LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California/94550

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**MECHANICAL AND FRICTIONAL BEHAVIOR
OF SKID TEST HEMISPHERICAL BILLETS**

L. Green

A. Weston

J. Van Velkinburg

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MECHANICAL AND FRICTIONAL BEHAVIOR OF SKID TEST HEMISPHERICAL BILLETS

Abstract

Accelerometer-instrumented hemispherical billets of several plastic-bonded explosives were impacted against both the standard abrasive SKID target and a special smooth steel target. Drop heights ranged from 3 in. to 14.1 ft. Preimpact angles were at 14°, 45°, and 90°. Various sizes of billets were dropped: 6-in. diam and 4 lb, 11-in. diam and 23 lb, 11.8-in.

diam and 28 lb, and 25.6-in. diam and 296 lb.

The accelerometer records are analyzed, and the resulting descriptions of SKID billet mechanical and frictional behavior are illustrated.

A total of 56 instrumented tests are reported. In three of these, the explosive ignited.

I. Introduction

In the SKID test, hemispherical billets of explosive material are caused to strike an abrasive target surface at an oblique angle. Explosive reactions consequential to this process are classified as to threshold and magnitude, as measures of the handling safety (sensitivity) of the tested explosives.^{1,2}

The series of tests reported here was carried out to better understand the mechanics of SKID test behavior. Standard and nonstandard sizes of explosive billets were instrumented with accelerometers. A primary test objective was to relate the accelerometer records to criteria for predicting SKID test ignitions. Possible relationships between the accelerometer records and the ignition processes are suggested in section VII. So far, the number of instrumented billet records

when ignitions occurred (three) is not enough to establish any of the suggested relationships as a valid ignition criterion.

On the other hand, the mechanical aspects of the Pantex version of the SKID test has been thoroughly explored in this series of experiments. The scope of the testing has included variation of the nature of the target surface as well as variations in billet size, explosive composition, drop height and preimpact angle. Friction coefficient has been measured as a function of time. In some instances, it exhibits change with time that could be an indication of contact region melting of the explosive.

SKID test ignitions are the result of mechanical and chemical explosive material behavior. It is interesting to point out that LX 04-1 and PBX 9011-02 are

very similar in SKID test mechanical behavior, even though PBX 9011-02 is much less likely to give an observable event. On the other hand, LX 07-1, LX 09-0 and PBX 9404-03, which are stiffer than LX 04-1, are more likely to give an observable event.

A separately reported previous test series³ in which billets were dropped vertically against a smooth rigid target surface generated necessary information concerning billet mechanical deformation.* That data has been curve-fitted and included as part of the data reduction process for the present series of billet drops. These curve fits are plotted in Appendix B, together with associated data from this test series that exhibit the phenomenon of "target flexibility."[†]

The experimental procedures and test setup are described in section II. Each billet was instrumented with two accelerometers, located equidistant from the hemispherical axis in the same plane and vertically oriented. The average sum of the accelerometer readings measured the billet acceleration normal to the target surface while the difference in the readings measured the billet angular acceleration. All derivations and analyses pertinent to reduction of the accelerometer data and generation of study results are described in Appendix A.

SKID test behavior is illustrated by the several sets of comparative curves included on the figures that follow sections IV-VIII. These curves follow a

*It was necessary to conduct the vertical drop series to determine contact diameter, a quantity not reliably measured in drops against the standard SKID surface.

[†]See section VIII-A, p. 53.

common format which is described in section III.

The study results are a description of billet mechanical behavior versus time and are derived from the accelerometer records. Quantities plotted versus time after initial billet contact include normal and drag stress, coefficient of friction, and generation of contact region sliding energy. The standard Pantex SKID test involves 11-in.-diam billets dropped at preimpact angles of 14 and 45 deg against an abrasive target. Results relating to this standard test are described in section IV. Sections V and VI describe drops of the standard-size billets against a smooth steel target and drops of larger billets. The drops to the smooth steel target are interesting not only as compared with drops to the abrasive target, but because of the clear indication of melting in the experimental curves for friction coefficient. On three instrumented drops yielding accelerometer records, billet ignitions were experienced. These ignitions are described in section VII; potential ignition criteria are suggested. Certain unique features of the SKID test important to the evaluation of SKID test results are described in section VIII. Of particular importance are assumptions concerning the mechanical action of the billet support cradle and possible eccentricity in the normal contact force reaction.

