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Reply to Attn of: SN3-91-19

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TO: Distribution

FROM: SN3/E.L. Christiansen

SUBJECT: Whipple Shield Sizing Equations

This memorandum provides Whipple shield sizing equations which are recommended for use in current Space Station Freedom (SSF) Work Package 2 (WP-2) trade study activities. These equations are modifications of the 1969 Cour-Palais predictor equations which were used by McDonnell Douglas to size WP-2 meteoroid and debris shielding for the SSF preliminary design review. Recent hypervelocity impact (HVI) test results have shown that the original 1969 Cour-Palais predictor improperly scales to the particle sizes that the WP-2 shields must be designed to protect against. The original equations have been modified to correct this scaling deficiency. Substantial increases to WP-2 shielding weight estimates are indicated by the modified equations. Several possibilities exist, however, to reduce the weight of WP-2 shielding (refer to memo SN3-91-25). These equations will be updated in the future as warranted by the results of ultra-high speed (>10 km/sec) HVI tests and further analyses.

BACKGROUND

For the preliminary design review (PDR), McDonnell Douglas Space Systems Company (MDSSC) baselined an aluminum Whipple (2-sheet) shield for meteoroid/debris protection of all WP-2 critical equipment (Ref.: McDonnell Douglas, MDC H4807, Structural Integrity Report, June 1990). MDSSC specified a 4.0 inch standoff distance and 2219-T62 aluminum for the PDR shields. A simplified method was used by MDSSC to size the thicknesses of the bumper and rear wall of the Whipple shields. A "design" particle size was calculated for each surface of a critical element from probability of no-failure requirements, environment models, surface area, and orientation considerations. The bumper thickness was determined by assuming it was 20% of the "design" particle diameter; i.e.,

$$t_b = 0.2\ d \tag{1}$$

1969 Cour-Palais Equation

The 1969 Cour-Palais predictor equation ("non-optimum") was used

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by MDSSC to derive rear wall thickness of PDR shielding. This predictor is given by Equation 2 (Ref. Cour-Palais: "Meteoroid Protection by Multiwall Structures," AIAA Paper No. 69-372, 1969).

$$t_w = 0.055\ (\delta_p\ \delta_b)^{1/6}\ M^{1/3}\ V_n/S^{0.5}\ (70/\sigma)^{0.5} \tag{2}$$

Nomenclature

d	projectile diameter (cm)
δ	density (g/cc)
M	projectile mass (g)
S	spacing between bumper and rear wall (cm)
σ	rear wall yield stress (ksi)
t	thickness (cm)
θ	impact angle (deg) measured from surface normal
V	projectile velocity (km/sec)
V_n	normal component of proj. velocity (km/sec) = V cos θ

Subscripts:

b	bumper
p	projectile
w	rear wall

The 1969 Cour-Palais Whipple equation was used in the Apollo program to extrapolate test data to meteoroid impact conditions. Meteoroid hazard assessments for the Apollo command module and lunar module were made using this equation.

HYPERVELOCITY IMPACT DATA

The 1969 Cour-Palais equation was derived from HVI data for particle diameters up to ~0.16 cm. However, it has been shown to be unconservative when scaling to particle diameters that the WP-2 shields must protect against (~1 cm). Table 1 contains a large historical HVI database for Whipple shields that has been updated with recent HVI test results. Projectiles up to 1.9 cm (10 g) are in the database. The following summarizes the range of HVI data in Table 1:

Parameter		Range
d	projectile diameter	0.04-1.9 cm
δ_p	projectile density	1.14-2.8 g/cc (nylon,glass,Al)
δ_b	bumper density	2.7-2.8 g/cc (aluminum alloys)
V_n	Velocity	6.5-7.5 km/sec (majority)
t_b/d	Bumper th'k to dia.	0.08-0.64
S/d	Spacing to dia.	13-96
σ	Yield Stress	18-70 ksi (aluminum alloys)

The Table 1 data set has been selected to be at or near the ballistic limit (i.e., perforation or spall threshold) of the rear wall. Of the 55 data points in Table 1, 23 are on the failure side of the ballistic limit (i.e., rear walls with perforations or detached spall) and 32 have thick enough rear walls to prevent failure.

Table 2 compares predictions made by the original Cour-Palais equation (Eq. 2) and the actual experimental rear wall thickness for the data set in Table 1. Table 3 summarizes Table 2 results and illustrates that the original 1969 Cour-Palais equation predicted only 30% of the failures in the data set. None of the successful predictions of failure occured with particle sizes greater than 0.2 cm. This implies that application of the 1969 Cour-Palais equation to particle threats of greater than 0.2 cm diameter, as was done to develop the WP-2 PDR shielding designs, will result in underestimating the required HVI shielding.

Table 3. 1969 Cour-Palais Equation Predictions

	1969 Cour-Palais
Predicted Failures*	7
Prediction Accuracy	30.4%
Mean tw calc/tw exp't	0.82
Standard Dev. tw calc/tw exp't	0.81
Predicted No-Failures**	27
Prediction Accuracy	84.4%
Mean tw calc/tw exp't	0.63
Standard Dev. tw calc/tw exp't	0.55

* Predicted failures out of the failures in Table 1: 23 data points
** Predicted no-failures out of the no-failures in Table 1: 32 data points

MODIFIED COUR-PALAIS WHIPPLE EQUATIONS

The HVI data in Table 1 has been used to modify the original Cour-Palais equations as given below (equations 3 and 4).

$$t_b = 0.25\ d\ \delta_p/\delta_b \tag{3}$$

$$t_w = C\ d^{0.5}\ (\delta_p\ \delta_b)^{1/6}\ M^{1/3}\ V_n/S^{0.5}\ (70/\sigma)^{0.5} \tag{4}$$

Where coefficient $C = 0.16\ cm^2\text{-}sec/g^{2/3}\text{-}km$.

Bumper thickness, in Equation 3, has been adjusted by the ratio of projectile to bumper density. This change will result in reductions in the MDSSC weight estimate for bumpers on surfaces of critical equipment that are only exposed to the meteoroid flux (because meteoroids are low density). The coefficient in

Equation 3 has been increased to 0.25 from the MDSSC PDR approach of using 0.20. This is required to reduce the possibility of underestimating the required rear wall thickness with small standoff distances (i.e., when $S/d < 15$). If standoff distance is increased ($S/d > 30$), then the original 0.20 coefficient can be substituted without reduction in accuracy.

Equation 4 is a slightly modified version of the 1969 Cour-Palais equation. The coefficient in the original equation (0.055) has been replaced with a diameter scaled coefficient ($0.16*d^{0.5}$) to reflect results of data from large particle hypervelocity impact testing. These equations are derived from the analysis of Cour-Palais. Data from Table 1 was used to derive the diameter-scaled coefficient in Equation 4. The "K" factor ($K = C * d^{0.5}$) curve fit to the data is shown in Figure 1.

As given in Table 4, the modified Cour-Palais equation more accurately predicts failure; successfully predicting over 65% of the failure cases. All 8 data points that Equation 4 did not successfully predict to fail were very marginal failures (detached spall without perforation or small perforations); and only 2 of the 8 are for larger particles (0.5 cm and larger). On the other hand, the original 1969 Cour-Palais equation successfully predicts only 7 of 23 failures; and all of these are for small particles (0.2 cm and smaller).

Table 4. Modified Cour-Palais Equation Predictions

	Modified Cour-Palais
Predicted Failures*	15
Prediction Accuracy	65.2%
Mean tw calc/tw exp't	1.15
Standard Dev. tw calc/tw exp't	0.45
Predicted No-Failures**	23
Prediction Accuracy	71.9%
Mean tw calc/tw exp't	0.90
Standard Dev. tw calc/tw exp't	0.36

* Predicted failures out of the failures in Table 1: 23 data points
** Predicted no-failures out of the no-failures in Table 1: 32 data points

A more conservative $0.19*d^{0.5}$ coefficient was originally proposed (Memo SN3-90-131, Christiansen: "Shield Sizing Equations", 10/12/90) to guarantee that the rear wall would not fail with $V_n > 6.5$ km/sec. However, projectile fragmentation and melting will increase between 6.5 and 7 km/sec. This will result in less rear wall damage as velocity increases from 6.5 to 7 km/sec. When "K" factors from HVI data shots with velocities less than 7 km/sec were adjusted to 7 km/sec, the proposed $0.16*d^{0.5}$

coefficient better fits the data (Figure 2).

Constraints:

The ballistic limit calculated by the modified equations is a local deformation without detached spall or fracture; that is, the no-failure criterion is no perforation or detached spall of the rear wall (corresponding to damage categories: D1-D2, E1-E2, F1-F3 as given in Figures 3-5). Equation 4 will potentially under predict the required rear wall thickness to prevent failure for normal component velocity (V_n) of less than 7 km/sec, S/d ratios of less than 15, and t_b/d ratios of less than 0.15. A set of ballistic limit equations for aluminum Whipple shields is given in memo SN3-91-21 that can be used over the entire debris velocity range from 0 to 15 km/sec. The modified Cour-Palais equation presented in this memo is included in the set of ballistic limit equations given in SN3-91-21.

