems by Rosenblatt who got fairly encouraging results.

In order to establish more clearly the significance of strain rate sensitivity in the cratering process a number of materials have been chosen which have exhibited an exagerated dynamic plastic response.

a) 1060 Aluminum is a commercially pure material which exhibits a greater sensitivity to rate than 1100.

b) 6061 - T6 Aluminum alloy is relatively insensitive to rate and will be used for comparison.

c) 1020 mild steel is sensitive to rate of loading and has an extremely well defined yield point when tested statically.

d) Pure lead, Pb, which is perfectly plastic and sensitive to rate will be considered.

Nominal one inch thick plates of each material will be obtained. Four by four inch targets will be cut from these plates and supplied to NASA-MSC for hypervelocity impact testing. The remainder of the plate will be machined into cylindrical specimens for compression testing.

Stress-strain-strain rate data will be obtained using both standard (Balwin) testing machines and a split Hopkinson pressure bar. These data will be analyzed and suitable visoplastic models will be used to analytically describe the materials. If at all possible, these models will be used to predict the final crater geometry resulting from impact of spherical projectiles at velocities from 3 to 6 km/sec.

It is hoped that the roll of strain rate sensitivity will be clearly established so that additional confidence may be placed in the penetration scaling equations presently being used.

ACKNOWLEDGEMENTS

The target preparation and crater measurements reported here were accomplished by Mr. Charles Nelson with the assistance of Mr. Roy E. Sewall. Mr. Nelson is presently studying for his Master of Science degree in Aerospace Engineering and is supported under this grant. Mr. Sewall is completing the requirements for a Bachelor of Science degree in Aerospace Engineering and is supported by the Space Technology Division.

The future work in identifying the roll of strain rate sensitivity in the hypervelocity cratering process will be accomplished by Mr. Basavaraju Chakrapani. Mr. Chakrapani is in Mechanical Engineering and will prepare his Ph.D. dissertation on this problem while supported by this grant. The dynamic stress-strain relations will be obtained by Mr. James S. Wilbeck. Mr. Wilbeck is a candidate for the Master of Science degree in Aerospace Engineering. He holds a NDEA fellowship and receives supplemental support from the Space Technology Division. Mr. Nelson will prepare his Masters thesis on the characterization of the materials with the appropriate viscoplastic models.

REFERENCES

1. "Hypervelocity Impact Studies Against Apollo - Types Structures Up to 16.5 km/sec", General Motors Corporation, G.M. Defense Research Laboratories, 1965.

2. Howell, W.G. and Whittrock, E.P., "Hypervelocity Impact Data For Cratering Studies"; Mechanics Division, Denver Research Institute, Denver, Colo., 1966.

3. Halperson, S.M.; Seventh Hypervelocity Impact Symposium; pp. 253-256.

4. Goodman, E.H., Liles, C.D., Sixth Symposium On Hypervelocity Impact, p. 563.

5. Sorensen, N.R., Seventh Hypervelocity Impact Symposium, p. 313.

6. Perzyna, P., "The Constitutive Equations for Rate Sensitive Plastic Materials," Quarterly of Applied Mathematics, Vol. 20, No. 4, 1963, pp. 321-332.

TABLE I

Hypervelocity Impact Data

TARGET NO.	PROJECTILE MATERIAL	PROJECTILE DIAMETER (in.)	VELOCITY (Km/sec)	TARGET MATERIAL	TARGET THICKNESS (in.)	DEPTH (in.)	VOLUME ($in.^3$)
B484	Alum	.0312	7.50	Alum	.50	.150	.0080
B485	Alum	.0312	5.55	Alum	.50	.231	.0548
B488	Alum	.0312	7.19	Alum	.50	.078	.0020
B489	Alum	.0312	6.46	Alum	.50	.081	.0002
B491	Alum	.0312	7.19	Alum	.50	.083	.0019
B504	Glass	.0312	7.19	Alum	.50	.165	.0087
2774	Lowden		4.2	Alum	.500	.479	.2853
2776	Lowden		3.6	Alum	.500	.041	.0006
2779	Lowden		3.8	Alum	.500	.249	.0411
2788	Microb		2.9	Alum	.500	.272	.0549
2804	Pyrex	.620	6.45	1100	.500	.173	.0830
2807	Pyrex	.0320	6.78	1100	.500	.092	.0015
2860	Pyrex	.125	3.57	Alum	.500	.258	.0289
2888	Pyrex	.0625	5.9	Alum	.500	.146	.0122
2941	Glass	.0625	6.07	Alum	.250	.155	.0107
2944	Alum	.125	5.94	1100	.250	.377	.0976