Various tables pertinent to this report are located in Appendix C. Tables C-1 and C-2 for explosive material composition and mechanical properties are self-explanatory. Table C-3 is arranged to show the comparative performance of different materials subjected to the standard

SKID test using 11-in.-diam billets and the abrasive target. Energy fluence, defined here as the incremental summation of contact drag stress and sliding velocity, is an integrated composite result of the mechanical behavior of any given billet impact. The time after impact for a given level of energy fluence to be attained is tabulated as a measure of the comparative mechanical performance of the various billets.

Table C-4 tabulates the same comparative performance data for the large 25.6-in.-diam billets. Tables C-5 and C-6 are the primary data summary tables. They tabulate direct experimental information and derived results for all 56 drops of this test series. Table C-7, a summary of data from the previous verti-

cal drop test series, is reproduced from Ref. 3. Table C-5 and Table C-7 tabulate formally similar data applicable to both the SKID test series and the vertical drop test series. Table C-6 tabulates additional data that were obtained in the SKID test series. Table C-8 is a nomenclature list pertaining to Tables C-1 through C-7.

Taken altogether, the body of data reported here is not inconsistent with a point of view that the energy fluence accumulated during the pressure rise time is related to observed "threshold" chemical reactions, and that if no reaction has become manifest before the time when the normal pressure has declined to 75% of its peak value, then a later reaction is not probable.

II. Experimental Setup and Procedures

A schematic diagram of the test setup is given in Fig. 1. Shown are the support poles and wires, release solenoid, hemispherical billet in saddle, impact block and position flag. A trifilar pendulum was arranged from long support poles so that a hemispherical sample freely supported in a wood laminate annular ring saddle could be dropped in an arc, the equator staying parallel to the ground, with the curved surface free to impact the target. By appropriate lengths of cables and placement of target, one could select various angles of impact. These experiments used impact angles of 14 and 45 deg only. By means of another pole

and cable, the wooden ring and sample were hoisted remotely and then allowed to drop by means of a solenoid release.

The target was a hard gritty surface made to resemble rough concrete, but was standardized for reproducibility. Graded white silica sand (average particle diameter 600 μ) was very thinly silver-plated by chemical deposition for oscilloscope triggering reasons. This sand was bonded by an electrically conductive epoxy to a steel plate, which was in turn bonded by a sand-filled epoxy to a large concrete pad placed on the ground.

The sample itself was a solid hemisphere, generally either 11.0 in. or

Fig. 1. Schematic diagram of SKID test setup.

25.6 in. in diameter. The size was kept constant in order to fit the annular ring cradle while allowing the weight to vary some with density. Three fine wires (0.005-in. diam) were stretched across the polar region of the hemisphere to make contact with the silver-plated sand upon impact, thus providing a voltage pulse for activating the oscilloscope trigger.

Principal data obtained were normal and rotational acceleration versus time for various HE compositions at various drop heights. An independent determination of the coefficient of restitution and final rotational velocity were obtained

from high-speed Fastax motion pictures whenever possible.

Figure 2 illustrates how the drop height was determined. A carpenter's chalk line was stretched between two stakes so that it was just contacting the sanded impact surface while simultaneously being parallel to the ground. An inert hemisphere of the same size and weight as the HE billet was placed in the saddle. The billet-saddle assembly was then raised to the correct height by means of the remote winch. Drop height was defined as the vertical distance from the pole of the hemisphere to the chalk line. When the height was determined to

Fig. 2. Schematic diagram of drop height determination for SKID test.

be correct, a position flag was secured to the support cable such that the flag lined up with a permanent mark on the support pole. The winch was then backed off until the billet was at a safe height (~1 ft). The HE hemisphere then replaced the inert one in the saddle, and the height was not changed until all operating personnel were inside the protective binder. Drop heights could be set reproducibly to within 1/4 in. by this method. With drop heights less than 1 ft the drop height could be set nonremotely; i.e., the HE billet itself was used to determine drop height. Using this method, there was no need to back off the winch once the height was set. Drop heights were set to within 1/16 in. reproducibly.