Technical Basis:

Technical rationale for using the proposed equation include:

- The approach is a conservative method for predicting the HVI response of Whipple shields to impact conditions beyond testing capability. Without test data and/or detailed analyses, a conservative approach is more appropriate for designing the protection systems of critical equipment since they are directly associated with crew safety and SSF survivability.

- The equation is a semi-analytical/empirical approach. It uses test data to "anchor" the prediction at the highest impact velocities attainable in the laboratory, and uses a conservative analytical approach to extrapolate to higher velocities.

- The basis of the proposed scaling equation is that the debris cloud impacting the rear wall will contain solid particulates under certain impact conditions (even at velocities ranging from 7-15 km/sec). These solid particles are the determining factor in sizing the rear wall. Late time fragments from the bumper, impacts of irregularly shaped debris particles (such as plates, rods, hollow objects, etc) and impacts at highly oblique angles or with high t_b/d ratios can potentially release solid fragments; and are a likely occurrence in the real environment.

BUMPER Application:

In probability analysis tools, such as the modified BUMPER program, an equation is needed that relates critical particle diameter to fail a given structure with impact velocity and angle. Rearranging Eq.4 results in the following penetration equation for the critical particle diameter causing failure:

$$d_{crit} = 3.918\ t_w^{2/3}\ \delta_p^{-1/3}\ \delta_b^{-1/9}\ V^{-2/3}\ \cos^{-2/3}\theta\ S^{1/3}\ (\sigma/70)^{1/3} \qquad (5)$$

This equation indicates the ballistic limit of a given structure (i.e., the impact conditions causing rear wall failure) scales with constant impactor kinetic energy (i.e., ballistic limit α K.E.$^{1/3}$ α $d_{crit}\ V_n^{2/3}\ \delta_p^{1/3}$ = a constant for a given structure). This is consistent with NASA practice for conservatively extrapolating beyond HVI test conditions (Ref. NASA SP-8042, NASA Space Vehicle Design Criteria: "Meteoroid Damage Assessment," May 1970, p.37), as well as the presumption that the debris cloud will contain solid particulates in a significant fraction of real encounters occuring at very high impact velocities (> 8 km/sec) and cratering theory for the penetration of solid particles into the rear wall.

An example of the critical particle size calculated by Eq. 5 that fails the MDSSC PDR design for the orbital debris shields on the propulsion module is shown as a function of velocity in Figure 6 (all materials are Al 2219-T62). This figure shows the bumper thickness to critical particle diameter ratio ranges from 0.28 to 0.47. A similar example is shown in Figure 7 for the debris shielding on the habitation and laboratory modules.

DESIGN IMPLICATIONS

Changing from the original 1969 Cour-Palais equation to the modified Cour-Palais equation will more than double rear wall thickness and weight for the debris particle sizes that are currently driving the design of WP-2 protection systems. Since the debris shields are ~70% of total shielding weight, an increase of approximately 80% to 90% in WP-2 shielding can be expected for using the proposed shield sizing equations to meet current requirements and environment--given no changes in design approach.

Weight Reduction Strategies

There are several options that could reduce shielding weight, without reducing protection performance. These options are presented in another memo SN3-91-25: "Weight Reduction Options for Meteoroid/Debris Shielding".

COMPARISON WITH WILKINSON PREDICTOR

The Wilkinson predictor is used by the WP-1 contractor (Boeing) to predict Whipple shield performance beyond test conditions. The Wilkinson predictor is given by the following equations (Ref. J.P.D. Wilkinson: "A Penetration Criterion for Double-Walled Structures Subject to Meteoroid Impact," AIAA Journal, Vol.7, No.10, pp.1937-1943, October 1969).

For $[t_b\ \delta_b/(\delta_p\ d)] > 1$:

$$t_w = M\ V/(1.44\ L_2\ S^2\ \delta_w) \tag{6}$$

For $[t_b\ \delta_b/(\delta_p\ d)] < 1$:

$$t_w = M^{4/3}\ \delta_b^{2/3}\ V/[1.44\ (\pi/6)^{1/3}\ L_2\ t_b\ \delta_b\ S^2\ \delta_w] \tag{7}$$

L_2 is a material constant (0.425 for Al 2024-T3, Al 2024-T4, and Al 2024-T351; 0.292 for Al 6061-T6; 0.345 for Al 7075-T6; 0.297 for Al 2014-T6; 0.28 for Al 2219T87; 0.20 for Al 3003-H12, Al 3003-H14, and Al 1100-H14).

The Wilkinson equations were applied to predict rear wall thickness using the data in Table 1. Table 5 shows that the Wilkinson equations are very unconservative for this data set. The calculated rear wall thicknesses required to prevent failure using Wilkinson were smaller than the actual experimental rear wall thicknesses for all 55 HVI tests; indicating no failure is expected to occur in any of the 55 cases. Thus, Wilkinson's accuracy in predicting shield failure is 0% for this data set. Since Wilkinson always predicted shield success, it was 100% accurate in predicting no-failure. However, for the no-failure data, the rear wall thickness calculated by Wilkinson averaged only 8% of the rear wall thickness used in the experiments. This is quite optimistic considering the data in Table 1 was intentionally selected to be close to the failure point of the shield.

The poor comparison between Wilkinson prediction and experiment is not unexpected. The Wilkinson equation was formulated almost entirely from analytical considerations, without use of experimental data to determine coefficients or material constants, and little attempt was made to compare predictions with experimental data.

COMPARISON WITH NYSMITH EQUATION

For some configurations, WP-4 contractors have used the Nysmith equation to extrapolate Whipple shield performance beyond test conditions. The Nysmith equation is given by the following equation (Refs: C.R. Nysmith: "An Experimental Impact Investigation of Aluminum Double-Sheet Structures," AIAA Paper No. 69-375, AIAA Hypervelocity Impact Conference, April 30 - May 2, 1969. C.R. Nysmith: "Pentration Resistance of Double-Sheet Structures At Velocities to 8.8 km/sec," NASA TN D-4568, May 1968.).

$$t_w = 5.08\ d\ V^{0.2778}\ (t_b/d)^{-0.5278}\ (S/d)^{-1.3889} \tag{8}$$

Table 5 shows the results of using Equation 8 to predict rear wall thickness for the data in Table 1. As indicated, Nysmith only predicts 13% of the test cases where the shield failed; an unconservative result. This is somewhat surprising. The Nysmith predictor is purely empirical (HVI test data is used in its formulation). The poor comparison here can be explained by noting that Nysmith formulated his equation using HVI data for glass projectiles on aluminum targets. Because the density of glass is less than aluminum, this correlation would underestimate the effect of aluminum projectiles. However, of more concern is use of the Nysmith equation to extrapolate beyond test conditions. The Nysmith equation is derived strictly from HVI data, and contains no theoretical justification for extrapolating beyond test conditions.

Table 5. Comparison of Wilkinson and Nysmith Equations

	Wilkinson	Nysmith
Predicted Failures*	0	3
Prediction Accuracy	0%	13.0%
Mean tw calc/tw exp't	0.15	0.58
Standard Dev. tw calc/tw exp't	0.18	0.39
Predicted No-Failures**	32	32
Prediction Accuracy	100%	100%
Mean tw calc/tw exp't	0.08	0.37
Standard Dev. tw calc/tw exp't	0.05	0.16

* Predicted failures out of the failures in Table 1: 23 data points
** Predicted no-failures out of the no-failures in Table 1: 32 data points