TABLE I

Hypervelocity Impact Data

TARGET NO.	PROJECTILE MATERIAL	PROJECTILE DIAMETER (in.)	VELOCITY (Km/sec)	TARGET MATERIAL	TARGET THICKNESS (in.)	DEPTH (in.)	VOLUME ($in.^3$)
2952	Alum	.125	6.68	2024-T4	.500	.258	.0564
2953	Alum	.125	7.04	2024-T4	.500	.274	.0534
2955	Alum	.125	6.78	2024-T4	.500	.294	.0717
2960	Pyrex	.0156	6.28	2024-T4	.375	.156	.0244
3008	Pyrex	.0625	7.02	2024-T4	.500	.177	.0137
3016	Pyrex	.0312	6.85	2024-T4	.375	.095	.00152
3022	Alum	.125	7.5	2024-T4	1.000	.270	.0763
3033	Bronze	.125	5.84	1100	.500	.143	.00915
3063	Alum	.0624	6.97	1100	.500	.175	.0373
3064	Alum	.0624	7.56	Alum	.500	.193	.0168
3126	Pyrex	.0391	7.08	1100	.375	.105	.0031
3148	Lowden		6.60	1100	.500	.443	.1220
3150	Lowden		6.72	1100	.500	.394	.1098
3152	Pyrex	.1252	7.62	1100	1.000	.357	.1083
3153	Pyrex	.1254	7.62	1100	.750	.368	.1159
3154	Alum	.1253	7.59	1100	.375	.391	.1342

TABLE I

Hypervelocity Impact Data

	PROJECTILE			TARGET			
TARGET NO.	MATERIAL	DIAMETER (in.)	VELOCITY (Km/sec)	MATERIAL	THICKNESS (in.)	DEPTH (in.)	VOLUME ($in.^3$)
3177	Glass	.009		1100	.375	.116	.00305
3274	Pyrex	.062	7.89	1100	.500	.188	.0168
3277	Pyrex	.062	7.92	1100	.500	.184	.0153
3913	Glass	.0660	7.26	Alum	.294	.171	.0122