Care was taken in placing the HE billet in the saddle to insure that the equatorial surface was level prior to dropping. This was accomplished by temporarily placing a small bubble level on the top surface and adjusting slightly the position of the billet until levelness was obtained. All

billets were placed in a 60°F environmental chamber for at least 8 hr before testing, transported from storage to the test site in specially-built foam boxes, and exposed to ambient conditions for no longer than 15 min prior to testing. Some billets could be reused after dropping. Before reuse, the pole area of the sample was skimmed on a lathe to remove the abraded and permanently deformed area.

Instrumentation consisted of accelerometers and associated electronic recording equipment and a Fastax high-speed motion picture camera. Each test utilized two Columbia Research Laboratories Model 606-3 accelerometers. Two plexiglas disks (3/4-in. diam, 1/4-in. thick, drilled and tapped to accept the accelerometer mounting stud) were permanently epoxied along a diameter of the equatorial surface to serve as accelerometer holders. Figure 3 is a photo of the accelerometers and the accelerometer holders in place on the sample. The billet was placed in the saddle so that upon dropping the line between the centers of the accelerometers was parallel to the arc described by the sample motion. The accelerometers were connected to charge amplifiers (Kistler Instrument Model 566) by means of 100 ft of low-noise, miniature coaxial cable having polyethylene insulation and a vinyl sheath. Acceleration traces were recorded on a Tektronix 555 dual beam oscilloscope using Polaroid type 57 film after being electronically filtered (2 kHz low pass) by a Spencer-Kennedy Model 302 variable filter. The oscilloscope was calibrated for amplitude and time at the beginning of each day of testing; the attenuation of the signal due to the filter was accounted for.

Fig. 3. Accelerometers in place on test explosive.

Accelerometers were obtained with a factory-certified calibration, and were recalibrated by Columbia during the test period. Fastax films were obtained for each drop. Camera

speed on all drops was approximately 4000 frames/sec; 1-kHz timing pips were recorded on the films by the Fastax power source to provide accurate timing information.

III. Format for Graphical Presentation of Comparative Results

The graphical format for presentation of results used in sections IV through VIII is now described. (It will be helpful to refer to Fig. 4 located in section IV.)

Billet performance is illustrated in sets of six graphs. In each set the performance of two billets is compared; the solid line represents one billet and the dotted line the other. For each graph, the abscissa is time after contact in milliseconds. The curves on each graph are now described in detail:

A. INPUT ACCELERATIONS

The billets were instrumented with two accelerometers, A_1 and A_2 , located and oriented to record normal and rotational acceleration (see Fig. A-1 of Appendix A). The plotted input accelerations are $A_n = (A_1 + A_2)/2$ and $A_r = (A_1 - A_2)/2$. The larger magnitude curve, A_n , is the normal acceleration of the billet, and A_r directly relates to the rotational acceleration.

B. COEFFICIENT OF FRICTION

The plotted friction coefficient is the result of dividing the tangential contact drag force by the normal contact compression force. When the assumed normal force eccentricity is equal to zero, the friction coefficient is directly proportional to the ratio of A_r and $A_n + g$.*

SLIDING AND TANGENTIAL VELOCITY

The curves for mass center tangential velocity and nominal contact surface sliding velocity, plotted in in./sec, both start from the same initial value. The sliding velocity falls off more rapidly than the tangential velocity. For the impacts at a preimpact angle of 45 deg, the sliding velocity curve usually will terminate at a negative value. This phenomenon is named "superrotation" and is discussed in section VIII-C.

D. CONTACT STRESS REACTIONS

Curves for both normal pressure and drag stress are plotted in lb/in.². The larger amplitude curves are for normal pressure. Some normal pressure curves

will exhibit "flattopping" behavior with two "knees" present. The time of the second knee will be about the same as the time for maximum billet approach.

E. NORMAL APPROACH

The "approach" of the billet measured in inches, is the normal displacement of its mass center that takes place after initial contact with the target. It is calculated as the direct double integration of the input curve for normal acceleration, A_n . The normal approach is larger than the contact deformation of the billet since it also includes deflection of the target surface. Target "flexibility" is discussed in section VIII-A.

F. SLIDING ENERGY FLUENCE

Sliding energy fluence, measured in cal/cm², is the direct incremental time accumulation of the multiple of contact drag stress and contact surface sliding velocity.* Together with normal pressure it is a quantity that, on the basis of limited data, appears to relate to observed billet ignitions.

*See Eq. (14), p. 72.

*See Eq. (30), p. 78.