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TABLE 1

Whipple Database

Site	Shot No.	Proj. Dia. (cm)	Proj. Dens. (g/cc)	Proj. Mass (g)	Bumper Dens. (g/cc)	Vel. (km/sec)	Impact Angle (deg)	Normal Vel. (km/sec)	Bumper Thk (cm)	tb/d	Spacing (cm)	S/d	Wall Th'k (cm)	tw/d	Wall Mat'l	Yield Stress (ksi)	(tb+tw)/d
JSC-HIRL	1487	0.040	2.713	0.000088	2.74	7.30	0	7.30	0.010	0.26	1.27	32	0.015	0.38	Al 3003-H12	18	0.640
JSC-HIRL	1481	0.040	2.796	0.000091	2.74	7.10	0	7.10	0.010	0.26	1.27	32	0.010	0.26	Al 3003-H12	18	0.512
JSC-HIRL	1476	0.040	2.796	0.000091	2.74	8.06	0	8.06	0.010	0.26	1.27	32	0.027	0.67	Al 3003-H14	21	0.928
JSC-orig.	4613	0.079	2.25	0.00059	2.78	7.13	0	7.13	0.025	0.32	5.08	64	0.025	0.32	Al2024-T3	47	0.640
JSC-orig.	4637	0.079	2.25	0.00059	2.78	7.22	0	7.22	0.015	0.19	5.08	64	0.025	0.32	Al2024-T3	47	0.512
JSC-orig.	4638	0.079	2.25	0.00059	2.78	7.53	0	7.53	0.015	0.19	7.62	96	0.025	0.32	Al2024-T3	47	0.512
JSC-orig.	A250	0.079	2.25	0.00059	2.78	6.52	0	6.52	0.030	0.38	2.54	32	0.030	0.38	Al7075-T6	70	0.768
JSC-orig.	A201	0.079	2.25	0.00059	2.78	6.70	0	6.70	0.030	0.38	7.62	96	0.030	0.38	Al1100-H14	17	0.768
JSC-orig.	4681	0.079	2.71	0.00071	2.78	7.34	0	7.34	0.051	0.64	2.54	32	0.041	0.51	Al2024-T3	47	1.152
JSC-orig.	4679	0.079	2.71	0.00071	2.78	7.16	0	7.16	0.051	0.64	7.62	96	0.025	0.32	Al2024-T3	47	0.960
JSC-orig.	4658	0.079	2.71	0.00071	2.78	7.25	0	7.25	0.015	0.19	5.08	64	0.025	0.32	Al2024-T3	47	0.512
JSC-HIRL	1435	0.080	2.796	0.00076	2.713	6.52	0	6.52	0.015	0.19	2.54	32	0.030	0.38	Al2024-T3	47	0.569
JSC-HIRL	1468	0.081	2.796	0.00078	2.713	6.70	0	6.70	0.015	0.19	2.54	31	0.030	0.38	Al2024-T3	47	0.565
JSC-orig.	4695	0.159	2.54	0.0053	2.78	7.56	0	7.56	0.051	0.32	5.08	32	0.064	0.40	Al2024-T3	47	0.720
JSC-orig.	4709	0.159	2.54	0.0053	2.78	7.26	0	7.26	0.025	0.16	5.08	32	0.064	0.40	Al2024-T3	47	0.560
JSC-orig.	4691	0.159	2.54	0.0053	2.78	7.25	0	7.25	0.051	0.32	7.62	48	0.041	0.26	Al2024-T3	47	0.576
JSC-orig.	4706	0.159	2.54	0.0053	2.78	7.26	0	7.26	0.025	0.16	7.62	48	0.041	0.26	Al2024-T3	47	0.416
JSC-orig.	4738	0.159	2.71	0.0057	2.78	7.20	0	7.20	0.051	0.32	5.08	32	0.064	0.40	Al2024-T3	47	0.720
JSC-orig.	4736	0.159	2.71	0.0057	2.78	7.31	0	7.31	0.051	0.32	7.62	48	0.041	0.26	Al2024-T3	47	0.576
JSC-HIRL	A1200	0.200	2.796	0.0117	2.78	6.93	0	6.93	0.015	0.08	6.4	32	0.483	2.41	Al6061-T6	36	2.489
JSC-HIRL	A1218	0.200	2.796	0.0117	2.78	6.93	0	6.93	0.015	0.08	6.4	32	0.318	1.59	Al2024-T3	47	1.664
JSC-HIRL	A1196	0.200	2.796	0.0117	2.78	7.20	0	7.20	0.036	0.18	6.4	32	0.159	0.79	Al2024-T3	47	0.972
JSC-HIRL	A1076	0.200	2.796	0.0117	2.713	6.37	0	6.37	0.064	0.32	6.0	30	0.041	0.20	Al6061-T6	36	0.521
JSC-HIRL	A1077	0.200	2.796	0.0117	2.713	6.77	0	6.77	0.041	0.20	6.0	30	0.064	0.32	Al6061-T6	36	0.521
JSC-HIRL	A1281	0.318	1.145	0.0192	2.713	6.70	0	6.70	0.025	0.08	10.16	32	0.081	0.26	Al2024-T3	47	0.336
JSC-HIRL	A235	0.318	2.78	0.0466	2.78	6.98	0	6.98	0.056	0.18	10.16	32	0.159	0.50	Al2024-T3	47	0.676
JSC-HIRL	A240	0.318	2.78	0.0466	2.78	6.58	0	6.58	0.081	0.26	10.16	32	0.127	0.40	Al2024-T3	47	0.656
JSC-HIRL	A151	0.318	2.713	0.0455	2.78	6.60	0	6.60	0.081	0.26	5.08	16	0.127	0.40	Al2024-T3	47	0.656
JSC-HIRL	B31	0.635	2.796	0.3748	2.713	7.08	0	7.08	0.127	0.20	20.32	32	0.229	0.36	Al6061-T6	36	0.560
JSC-HIRL	B37	0.635	2.796	0.3748	2.796	6.39	0	6.39	0.159	0.25	10.16	16	0.318	0.50	Al6061-T6	36	0.750

TABLE 1 (Cont.)

Whipple Database

Site	Shot No.	Proj. Dia. (cm)	Proj. Dens. (g/cc)	Proj. Mass (g)	Bumper Dens. (g/cc)	Vel. (km/sec)	Impact Angle (deg)	Normal Vel. (km/sec)	Bumper Thk (cm)	tb/d	Spacing (cm)	S/d	Wall Th'k (cm)	tw/d	Wall Mat'l	Yield Stress (ksi)	(tb+tw)/d
BOEING	85-24F	0.635	2.78	0.3727	2.713	6.00	0	6.00	0.159	0.25	15.24	24	0.318	0.50	Al2219-T87	52	0.750
BOEING	85-13	0.635	2.78	0.3727	2.713	5.88	0	5.88	0.159	0.25	15.24	24	0.318	0.50	Al2219-T87	52	0.750
BOEING	85-16	0.762	2.78	0.6440	2.713	7.00	0	7.00	0.159	0.21	15.24	20	0.318	0.42	Al2219-T87	52	0.625
BOEING	85-20C	0.762	2.78	0.6440	2.713	6.40	0	6.40	0.159	0.21	15.24	20	0.318	0.42	Al2219-T87	52	0.625
MSFC	86-2	0.793	2.71	0.7076	2.713	6.98	0	6.98	0.159	0.20	10.16	12.8	0.318	0.40	Al2219-T87	52	0.601
MSFC	86-1	0.793	2.71	0.7076	2.713	6.90	0	6.90	0.159	0.20	10.16	12.8	0.318	0.40	Al2219-T87	52	0.601
AMES	A1895	0.953	2.796	1.2651	2.78	6.89	0	6.89	0.159	0.17	30.48	32	0.318	0.33	Al6061-T6	36	0.500
AMES	A1868	0.953	2.796	1.2651	2.78	7.10	0	7.10	0.159	0.17	30.48	32	0.318	0.33	Al6061-T6	36	0.500
AMES	A86/1	0.953	2.796	1.2651	2.78	6.65	0	6.65	0.159	0.17	30.48	32	0.635	0.67	Al2024-T351	47	0.833
AMES	A1917	0.953	2.796	1.2651	2.78	6.72	0	6.72	0.159	0.17	22.86	24	0.483	0.51	Al2024-T351	47	0.673
AMES	A1899	0.953	2.796	1.2651	2.78	6.83	0	6.83	0.159	0.17	15.24	16	0.635	0.67	Al2024-T351	47	0.833
AMES	A1875	0.953	2.796	1.2651	2.78	6.75	0	6.75	0.159	0.17	30.48	32	0.318	0.33	Al6061-T6	36	0.500
AMES	A86/3	0.953	2.796	1.2651	2.78	6.65	0	6.65	0.159	0.17	30.48	32	0.229	0.24	Al2024-T3	47	0.407
AMES	A86/4	0.953	2.796	1.2651	2.78	6.40	0	6.40	0.483	0.51	30.48	32	0.229	0.24	Al2024-T3	47	0.747
AMES	A1918	0.953	2.796	1.2651	2.78	6.83	0	6.83	0.159	0.17	38.10	40	0.318	0.33	Al2024-T3	47	0.500
AMES	A86/2	0.953	2.796	1.2651	2.78	6.64	0	6.64	0.318	0.33	30.48	32	0.229	0.24	Al2024-T3	47	0.573
AMES	A86/5	0.953	2.796	1.2651	2.78	6.47	0	6.47	0.159	0.17	30.48	32	0.318	0.33	Al2024-T3	47	0.500
AMES	A1913	1.270	2.796	2.9988	2.78	6.71	0	6.71	0.318	0.25	50.80	40	0.483	0.38	Al6061-T6	36	0.630
AMES	A1921	1.270	2.796	2.9988	2.78	6.80	0	6.80	0.159	0.13	22.86	18	0.635	0.50	Al2024-T351	47	0.625
AMES	A1907	1.270	2.796	2.9988	2.78	6.53	0	6.53	0.318	0.25	50.80	40	0.483	0.38	Al2024-T351	47	0.630
MDAC	MD28	1.908	2.78	10.1106	2.78	7.08	0	7.08	0.406	0.21	57.15	30.0	0.968	0.51	Al2024-T351	47	0.720
MDAC	MD31	1.908	2.78	10.1106	2.78	7.15	0	7.15	0.813	0.43	57.15	30.0	0.800	0.42	Al2024-T351	47	0.845
MDAC	MD29	1.908	2.78	10.1106	2.78	7.08	0	7.08	0.406	0.21	76.2	39.9	0.622	0.33	Al2024-T351	47	0.539
MDAC	MD27	1.908	2.78	10.1106	2.78	7.15	0	7.15	0.406	0.21	28.575	15.0	2.827	1.48	Al2024-T351	47	1.695
MDAC	MD30	1.908	2.78	10.1106	2.78	7.27	0	7.27	0.203	0.11	57.15	30.0	1.626	0.85	Al2024-T351	47	0.958

TABLE 1 (Cont.)