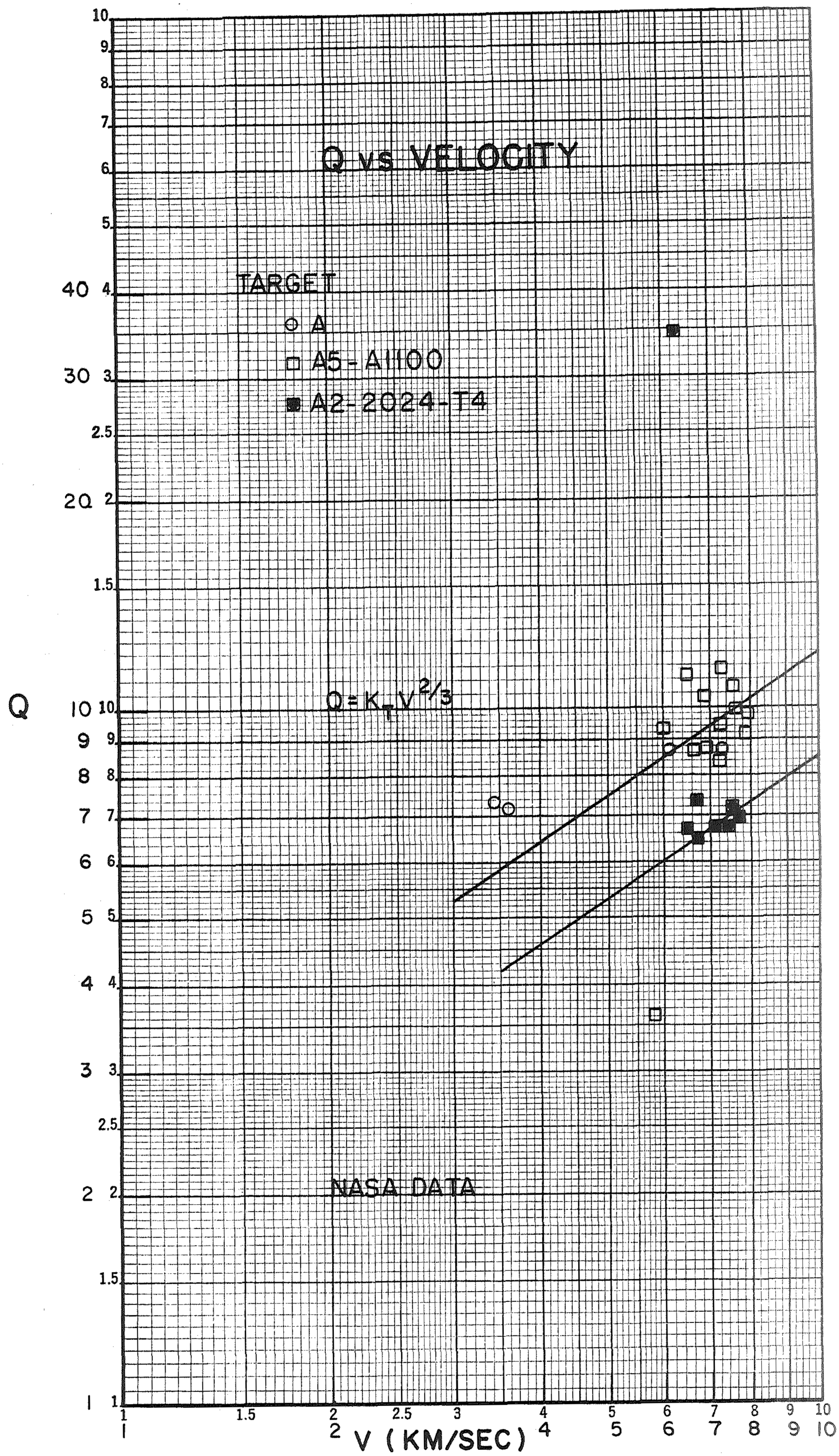

Q vs VELOCITY
TARGET
○ A
□ A5-A1100
■ A2-2024-T4
Q = K_T V^2/3
NASA DATA
Q
V (KM/SEC)
KEUFFEL & ESSER CO.