IV. Behavior of 11-in. Billets Dropped Against the Standard SKID Target

The 11-in.-diam Pantex billets are considered standard for these tests. Consequently, the comparative behavior of billets of this size is of

prime interest. In this section, sets of curves are presented that illustrate important practical features of the SKID test.

Standard billet drops are compared in the following figures:

- Figures 4-7 illustrate the drop-to-drop variation that occurred when duplicate drops were performed with billets of the same explosive.
- Figures 8-18 illustrate the variations that occurred when billets of different explosives impacted the target at the same nominal initial conditions.
- Figures 19-24 illustrate the variations that occurred with billets of the same material when the pre-impact angle was held constant and the drop height was varied.
- Figures 25 and 26 illustrate the variations that occurred with billets of the same material when the drop height was held constant and the preimpact angle was varied.
- Figure 27 shows a standard target and the contact region of a standard billet of PBX 9404-03 following a 45-deg drop from 3.5 ft. The residue on the target surface is powdery.

In comparing Figs. 4, 5, 6 and 7 with Figs. 15, 16 and 17, note that the duplicate drop variation in billets of the same material can be quite large and is often of the same order of magnitude as that between different materials. Note the definite "flattopping" apparent in the normal pressure curves of Figs. 9, 19 and

21; observe that the declining pressure "knee" occurs at the time of maximum approach. Observe Figs. 13 and 14 for a comparison between PBX 9011-02 and PBX 9404-03. In general, these materials bound the experimental range for the reported explosive formulations. From Figs. 8, 9, 10 and 11 note that LX 04-1 substantially is similar to PBX 9011-02. From Figs. 14 and 17 note that LX 07-1 and LX 09-0 mechanically can act in a manner similar to PBX 9404-03 at a pre-impact angle of 45 deg. From Figs. 16 and 18 note that the accumulation of energy fluence for LX 07-1 and LX 09-0 at a preimpact angle of 14 deg appears similar to that for PBX 9011-02; the stiffer normal loading behavior or the LX 07-1 and the LX 09-0 are compensated for by the greater friction of the PBX 9011-02. For all curves, note that normal pressure attains its maximum prior to the time of maximum approach.

From Fig. 19, a 45-deg impact, note that the large change in drop height was accompanied by only a small change in coefficient of friction. On the other hand, Figs. 22, 23, and 24 for 14-deg impacts exhibit curves for coefficient of friction that do change in shape and level with change in drop height. Coefficient of friction curves that have a concave-upwards shape when plotted against time are discussed in section V in connection with contact melting of the explosive.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9404-03	PBX9404-03
TARGET SURFACE IS	STD SK10	STD SK10
DROP HEIGHT IN FEET	3.50	3.50
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET WEIGHT IN POUNDS	23.150	23.35

Fig. 4. Duplicate drop variation for PBX 9404-03.

DISPLAY CURVES ARE
 MATERIALS ARE
 TARGET SURFACE IS
 DROP HEIGHT IN FEET
 PRE-IMPACT ANGLE IN DEGREES
 BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX09-0	LX09-0
STD SKID	STD SKID
3.50	3.50
45.0	45.0
22.88	22.68

Fig. 5. Duplicate drop variation for LX 09-0.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX07-1	LX07-1
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	3.50	3.50
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET WEIGHT IN POUNDS	23.10	23.10

Fig. 6. Duplicate drop variation for LX-07-1.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9011-02
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	1.25	1.25
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	21.70	21.14

Fig. 7. Duplicate drop variation for PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	PBX9011-02
STD SKID	STD SKID
7.10	7.10
45.0	45.0
25.51	22.10

Fig. 8. Different materials, LX 04-1 versus PBX 9011-02.