Whipple Database

Site	Shot No.	K	K'	K''*V	K''	BL?	Category	Comments
JSC-HIRL	1487	0.0191	0.0267	0.701	0.0961	YES	F3	No perfs; impulsive bulge with dimples
JSC-HIRL	1481	0.0129	0.0181	0.461	0.0649	UNDER	F4	Several perfs; impulsive bulge with dimples
JSC-HIRL	1476	0.0323	0.0453	1.306	0.1620	YES	F3	No perfs; v.slight impulsive bulge
JSC-orig.	4613	0.0578	0.0785	1.463	0.2052	YES	E2	No perfs or spall:v.fine filament craters
JSC-orig.	4637	0.0571	0.0775	1.463	0.2027	UNDER	E4	No tear or hole;v.small perfs in 2.7cm ring
JSC-orig.	4638	0.0671	0.0910	1.792	0.2380	UNDER	E4	No tear or hole;v.small perfs in 4.4cm ring
JSC-orig.	A250	0.0655	0.0889	1.515	0.2324	YES	E2	No hole or spall; near perf
JSC-orig.	A201	0.0544	0.0738	1.293	0.1930	UNDER	E4	No hole or spall; 1 perf
JSC-orig.	4681	0.0579	0.0811	1.508	0.2055	YES	D2	No tear or perfs; small central dimples
JSC-orig.	4679	0.0643	0.0900	1.633	0.2281	YES	D2	No tear or perfs; small central dimples
JSC-orig.	4658	0.0518	0.0725	1.333	0.1839	UNDER	E4	No tear or hole;v.small perfs in 2.7cm ring
JSC-HIRL	1435	0.0478	0.0669	1.098	0.1685	YES	E2	No tear or hole; dimples
JSC-HIRL	1468	0.0461	0.0646	1.086	0.1620	YES	E2	No tear or hole; dimples
JSC-orig.	4695	0.0642	0.0889	1.217	0.1610	YES	E2	No tear or perfs; small central craters
JSC-orig.	4709	0.0668	0.0925	1.217	0.1677	YES	E2	No tear or perfs; 2cm dimple ring
JSC-orig.	4691	0.0524	0.0726	0.954	0.1316	UNDER	E4	No tear or hole; 3 small perfs
JSC-orig.	4706	0.0524	0.0725	0.954	0.1314	UNDER	E4	No tear or hole; perf ring 3.4 cm; 4 perfs
JSC-orig.	4738	0.0652	0.0913	1.178	0.1637	OVER	E1	No tear,hole or perfs; small central craters
JSC-orig.	4736	0.0503	0.0705	0.924	0.1264	UNDER	E4	No tear or hole; perf ring 5.6 cm; 4 perfs
JSC-HIRL	A1200	0.3953	0.5563	6.125	0.8839	OVER	D1	Too thick; central craters
JSC-HIRL	A1218	0.2971	0.4182	4.604	0.6644	UNDER	D3	Thin central spall 4mm dia
JSC-HIRL	A1196	0.1430	0.2013	2.302	0.3198	YES	E2	No tear,hole or perfs; small central craters
JSC-HIRL	A1076	0.0353	0.0495	0.503	0.0789	UNDER	E4	Numerous perforations and spall dimples
JSC-HIRL	A1077	0.0519	0.0727	0.786	0.1161	YES	E2	No perfs, numerous spall (attached) dimples
JSC-HIRL	A1281	0.0980	0.1184	1.165	0.1739	UNDER	E4	Many small, dispersed perforations
JSC-HIRL	A235	0.1174	0.1651	1.454	0.2084	YES	E3	No hole or tear; 1 spall split
JSC-HIRL	A240	0.0996	0.1401	1.164	0.1768	YES	E2	No hole or tear; attached spall
JSC-HIRL	A151	0.0711	0.0996	0.833	0.1262	UNDER	D4	Hole, detached spall, cracks
JSC-HIRL	B31	0.1033	0.1448	0.918	0.1296	YES	E2	Central and ring dimples/spallation
JSC-HIRL	B37	0.1118	0.1575	0.897	0.1403	UNDER	E4	Small hole, detached spall (30 mm dia.)

K=tw*(Y/70)^0.5*S^0.5/((p proj*p bump)^(1/6)*M^(1/3)*Vn)
K'=tw*(Y/70)^0.5*S^0.5/(M^(1/3)*Vn)
K''=tw*(Y/70)^0.5*S^0.5/(d^0.5*(p proj*p bump)^(1/6)*M^(1/3)*Vn)

TABLE 1 (Cont.)

Whipple Database

Site	Shot No.	K	K'	K''*V	K''	BL?	Category	Comments
BOEING	85-24F	0.1767	0.2474	1.330	0.2217	YES	E2	
BOEING	85-13	0.1803	0.2525	1.330	0.2262	YES	E2	
BOEING	85-16	0.1262	0.1767	1.012	0.1446	YES	E2	
BOEING	85-20C	0.1380	0.1933	1.012	0.1581	UNDER	D4	
MSFC	86-2	0.1006	0.1402	0.788	0.1129	UNDER	F5	
MSFC	86-1	0.1017	0.1419	0.788	0.1142	UNDER	F5	
AMES	A1895	0.1199	0.1687	0.846	0.1228	YES	F3	Dented; no tear or spall; #1868 repeat
AMES	A1868	0.1163	0.1637	0.846	0.1192	YES	F3	Dented; no tear or spall; A86/5 w/6061-T6
AMES	A86/1	0.2838	0.3994	1.934	0.2908	OVER	D1	No hole or spall; front surface erosion
AMES	A1917	0.1848	0.2601	1.273	0.1894	YES	D2	No hole or tear; attached spall with crack
AMES	A1899	0.1954	0.2750	1.367	0.2002	UNDER	D3	No hole or tear; thin, 5cm detached spall
AMES	A1875	0.1223	0.1722	0.846	0.1254	YES	F3	Dented; no tear or spall; #1868 w/ 2mm press.
AMES	A86/3	0.1022	0.1438	0.696	0.1047	UNDER	F4	Dented with 0.16 cm crack; incip spall ring
AMES	A86/4	0.1062	0.1494	0.696	0.1088	UNDER	E4	No hole or tear; perf ring; no central spall
AMES	A1918	0.1545	0.2174	1.081	0.1583	YES	E2	No hole or perf; ring & central incip spalls
AMES	A86/2	0.1023	0.1440	0.696	0.1048	YES	F2	No hole or tear; impulsive dent;1 incip spall
AMES	A86/5	0.1458	0.2053	0.967	0.1494	UNDER	F4	Dented with 3 cracks; 3 sm perfs; thin spall
AMES	A1913	0.1811	0.2549	1.078	0.1607	YES	D2	No tear or spall; some impulsive denting
AMES	A1921	0.1803	0.2537	1.088	0.1600	UNDER	D3	No hole or tear; thin 7.6cm detached spall
AMES	A1907	0.2127	0.2993	1.232	0.1887	UNDER	E4	No tear; 1 perf 0.48cm; attached spall
MDAC	MD28	0.2785	0.3916	1.427	0.2016	YES	E2	No hole or tear; attached spall dimples
MDAC	MD31	0.2280	0.3206	1.180	0.1651	YES	E2	No hole or tear; attached spall dimples
MDAC	MD29	0.2068	0.2907	1.060	0.1497	UNDER	E3	No hole or tear; incip spalls, some detached
MDAC	MD27	0.5696	0.8009	2.948	0.4124	YES	D2	No hole or tear; attached spall, split
MDAC	MD30	0.4556	0.6406	2.398	0.3298	YES	D2	No hole or tear; attached spall, split

K=tw*(Y/70)^0.5*S^0.5/((p proj*p bump)^(1/6)*M^(1/3)*Vn)

K'=tw*(Y/70)^0.5*S^0.5/(M^(1/3)*Vn)

K''=tw*(Y/70)^0.5*S^0.5/(d^0.5*(p proj*p bump)^(1/6)*M^(1/3)*Vn)