FIG I

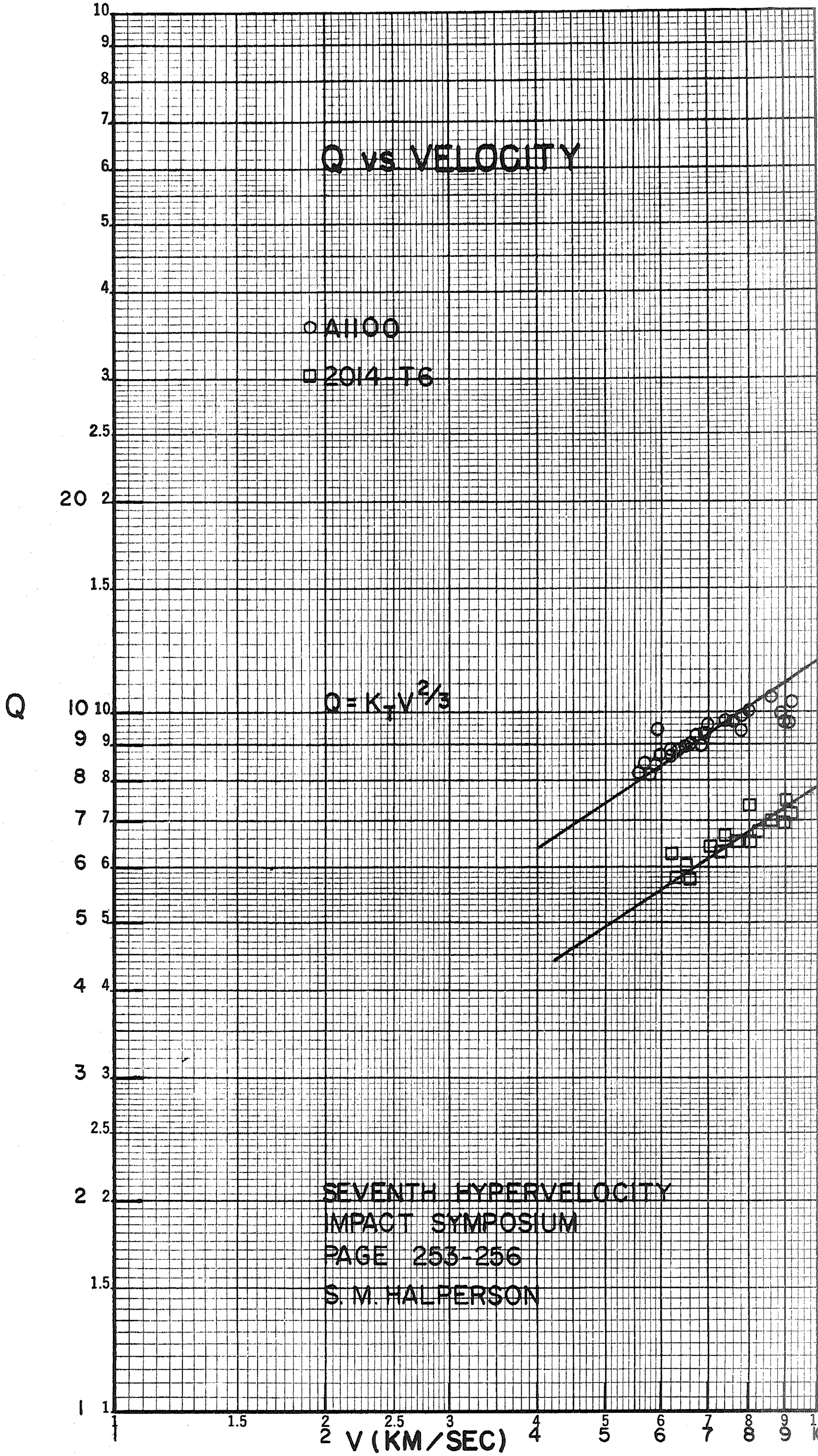

Q vs VELOCITY
○ A1100
□ 2014-T6
Q = K_T V^2/3
SEVENTH HYPERVELOCITY
IMPACT SYMPOSIUM
PAGE 253-256
S. M. HALPERSON
Q
V (KM/SEC)

FIG 2