Fig. 9. Different materials, LX 04-1 versus PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET HEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	PBX9011-02
STD SKID	STD SKID
3.50	3.50
45.0	45.0
23.56	22.20

Fig. 10. Different materials, LX 04-1 versus PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	PBX9011-02
STD SK10	STD SK10
1.25	1.25
14.0	14.0
23.51	21.14

Fig. 11. Different materials, LX 04-1 versus PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	PBX9404-03
STD SKID	STD SKID
3.50	3.50
45.0	45.0
25.56	25.56

Fig. 12. Different materials, LX 04-1 versus PBX 9404-03.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	3.50	3.50
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET HEIGHT IN POUNDS	22.20	25.50

Fig. 13. Different materials, PBX 9011-02 versus PBX 9404-03.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	3.00	3.00
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET HEIGHT IN POUNDS	21.94	23.20

Fig. 14. Different materials, PBX 9011-02 versus PBX 9404-03.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX09-0	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	3.50	3.50
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET HEIGHT IN POUNDS	22.60	23.50

Fig. 15. Different materials, LX 09-0 versus PBX 9404-03.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX09-0	PBX9011-02
STD SKID	STD SKID
9.00	9.00
14.0	14.0
22.00	21.94

Fig. 16. Different materials, LX 09-0 versus PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID
LX07-1
STD SKID
3.50
45.0
23.10

DOTTED
PBX9404-03
STD SKID
3.50
45.0
23.50

Fig. 17. Different materials, LX 07-1 versus PBX 9404-03.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX07-1	PBX9011-02
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	2.00	2.00
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	25.15	21.94

Fig. 18. Different materials, LX 07-1 versus PBX 9011-02.

Fig. 19. Change in drop height at pre-impact angle of 45 degrees, PBX 9011-02.

Fig. 20. Change in drop height at pre-impact angle of 45 degrees, PBX 9011-02.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BULLET WEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	LX04-1
STD SKID	STD SKID
7.10	3.50
45.0	45.0
23.91	23.56

Fig. 21. Change in drop height at pre-impact angle of 45 degrees, LX 04-1.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9011-02
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	7.10	6.88
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	21.94	21.94

Fig. 22. Change in drop height at pre-impact angle of 14 degrees, PBX 9011-02.

Fig. 23. Change in drop height at pre-impact angle of 14 degrees, PBX 9011-02.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBK9011-02	PBK9011-02
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	1.25	0.88
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	21.14	21.94

Fig. 24. Change in drop height at pre-impact angle of 14 degrees, PBX 9011-02.

Fig. 25. Change in pre-impact angle at drop height of 7.1 feet, PBX 9011-02.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9011-02
TARGET SURFACE IS	STD SKIS	STD SKIS
DROP HEIGHT IN FEET	3.50	3.50
PRE-IMPACT ANGLE IN DEGREES	45.0	14.0
BILLET WEIGHT IN POUNDS	22.20	21.76

Fig. 26. Change in pre-impact angle at drop height of 3.5 feet, PBX 9011-02.

Fig. 27. (a) Standard target surface after impact by 11-in. PBX 9404 billet from 3.5 ft at 45 deg.
(b) Abraded area of billet after above impact.

V. Behavior of 11-in. Billets Dropped Against a Smooth Steel Target

Five standard 11-in. billets of LX 04-1 and PBX 9011-02 have been dropped against a smooth steel target at preimpact angles of 14 and 45 deg. Figures 28 through 32 illustrate the smooth target performance of these billets versus that for equivalent drops of billets of the same material striking the standard abrasive target.

An interesting feature of these drops is the concave curve for friction coefficient versus time, particularly for those billets that strike the target at a preimpact angle of 45 deg. This concave shape plus low average value for friction coefficient indicates substantial melting.* Residue from the melting was clearly present on the target when it was inspected following each drop (see Fig. 38, section VI).

Assuming that concave curves for the friction coefficient are an indication of

melting, then Fig. 22, 23 and 24, for PBX 9011-02 billets impacted at 14 deg show a clear trend of increased melting with drop height. The same appears true for large 25.6-in. billets of PBX 9404-03 impacted at 45 deg (see Fig. 36, section VI). For a given billet size and preimpact angle, contact stress and sliding velocity increase with drop height, leading to a faster accumulation of sliding energy fluence. Thus, this observed trend of increased melting with increased drop height is as it should be.

Figure 33 is of interest in its comparison of the performance of an LX 04-1 billet dropped vertically to the smooth steel target from 2.5 ft and an LX 04-1 billet striking the same target from a drop height of 5.0 ft and a preimpact angle of 45 deg. Both these billets have the same preimpact normal velocity. The normal acceleration and pressure curves for the vertical drop are somewhat more symmetrical than those for the 45-deg drop; otherwise their normal motion behavior substantially is similar.