TABLE 2

Whipple Database

Site	Shot No.	Modified Cour-Palais Equation Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)	Original C-P Non-Opt. Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)
JSC-HIRL	1487	0.0254	1.665	1	0	0		0.0438	2.873	1	0	0	
JSC-HIRL	1481	0.0251	2.466	1	1		1	0.0432	4.256	1	1		1
JSC-HIRL	1476	0.0263	0.987	0	1	1		0.0454	1.704	1	0	0	
JSC-orig.	4613	0.0198	0.780	0	1	1		0.0242	0.951	0	1	1	
JSC-orig.	4637	0.0201	0.789	0	0		0	0.0245	0.963	0	0		0
JSC-orig.	4638	0.0171	0.672	0	0		0	0.0208	0.820	0	0		0
JSC-orig.	A250	0.0210	0.688	0	1	1		0.0256	0.840	0	1	1	
JSC-orig.	A201	0.0253	0.829	0	0		0	0.0308	1.011	1	1		1
JSC-orig.	4681	0.0316	0.779	0	1	1		0.0386	0.950	0	1	1	
JSC-orig.	4679	0.0178	0.702	0	1	1		0.0217	0.856	0	1	1	
JSC-orig.	4658	0.0221	0.870	0	0		0	0.0270	1.062	1	1		1
JSC-HIRL	1435	0.0289	0.950	0	1	1		0.0351	1.152	1	0	0	
JSC-HIRL	1468	0.0301	0.987	0	1	1		0.0364	1.193	1	0	0	
JSC-orig.	4695	0.0631	0.994	0	1	1		0.0544	0.857	0	1	1	
JSC-orig.	4709	0.0606	0.954	0	1	1		0.0523	0.823	0	1	1	
JSC-orig.	4691	0.0494	1.216	1	1		1	0.0426	1.049	1	1		1
JSC-orig.	4706	0.0495	1.217	1	1		1	0.0427	1.050	1	1		1
JSC-orig.	4738	0.0621	0.978	0	1	1		0.0536	0.843	0	1	1	
JSC-orig.	4736	0.0515	1.266	1	1		1	0.0444	1.092	1	1		1
JSC-HIRL	A1200	0.0874	0.181	0	1	1		0.0671	0.139	0	1	1	
JSC-HIRL	A1218	0.0765	0.241	0	0		0	0.0588	0.185	0	0		0
JSC-HIRL	A1196	0.0794	0.500	0	1	1		0.0611	0.385	0	1	1	
JSC-HIRL	A1076	0.0824	2.027	1	1		1	0.0633	1.558	1	1		1
JSC-HIRL	A1077	0.0875	1.379	1	0	0		0.0673	1.060	1	0	0	
JSC-HIRL	A1281	0.0748	0.920	0	0		0	0.0456	0.561	0	0		0
JSC-HIRL	A235	0.1219	0.768	0	1	1		0.0744	0.468	0	1	1	
JSC-HIRL	A240	0.1149	0.905	0	1	1		0.0701	0.552	0	1	1	
JSC-HIRL	A151	0.1610	1.268	1	1		1	0.0982	0.774	0	0		0
JSC-HIRL	B31	0.2822	1.235	1	0	0		0.1217	0.533	0	1	1	
JSC-HIRL	B37	0.3620	1.140	1	1		1	0.1562	0.492	0	0		0

TABLE 2 (Cont.)

Whipple Database

Site	Shot No.	Modified Cour-Palais Equation Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)	Original C-P Non-Opt. Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)
BOEING	85-24F	0.2291	0.722	0	1	1		0.0988	0.311	0	1	1	
BOEING	85-13	0.2245	0.707	0	1	1		0.0969	0.305	0	1	1	
BOEING	85-16	0.3514	1.107	1	0	0		0.1384	0.436	0	1	1	
BOEING	85-20C	0.3213	1.012	1	1		1	0.1265	0.398	0	0		0
MSFC	86-2	0.4498	1.417	1	1		1	0.1736	0.547	0	0		0
MSFC	86-1	0.4447	1.401	1	1		1	0.1716	0.541	0	0		0
AMES	A1895	0.4137	1.303	1	0	0		0.1457	0.459	0	1	1	
AMES	A1868	0.4263	1.343	1	0	0		0.1501	0.473	0	1	1	
AMES	A86/1	0.3494	0.550	0	1	1		0.1231	0.194	0	1	1	
AMES	A1917	0.4077	0.845	0	1	1		0.1436	0.298	0	1	1	
AMES	A1899	0.5075	0.799	0	0		0	0.1788	0.282	0	0		0
AMES	A1875	0.4052	1.276	1	0	0		0.1427	0.450	0	1	1	
AMES	A86/3	0.3494	1.528	1	1		1	0.1231	0.538	0	0		0
AMES	A86/4	0.3363	1.471	1	1		1	0.1184	0.518	0	0		0
AMES	A1918	0.3210	1.011	1	0	0		0.1131	0.356	0	1	1	
AMES	A86/2	0.3489	1.526	1	0	0		0.1229	0.538	0	1	1	
AMES	A86/5	0.3400	1.071	1	1		1	0.1197	0.377	0	0		0
AMES	A1913	0.4804	0.995	0	1	1		0.1465	0.304	0	1	1	
AMES	A1921	0.6352	1.000	1	1		1	0.1938	0.305	0	0		0
AMES	A1907	0.4092	0.848	0	0		0	0.1248	0.259	0	0		0
MDAC	MD28	0.7680	0.794	0	1	1		0.1911	0.198	0	1	1	
MDAC	MD31	0.7756	0.969	0	1	1		0.1930	0.241	0	1	1	
MDAC	MD29	0.6651	1.069	1	1		1	0.1655	0.266	0	0		0
MDAC	MD27	1.0969	0.388	0	1	1		0.2730	0.097	0	1	1	
MDAC	MD30	0.7886	0.485	0	1	1		0.1963	0.121	0	1	1	

TABLE 2 (Cont.)

Whipple Database

Site	Shot No.	Wilkinson Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)	Nysmith Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)
JSC-HIRL	1487	0.0020	0.129	0	1	1		0.0058	0.383	0	1	1	
JSC-HIRL	1481	0.0020	0.200	0	0		0	0.0058	0.570	0	0		0
JSC-HIRL	1476	0.0023	0.087	0	1	1		0.0060	0.225	0	1	1	
JSC-orig.	4613	0.0002	0.009	0	1	1		0.0039	0.155	0	1	1	
JSC-orig.	4637	0.0004	0.016	0	0		0	0.0052	0.204	0	0		0
JSC-orig.	4638	0.0002	0.007	0	0		0	0.0030	0.117	0	0		0
JSC-orig.	A250	0.0009	0.030	0	1	1		0.0091	0.300	0	1	1	
JSC-orig.	A201	0.0002	0.006	0	0		0	0.0020	0.066	0	0		0
JSC-orig.	4681	0.0007	0.018	0	1	1		0.0072	0.177	0	1	1	
JSC-orig.	4679	0.0001	0.003	0	1	1		0.0016	0.061	0	1	1	
JSC-orig.	4658	0.0006	0.023	0	0		0	0.0052	0.204	0	0		0
JSC-HIRL	1435	0.0024	0.080	0	1	1		0.0136	0.447	0	1	1	
JSC-HIRL	1468	0.0026	0.085	0	1	1		0.0141	0.461	0	1	1	
JSC-orig.	4695	0.0026	0.041	0	1	1		0.0209	0.330	0	1	1	
JSC-orig.	4709	0.0050	0.079	0	1	1		0.0299	0.470	0	1	1	
JSC-orig.	4691	0.0011	0.027	0	0		0	0.0118	0.290	0	0		0
JSC-orig.	4706	0.0022	0.055	0	0		0	0.0170	0.418	0	0		0
JSC-orig.	4738	0.0028	0.044	0	1	1		0.0207	0.325	0	1	1	
JSC-orig.	4736	0.0013	0.031	0	0		0	0.0118	0.291	0	0		0
JSC-HIRL	A1200	0.0229	0.048	0	1	1		0.0549	0.114	0	1	1	
JSC-HIRL	A1218	0.0153	0.048	0	0		0	0.0549	0.173	0	0		0
JSC-HIRL	A1196	0.0068	0.043	0	1	1		0.0355	0.224	0	1	1	
JSC-HIRL	A1076	0.0058	0.144	0	0		0	0.0274	0.675	0	0		0
JSC-HIRL	A1077	0.0097	0.153	0	1	1		0.0353	0.556	0	1	1	
JSC-HIRL	A1281	0.0038	0.047	0	0		0	0.0842	1.036	1	1		1
JSC-HIRL	A235	0.0105	0.066	0	1	1		0.0562	0.354	0	1	1	
JSC-HIRL	A240	0.0068	0.053	0	1	1		0.0454	0.357	0	1	1	
JSC-HIRL	A151	0.0259	0.204	0	0		0	0.1189	0.936	0	0		0
JSC-HIRL	B31	0.0290	0.127	0	1	1		0.1055	0.461	0	1	1	
JSC-HIRL	B37	0.0814	0.256	0	0		0	0.2386	0.751	0	0		0

TABLE 2 (Cont.)