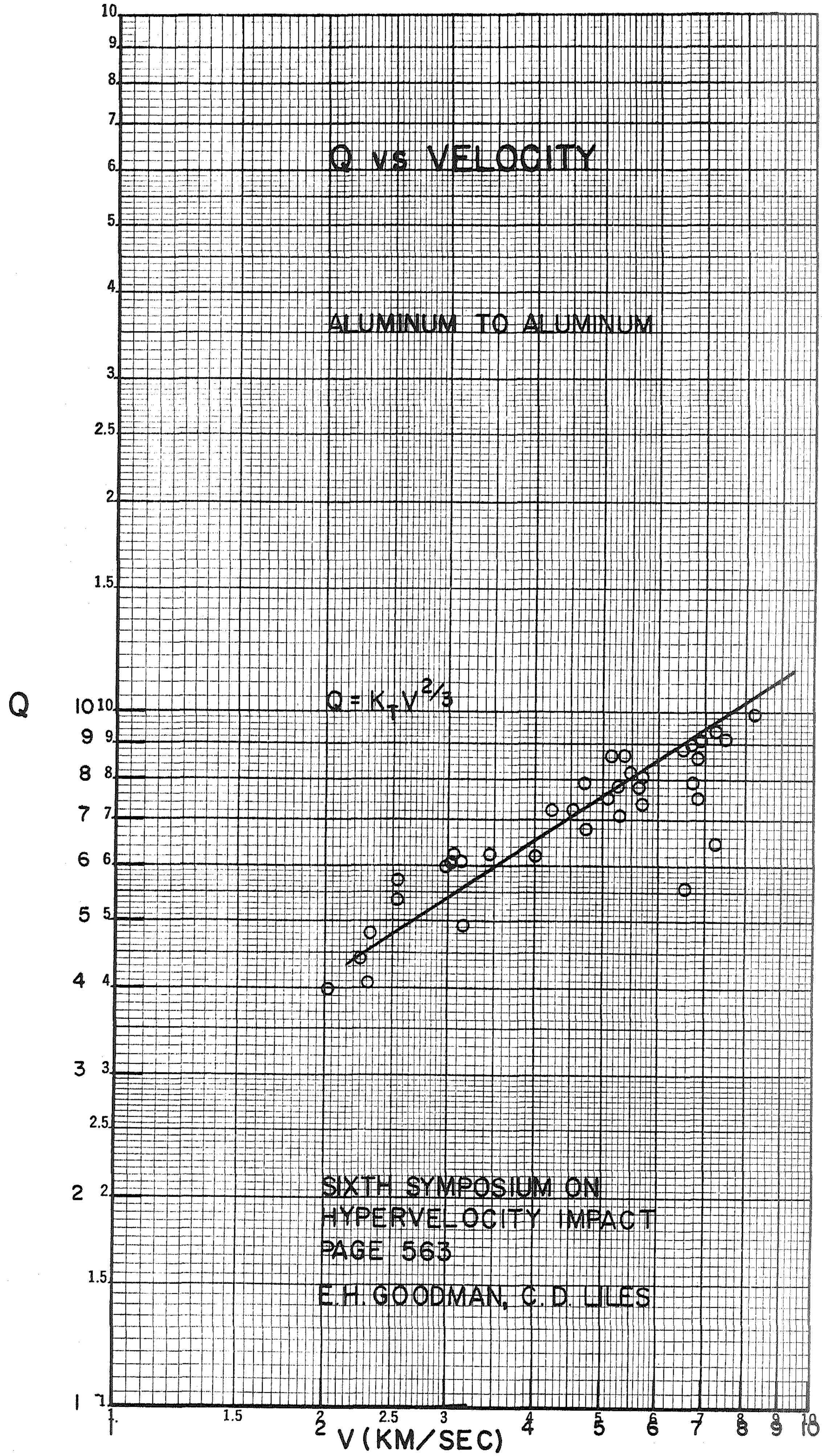

Q vs VELOCITY
ALUMINUM TO ALUMINUM
Q = K_T V^2/3
SIXTH SYMPOSIUM ON
HYPERVELOCITY IMPACT
PAGE 563
E.H. GOODMAN, C.D. LILES
Q
V (KM/SEC)
KEUFFEL & ESSER CO.