* It is probable that some contact melting occurs in nearly all SKID drops, regardless of billet size. Here, the clear indication of melting is noteworthy.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LY04-1	LY04-1
TARGET SURFACE IS	SMTH STEEL	STD SKID
DROP HEIGHT IN FEET	7.10	7.10
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET WEIGHT IN POUNDS	22.30	23.51

Fig. 28. Smooth steel surface versus standard SKID surface at 45 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX24-1	LX24-1
TARGET SURFACE IS	SMTH STEEL	STD SKID
DROP HEIGHT IN FEET	5.00	5.00
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET WEIGHT IN POUNDS	22.26	22.92

Fig. 29. Smooth steel surface versus standard SKID surface at 45 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX04-1	LX04-1
TARGET SURFACE IS	SMTH STEEL	STD SKID
DROP HEIGHT IN FEET	1.25	1.25
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	25.35	25.51

Fig. 30. Smooth steel surface versus standard SKID surface at 14 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PB9011-52	PB9011-52
TARGET SURFACE IS	SMTH STEEL	STD SKID
DROP HEIGHT IN FEET	5.00	5.00
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET HEIGHT IN POUNDS	21.52	22.20

Fig. 31. Smooth steel surface versus standard SKID surface at 45 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9011-02
TARGET SURFACE IS	SMTH STEEL	STD SKID
DROP HEIGHT IN FEET	1.25	1.25
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	21.16	21.70

Fig. 32. Smooth steel surface versus standard SKID surface at 14 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX24-1	LX24-1
TARGET SURFACE IS	SMTH STEEL	SMTH STEEL
DROP HEIGHT IN FEET	2.50	5.00
PRE-IMPACT ANGLE IN DEGREES	45	45
BILLET WEIGHT IN POUNDS	23.49	22.26

Fig. 33. Vertical drop versus 45 degree drop to smooth steel surface.

VI. Behavior of 25.6-in. Billets Dropped Against the Standard SKID Target

Nine drops were performed using 25.6-in.-diam billets of PBX 9404-03. The nominal weight of these billets was on the order of 295 lb. There were six drops at a preimpact angle of 45 deg, ranging from a low drop height of 3.9 in. to a high drop height of 22 in. Three drops were performed at a preimpact angle of 14 deg—a nonignition from a drop height of 3 in. and two ignitions, one from a drop height of 3.9 in. and one from a drop height of 6 in. The accelerometer record for the billet dropped from 6 in. was lost.

Figure 34 illustrates the change in response at a preimpact angle of 45 deg when drop height is varied. Figure 35 illustrates the change in response when preimpact angle is changed. Figures 36 and 37 illustrate the behavior of the standard 11-in. billets compared to the 25.6-in. billets. The record for the billet that ignited when dropped from 3.9 in. at a preimpact angle of 14 deg (Fig. 39) can be found following section VII in which billet ignition behavior is described.

For billets of both sizes and all initial drop conditions, the maximum normal stress occurs prior to the time of maximum normal approach. However, the relative time lag is much greater for the large billets where the time of maximum normal approach occurs close to the end of contact. The general shape of the curves that show contact stress versus time for the larger billets indicate a more "flowing" mode of behavior. This

variation in time lag behavior also is noted and discussed in Ref. 1.

Also, differences appear in the drag behavior of the two sizes of billets. First, consider those billets striking the target at a preimpact angle of 45 deg. The 25.6-in. billets dropped from heights of 7 in. and greater exhibit a friction coefficient curve that is concave and rising with time (see Fig. 36). For 25.6-in. billets dropped from heights less than 7 in. the friction coefficient curve continues to rise with time, but it is no longer clearly concave. In any event, this behavior contrasts with the more or less convex curves for friction coefficient versus time obtained for the standard 11-in. billets.

For billets striking the target at a preimpact angle of 14 deg, the shape of the curves for friction coefficient for both sizes of billet appear flat to slightly concave (see Fig. 37). The friction coefficient for the standard 11-in. billet is less than that for the 25.6-in. billet and it is more noticeably concave. As discussed in section IV, this comparison in friction coefficient versus time indicates more intense contact melting for the 11-in. billet. Both the normal contact stress and sliding velocity for the 11-in. billet are much larger than for the 25.6-in. billet; thus the more rapid accumulation of energy fluence into the smaller billet leads to increased contact melting.