Site	Shot No.	Wilkinson Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)	Nysmith Calc Wall Th'k (cm)	tw calc to tw ratio	Perf. Pred. (1=Y)	Pred. Accurate? (1=Y)	No-Perf. Acc? (1=Y)	Perf. Acc? (1=Y)
BOEING	85-24F	0.0343	0.108	0	1	1		0.1335	0.420	0	1	1	
BOEING	85-13	0.0336	0.106	0	1	1		0.1327	0.418	0	1	1	
BOEING	85-16	0.0831	0.262	0	1	1		0.2371	0.747	0	1	1	
BOEING	85-20C	0.0759	0.239	0	0		0	0.2313	0.729	0	0		0
MSFC	86-2	0.2077	0.654	0	0		0	0.4674	1.472	1	1		1
MSFC	86-1	0.2053	0.647	0	0		0	0.4659	1.468	1	1		1
AMES	A1895	0.0496	0.156	0	1	1		0.1728	0.544	0	1	1	
AMES	A1868	0.0511	0.161	0	1	1		0.1743	0.549	0	1	1	
AMES	A86/1	0.0319	0.050	0	1	1		0.1712	0.270	0	1	1	
AMES	A1917	0.0574	0.119	0	1	1		0.2560	0.530	0	1	1	
AMES	A1899	0.1312	0.207	0	0		0	0.4515	0.711	0	0		0
AMES	A1875	0.0486	0.153	0	1	1		0.1719	0.541	0	1	1	
AMES	A86/3	0.0319	0.140	0	0		0	0.1712	0.749	0	0		0
AMES	A86/4	0.0101	0.044	0	0		0	0.0942	0.412	0	0		0
AMES	A1918	0.0210	0.066	0	1	1		0.1265	0.398	0	1	1	
AMES	A86/2	0.0159	0.070	0	1	1		0.1187	0.519	0	1	1	
AMES	A86/5	0.0311	0.098	0	0		0	0.1699	0.535	0	0		0
AMES	A1913	0.0275	0.057	0	1	1		0.1355	0.281	0	1	1	
AMES	A1921	0.1835	0.289	0	0		0	0.5943	0.936	0	0		0
AMES	A1907	0.0178	0.037	0	0		0	0.1345	0.279	0	0		0
MDAC	MD28	0.0601	0.062	0	1	1		0.3360	0.347	0	1	1	
MDAC	MD31	0.0304	0.038	0	1	1		0.2337	0.292	0	1	1	
MDAC	MD29	0.0338	0.054	0	0		0	0.2253	0.362	0	0		0
MDAC	MD27	0.2429	0.086	0	1	1		0.8822	0.312	0	1	1	
MDAC	MD30	0.1235	0.076	0	1	1		0.4880	0.300	0	1	1	

FIGURE 1

Whipple Shield "K" Factor

Modified Cour–Palais Whipple Non–Opt Eq

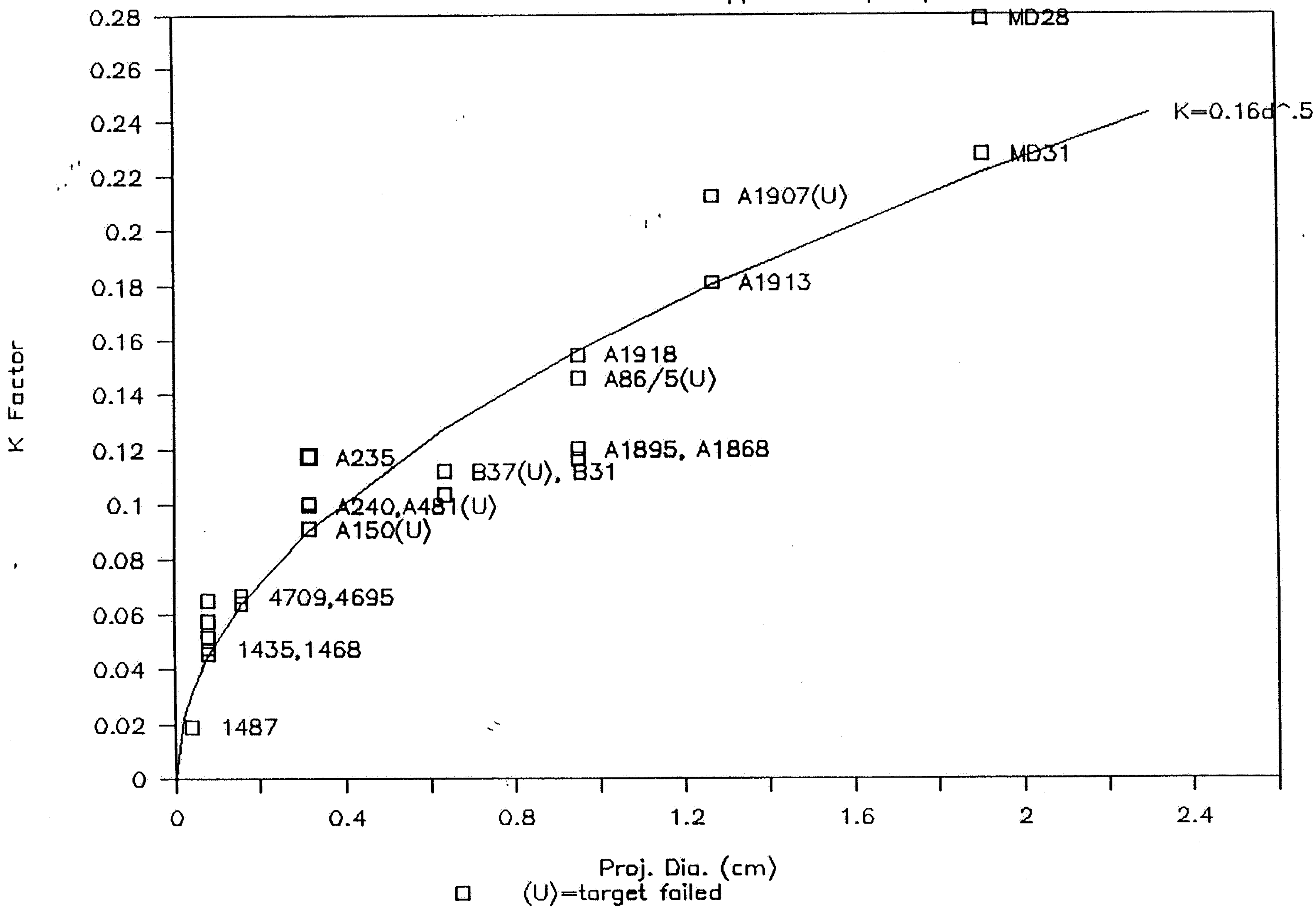
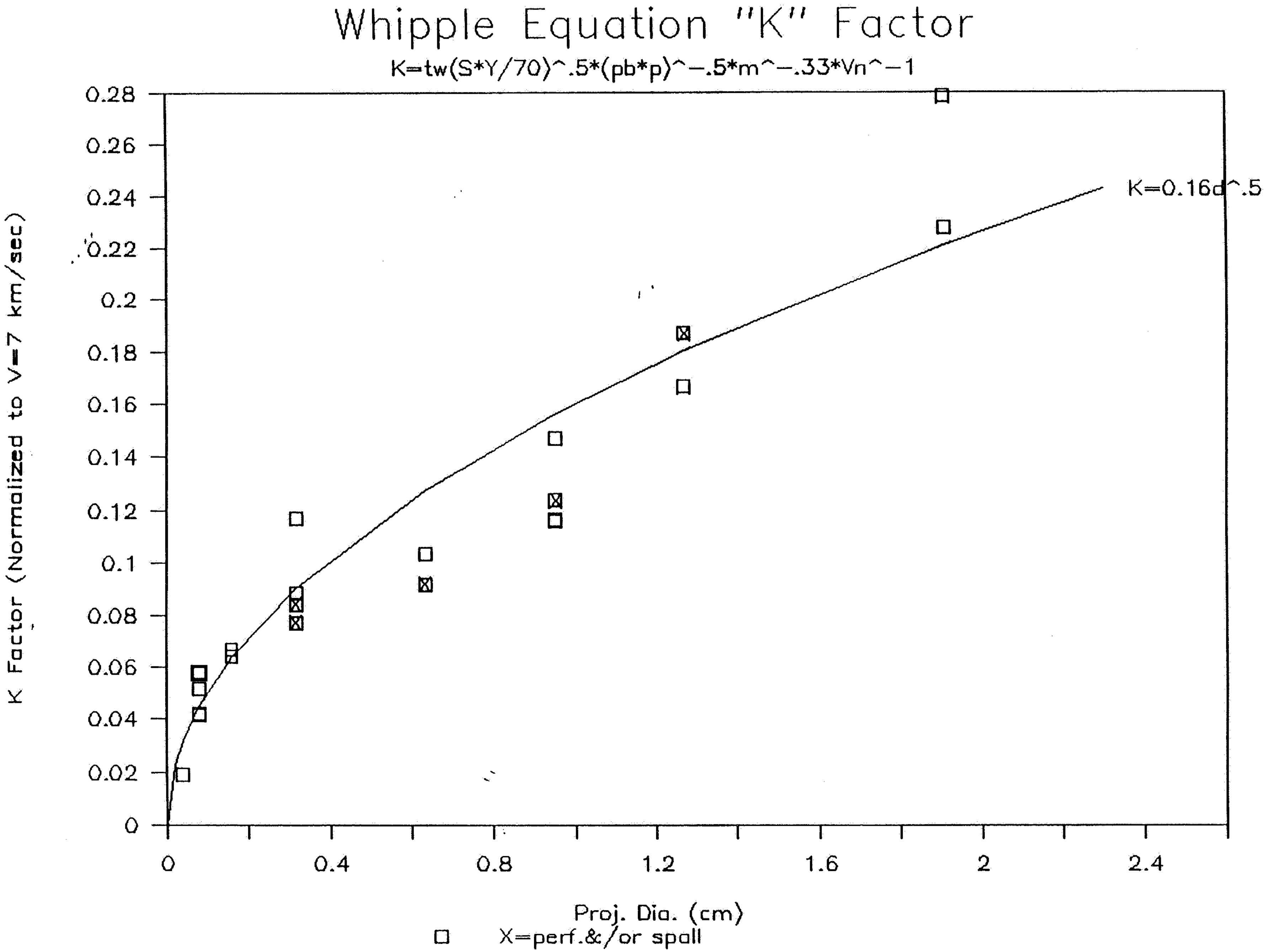