FIG 3

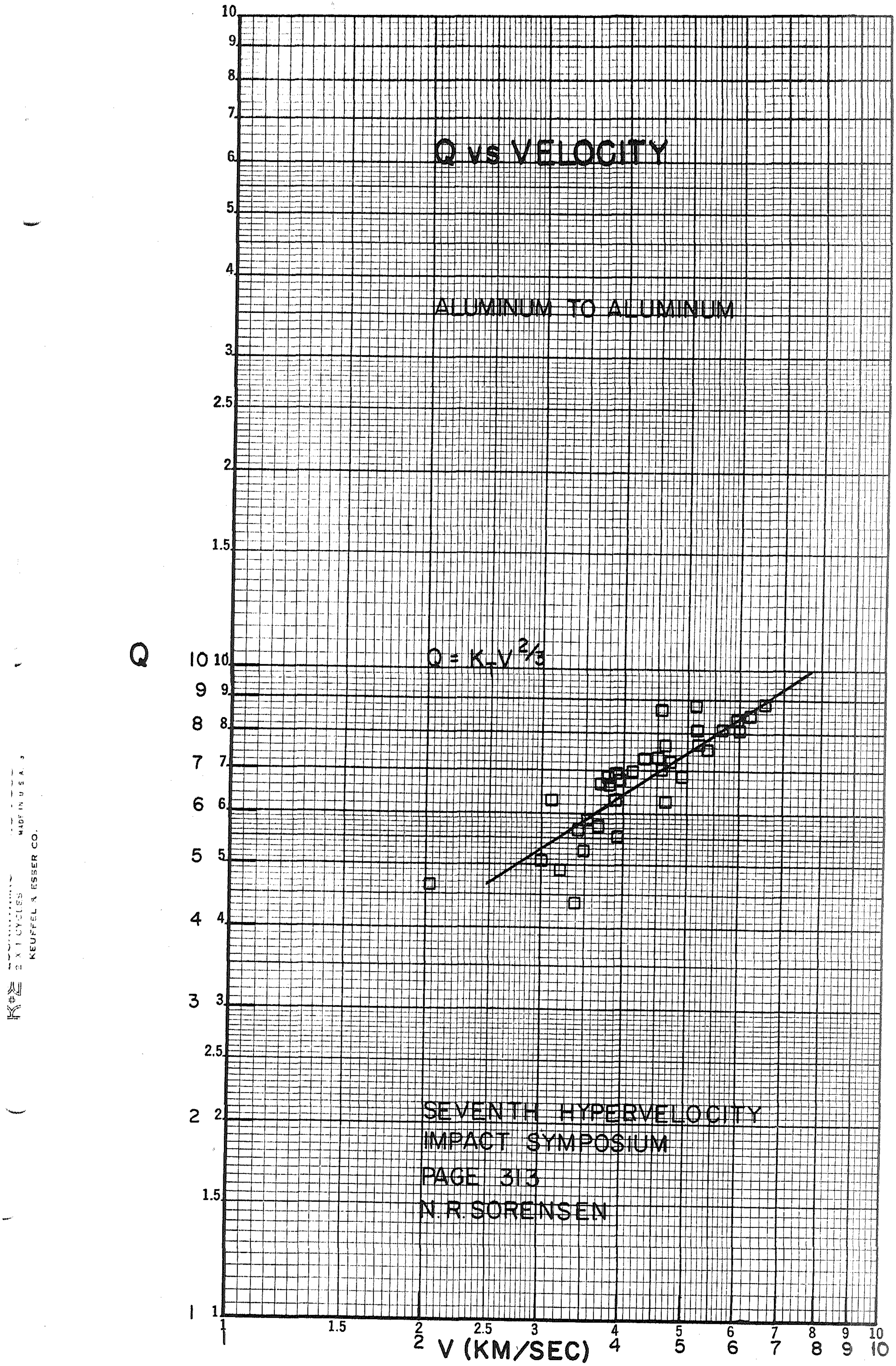

Q vs VELOCITY
ALUMINUM TO ALUMINUM
Q = K₁V^2/3
SEVENTH HYPERVELOCITY
IMPACT SYMPOSIUM
PAGE 313
N.R. SORENSEN
Q
V (KM/SEC)
KEUFFEL & ESSER CO.
MADE IN U.S.A.