Concave friction coefficient curves were observed when 11-in. billets were dropped against a smooth steel target. It

was postulated that this friction behavior indicates substantial melting of material in the billet contact region. Residue left on the abrasive target after the large billet drops, and residue left on the smooth steel target following the 11-in. billet drops is similar in appearance and texture. The top photograph of Fig. 38 exhibits the target residue following the 14-deg instrumented drop that generated the dotted line performance illustrated in Fig. 35 and 36. The very long smear track occurred because the coefficient of restitution for this billet was quite low, while its rotational inertia is quite large. After a minimal rebound, the billet continued to slide along the target. The bottom photograph illustrates the residue on the smooth steel target following the drop of a standard 11-in. billet. Here, the spot is almost circular.

It is suggested that the rising characteristic in the curves for friction coeffi-

cient versus time for the 45-deg, 25.6-in. billets is at least partly a result of the "flowing" behavior evidenced by the very late timing to maximum billet approach. Contact area is directly proportional to normal approach. For these large billets the contact area continues to increase long after the normal loading begins to decline. The new comparatively cold material coming into contact maintains a high drag on the billet, even though the material toward the center of the contact region has been softened and probably melted by the prior frictional heating.

The buildup of a wedge of wear material resulting in an eccentric location of the resultant contact force reaction also may be involved in producing high drag after the normal force reaction has declined. This mechanism is discussed in connection with the phenomenon of "super-rotation" in section VIII-C.

Fig. 34. Large billets, PBX 9404-03, drops at 45 degree pre-impact angle.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9404-03	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	1.50	0.25
PRE-IMPACT ANGLE IN DEGREES	45.0	14.0
BILLET HEIGHT IN POUNDS	295.00	295.00

Fig. 35. Large billets, PBX 9404-03, 45 degree drop versus 14 degree drop.

DISPLAY CURVES ARE.	SOLID	DOTTED
MATERIALS ARE	PBX9404-03	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	3.50	1.85
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET WEIGHT IN POUNDS	23.05	285.00

Fig. 36. Small billet versus large billet at pre-impact angle of 45 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9404-03	PBX9404-03
TARGET SURFACE IS	STD SK10	STD SK10
DROP HEIGHT IN FEET	0.88	0.25
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	23.20	296.00

Fig. 37. Small billet versus large billet at pre-impact angle of 14 degrees.

Fig. 38. (a) Target residue from the PBX 9404 drop illustrated in Figs. 35 and 36 (dotted line) against standard SKID surface.
(b) Target residue from the PBX 9011 drop illustrated in Fig. 32 (solid line) against smooth steel.

VII. Billet Ignition Behavior

Accelerometer records exist on three billets that ignited. One of these billets was a large 25.6-in. billet of PBX 9404-03 that struck the standard abrasive target at a preimpact angle of 14 deg from a drop height of 3.9 in. Its performance is

illustrated as the solid line billet of Fig. 39. The other two ignitions involved slightly nonstandard 11.8-in.-diam billets of LX 09-0 dropped in connection with an aging study. These LX 09-0 billets were all fabricated from the same lot of

molding powder. In Fig. 40 a control billet ignition is compared to an aged billet non-ignition, both billets striking the target at 14 deg from a drop height of 0.88 ft. In Fig. 41 a control billet nonignition is compared to an aged billet ignition, both billets striking the target at 45 deg from a drop height of 3.5 ft.

The aging study is subject matter for a separate report. It is pertinent here simply to note that no significant difference exists in the observed SKID test mechanical performance between the aged and control billets.

In Fig. 42 the 14-deg PBX 9404-03 large billet ignition is compared to the 14-deg LX 09-0 ignition. In Fig. 43 the 45-deg LX 09-0 ignition is compared to the 14-deg LX 09-0 ignition. It is of interest to observe that the sliding energy fluence accumulated by the time the normal pressure has risen to 95% of its peak value is about the same for all three of these instrumented billet ignitions. This observation is consistent with theories and data advanced by AWRE personnel in Refs. 4 and 5. In those papers it was suggested that if ignitions are to occur in explosive compositions that melt, it is necessary that the products of the initial reaction be confined to prevent the heat losses which would occur with gas leakage. Here it is suggested that even though these ignitions apparently were experienced well after the duration of the rise-time portion of the pressure pulse, the

important initiation events occurred during the pressure pulse risetime when the rising pressure gradient acted to contain the products of reaction. The reaction initiated in early time required additional delay time to grow into an observable ignition.