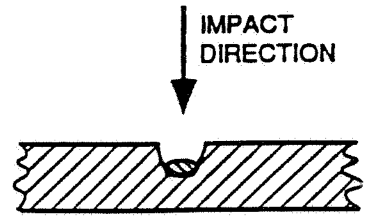
FIGURE 2



Whipple Equation "K" Factor
K=tw(S*Y/70)^.5*(pb*p)^-.5*m^-.33*Vn^-1
K=0.16d^.5
K Factor (Normalized to V=7 km/sec)
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.4
0.8
1.2
1.6
2
2.4
Proj. Dia. (cm)
X=perf.&/or spall

<u>Class</u>

CATEGORY A: SINGLE CRATER PATTERN - LOW VELOCITY
PROJECTILE REMAINS INTACT

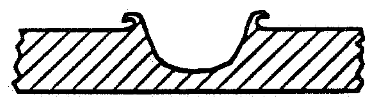


A1
- NO PERFORATION OR REAR SURFACE DEFORMATION
- CRATER DIAMETER APPROXIMATE SIZE OF PROJECTILE

A2
- NO PENETRATION
- CRACKS OR SPLITTING MAY BE PRESENT
- REAR SURFACE DEFORMATION

A3
- PENETRATION
- HOLE DIAMETER APPROXIMATE SIZE OF PROJECTILE

CATEGORY B: SINGLE CRATER PATTERN - HYPERVELOCITY
PROJECTILE REMAINS INTACT



B1
- NO PERFORATION OR REAR SPALL
- SINGLE ROUNDED CRATER
- FRONT SURFACE LIP OR SPALLATION

B2
- NO PERFORATION, BUT WITH ATTACHED REAR SPALL
- SINGLE ROUNDED CRATER
- FRONT SURFACE LIP OR SPALLATION

B3
- NO PERFORATION, BUT WITH DETACHED REAR SPALL
- SINGLE ROUNDED CRATER
- FRONT SURFACE LIP OR SPALLATION
- LIGHT TIGHT

B4
- PERFORATION DUE TO CRATER AND REAR SPALL MEETING (HOLE DIAMETER < 2 mm)
- FRONT SURFACE LIP OR SPALLATION
- NOT LIGHT TIGHT

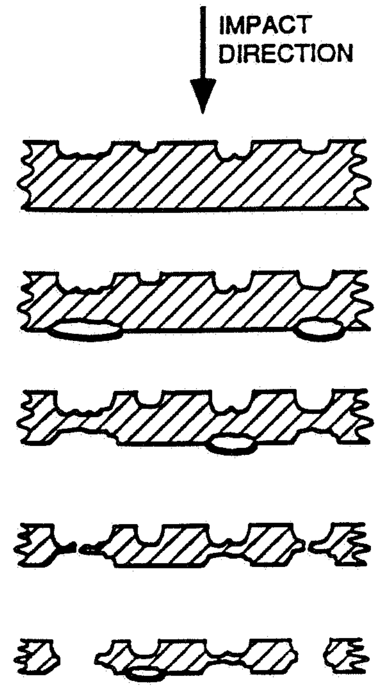
B5
- PENETRATION
- HOLE FORMED BY CRATER AND DETACHED SPALL (HOLE DIAMETER ≥ 2 mm)
- FRONT AND REAR SURFACE LIPS OR SPALLATION

FIGURE 3. **Damage Classification for Shielded Metallic Targets**

REF. Dahl and Cour-Palais: "Standardization of Impac
Damage Classification and Measurements for
Metallic Targets", 1990

Class

CATEGORY C: MULTIPLE CRATER PATTERN
PROJECTILE BREAKS UP INTO COARSE AND FINE FRAGMENTS



C1
- NO PERFORATION, REAR SURFACE DEFORMATION OR SPALL
- RANDOM SURFACE CRATERS, PITTING OR EROSION

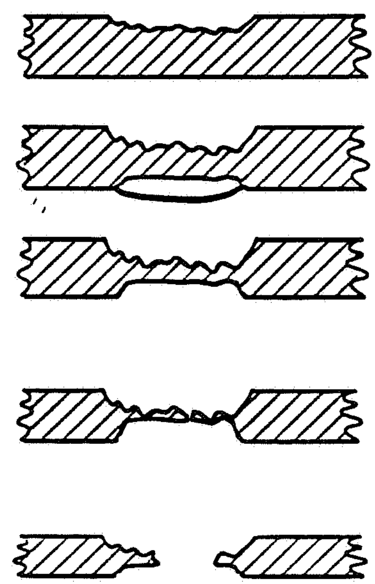
C2
- NO PERFORATION, BUT WITH ATTACHED SPALL(S) OR REAR SURFACE DEFORMATION
- RANDOM SURFACE CRATERS, PITTING, OR EROSION

C3
- NO PERFORATION, BUT WITH DETACHED SPALL(S)
- RANDOM SURFACE CRATERS, PITTING OR EROSION
- LIGHT TIGHT

C4
- PERFORATION
- CRACKS OR SMALL HOLE(S) (ALL HOLE DIAMETERS < 2 mm)
- NOT LIGHT TIGHT

C5
- PENETRATION
- LARGE HOLE(S) (APPLICABLE IF ANY HOLE DIAMETER ≥ 2 mm)

CATEGORY D: CENTRAL CRATER PATTERN
PROJECTILE BREAKS UP INTO FINE PARTICLES



D1
- NO PERFORATION OR REAR SPALL
- CENTRAL SURFACE CRATER, PITTING OR EROSION

D2
- NO PERFORATION, BUT WITH ATTACHED SPALL
- CENTRAL SURFACE CRATER, PITTING, OR EROSION

D3
- NO PERFORATION, BUT WITH DETACHED SPALL
- CENTRAL SURFACE CRATER, PITTING OR EROSION
- LIGHT TIGHT

D4
- PERFORATION
- CRACKS OR SMALL HOLE(S) DUE TO CRATER AND SPALL MEETING (ALL HOLE DIAMETERS < 2 mm)
- NOT LIGHT TIGHT

D5
- PENETRATION
- LARGE HOLE(S) FORMED BY CRATER AND DETACHED SPALL (APPLICABLE IF ANY HOLE DIAMETER ≥ 2 mm)

FIGURE 4. **Damage Classification for Shielded Metallic Targets (Cont.)**

REF. Dahl and Cour-Palais: "Standardization of Impact Damage Classification and Measurements for Metallic Targets", 1990

Class

CATEGORY E: RING CRATER PATTERN

PROJECTILE BREAKS UP INTO VERY FINE PARTICLES

E1
- NO PERFORATION OR REAR SPALL
- RING CRATERS SURROUND CENTRAL SURFACE CRATER, PITTING, OR EROSION

E2
- NO PERFORATION
- RING CRATERS WITH SPALL PIMPLES ATTACHED AND/OR CENTRAL SPALL ATTACHED
- CENTRAL SURFACE CRATER, PITTING, OR EROSION

E3
- NO PERFORATION
- RING CRATERS WITH SPALL PIMPLES DETACHED AND/OR CENTRAL SPALL DETACHED
- CENTRAL SURFACE CRATER, PITTING, OR EROSION
- LIGHT TIGHT