FIG 4

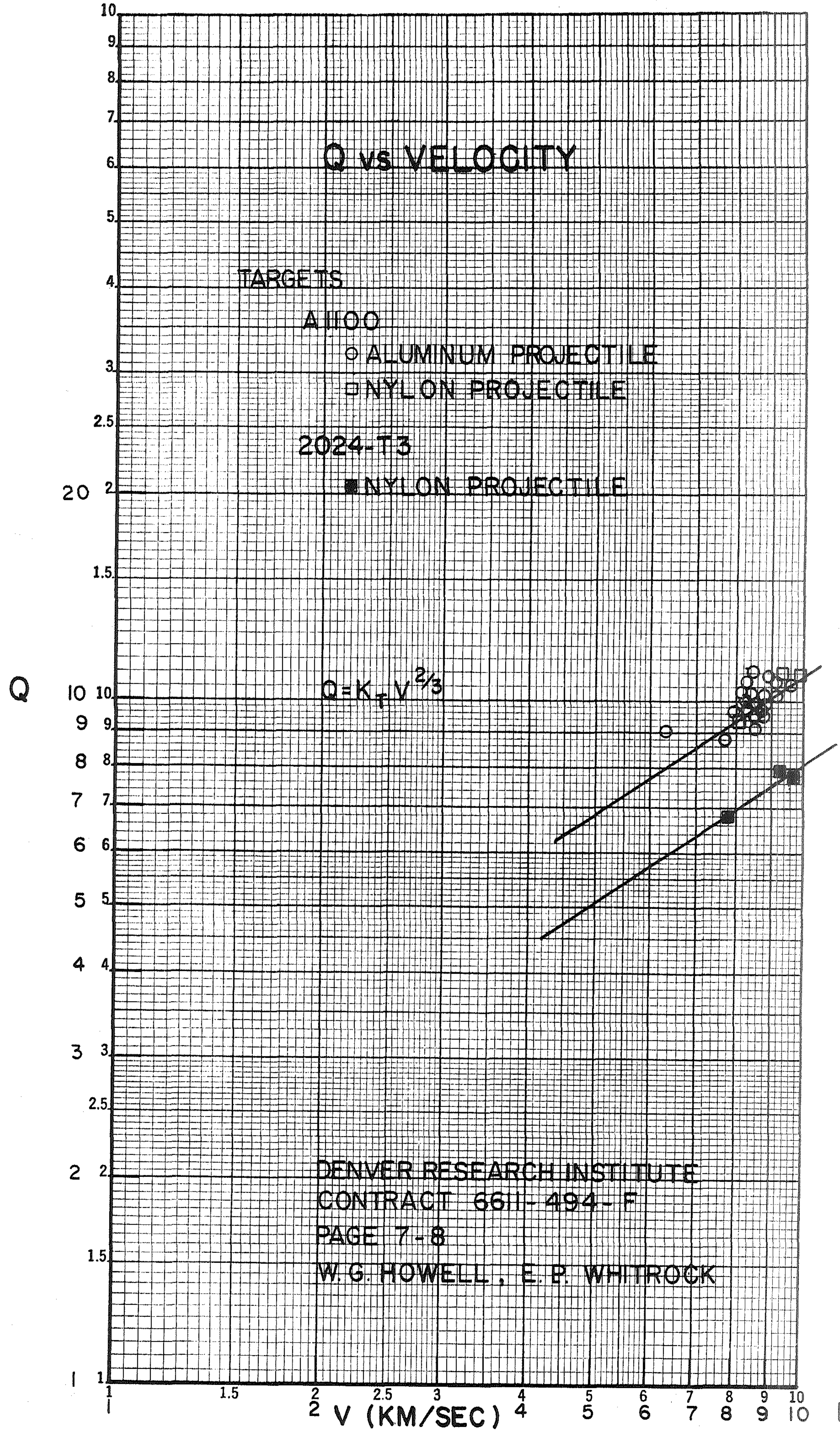
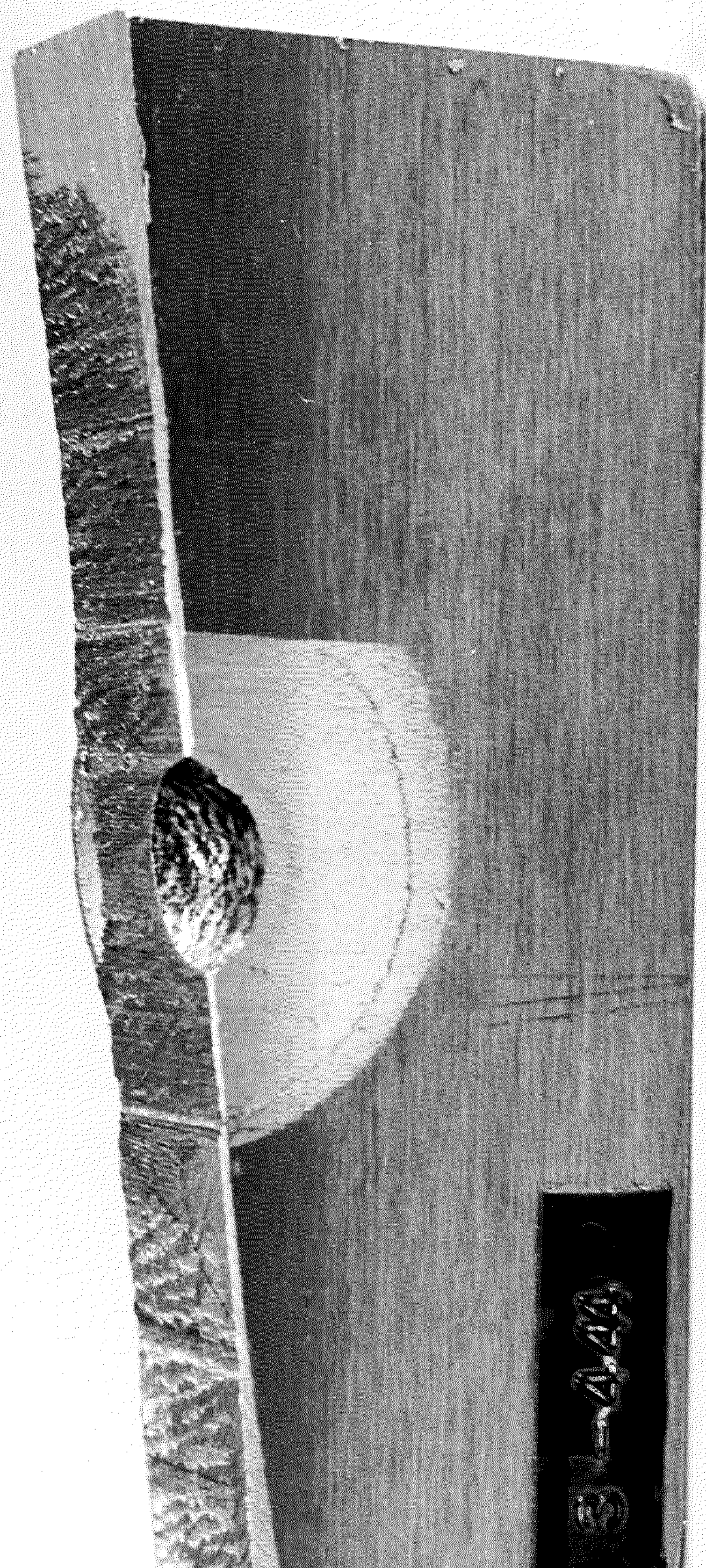