E4
- PERFORATION
- HOLE(S) DUE TO CRATER(S) AND SPALL(S) MEETING
- NOT LIGHT TIGHT

E5
- PENETRATION
- LARGE HOLE PUNCHED OUT DUE TO RING PERFORATIONS AND IMPULSIVE LOAD

CATEGORY F: NON-PARTICULATE IMPULSIVE LOADING

PROJECTILE BECOMES MOLTEN LIQUID OR VAPOR

F1
- NO PERFORATION OR REAR SPALL
- SURFACE PITTING OR MOLTEN SPLASH

F2
- NO PERFORATION
- SPALL PRESENT, ATTACHED OR DETACHED
- SURFACE PITTING OR MOLTEN SPLASH

F3
- NO PERFORATION
- DENTED, BUT INTACT
- SURFACE PITTING OR MOLTEN SPLASH
- LIGHT TIGHT

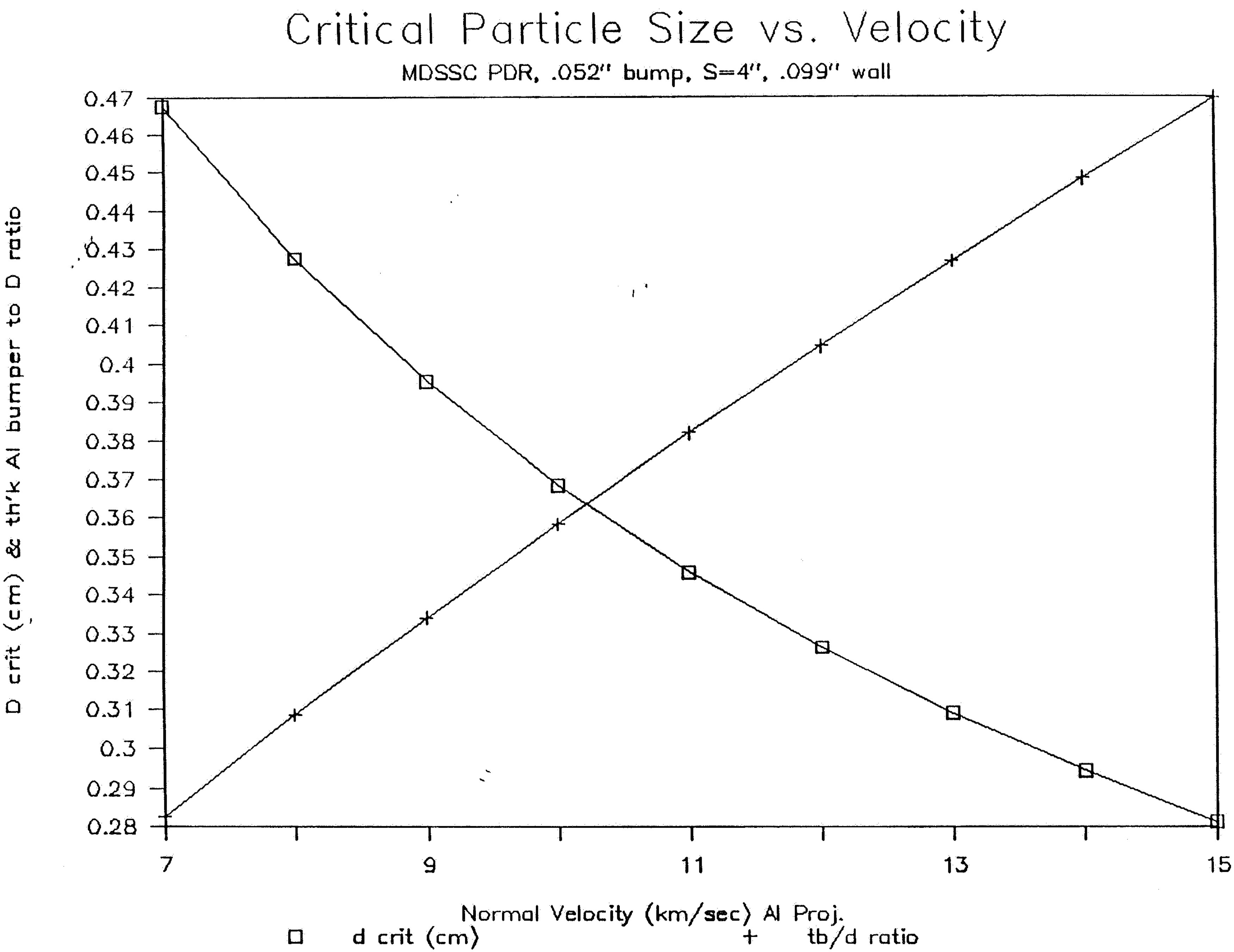
F4
- PERFORATION
- DENTED AND SPLIT
- SURFACE PITTING OR MOLTEN SPLASH
- NOT LIGHT TIGHT

F5
- PENETRATION BY IMPULSIVE LOAD FAILURE
- PETALLED HOLE
- SURFACE PITTING OR MOLTEN SPLASH

FIGURE 5. **Damage Classification for Shielded Metallic Targets (Cont.)**

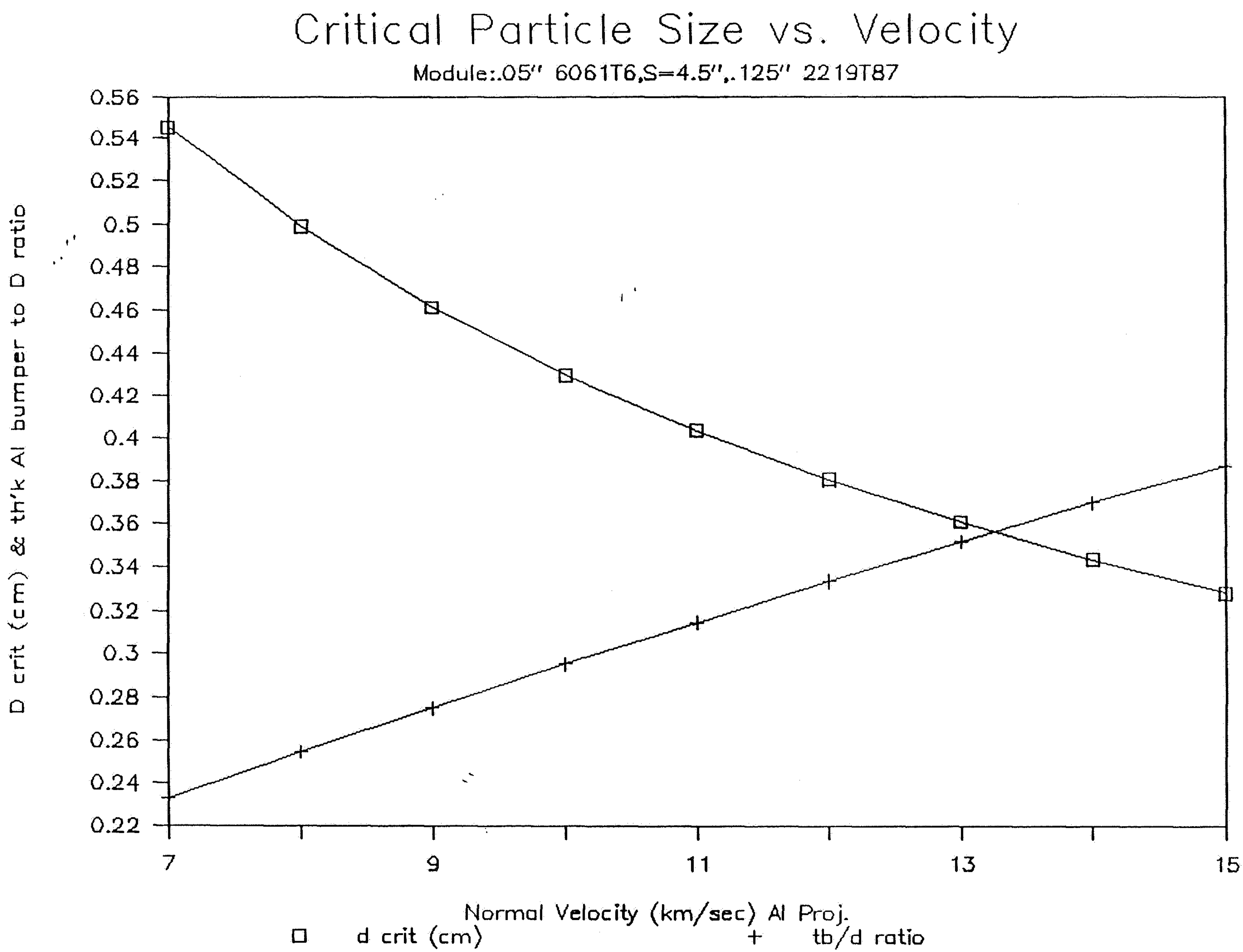
REF. Dahl and Cour-Palais: "Standardization of Impact Damage Classification and Measurements for Metallic Targets", 1990

FIGURE 6



Critical Particle Size vs. Velocity
MDSSC PDR, .052" bump, S=4", .099" wall
D crit (cm) & th'k Al bumper to D ratio
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0.4
0.39
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.3
0.29
0.28
7
9
11
13
15
Normal Velocity (km/sec) Al Proj.
d crit (cm)
tb/d ratio

FIGURE 7



Critical Particle Size vs. Velocity
Module:.05" 6061T6,S=4.5",.125" 2219T87
D crit (cm) & th'k Al bumper to D ratio
0.56
0.54
0.52
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
7
9
11
13
15
Normal Velocity (km/sec) Al Proj.
d crit (cm)
tb/d ratio