Q vs VELOCITY
TARGETS
A1100
○ ALUMINUM PROJECTILE
□ NYLON PROJECTILE
2024-T3
■ NYLON PROJECTILE
Q=K_T V^2/3
DENVER RESEARCH INSTITUTE
CONTRACT 6611-494-F
PAGE 7-8
W.G. HOWELL, E.P. WHITROCK
Q
V (KM/SEC)
KEUFFEL & ESSER CO.

FIG 5



KNOOP HARDNESS VS DISTANCE FROM CRATER SURFACE

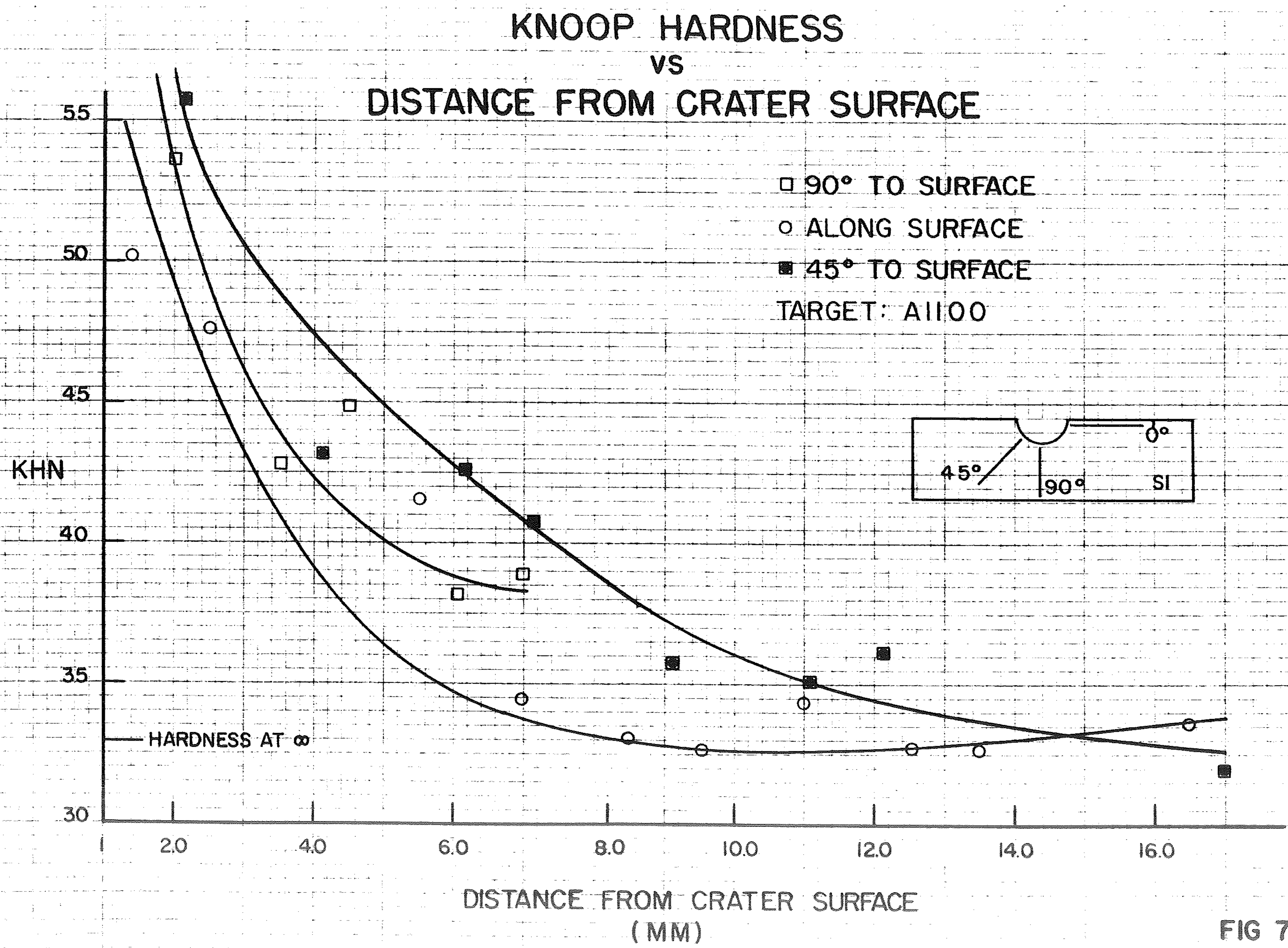
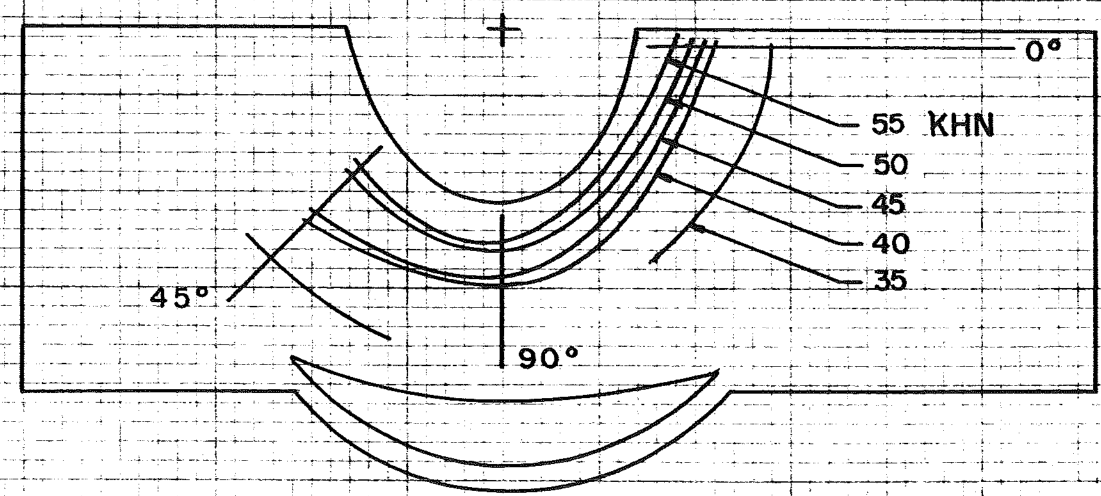


FIG 7

PLOT OF KNOOP HARDNESS CONTOUR AS A FUNCTION OF CRATER POSITION



TARGET: A1100

SCALE: 1 IN = 1 CM

FIG 8