The initiating events may have been sandy grit-to-grit contacts occurring in the target surface, as suggested in the AWRE reports. This point of view is supported by Fig. 44, which is 10X photomicrograph of the standard skid surface that illustrates the random stacking of the sand grits.

Additional SKID test ignition and ignition timing data obtained prior to this series of accelerometer-instrumented drops tends to support the view that ignitions are related to the accumulation of sliding energy fluence during the period of time in which the normal contact pressure is rising. This additional information is somewhat indirect, and its data reduction process involves a level of subjective deduction that makes it subject matter for a separate report.

Billet sliding surface temperature rise based upon a simple conduction model also was calculated, as were values for energy fluence and temperature rise based upon normal billet motion as well as sliding motion. These other quantities do not appear to be related to observed billet ignition performance.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9404-03	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	0.33	0.25
PRE-IMPACT ANGLE IN DEGREES	14.0	14.0
BILLET WEIGHT IN POUNDS	292.00	296.00

Fig. 39. Fourteen degree ignition, PBX 9404-03, 25.6 inch billets.

Fig. 40. Fourteen degree ignition, LX 09-0 aging study, 11.8 inch diameter billets.

Fig. 41. Forty-five degree ignition, LX 09-0 aging study, 11.8 inch diameter billets.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX09-0 CON	PBX9404-03
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	0.08	0.33
PRE-IMPACT ANGLE IN DEGREES	14.5	14.5
BILLET WEIGHT IN POUNDS	28.22	292.00

Fig. 42. Comparison of 14 degree ignitions, 11.8 LX 09-0 versus 25.6 PBX 9404-03.

Fig. 43. Comparison of 14 degree ignition and 45 degree ignition, 11.8 LX 90-0.

Fig. 44. Ten-power photomicrograph of standard SKID test target surface.

VIII. Discussion of Special SKID Test Features

In this section, three features of the SKID test are described as they appear in the processed accelerometer records. These are an observed phenomenon named "target flexibility," which is the analytically necessary mechanical interaction between the explosive billet and its support cradle, and an observed phenomenon named "superrotation." These three features have implications that relate to the proper interpretation of the Pantex SKID test results.

A. TARGET FLEXIBILITY

During a SKID test impact, the normal approach of the billet has two components: (1) there is contact deformation in the billet, and (2) the target surface deflects. A target flexibility factor has been defined

as the ratio between the contact deformation of the billet and the total approach of the billet. For a standard 11-in. billet striking a standard target, target deflection accounts for nearly 35% of the normal approach; thus the target flexibility factor approximates a value of 0.65. For a rigid target, the flexibility factor would have a value of 1.0.

Maximum billet contact diameters were measured in previous series³ of instrumented vertical billet drops to a special smooth steel target which is assumed to be a rigid target. The experimental determination of target flexibility factor is the result of comparing the accelerometer records obtained in the present series of SKID drops to the records obtained in the prior series. So far as normal billet motion is concerned drops

to the regular SKID target stay in contact longer, have a larger magnitude approach, but generate a smaller magnitude curve for normal acceleration. Figures 45 through 47 compare drops to the regular SKID target with drops to the special vertical drop target.

In Appendix B, the appropriate data^{*} from the previous series of vertical drops are plotted and curve-fitted. Then equivalent points obtained in this series of drops to the standard skid surface are plotted against the vertical drop curve-fits. An individual target flexibility factor was calculated for each standard SKID surface drop. These were then averaged to determine the factors used in the data reduction calculation procedure leading to the results curves plotted in this report, and to the summary data tabulated in Tables C-3, C-4, C-5 and C-6. Derivations relating to the determination of contact area and target flexibility factor are described in detail in Appendix A, section 5.

For a given billet size and billet material, the magnitude of the target flexibility factor appears to be substantially unaffected by variation in preimpact normal velocity or preimpact angle. Also, variation due to billet material composition appears to be small and has been ignored. Billet size does appear to affect the magnitude of the target flexibility factor.

Targets appear to be more rigid to large billets than they do to smaller billets. A simple theory in support of this

is derived in Appendix A, section 5.

Large billets deform more than small billets; thus more of the total approach is accountable to the billet. It is assumed that target deflection is a result of the average pressure reaction rather than total force reaction, i.e., that the target surface acts like a set of "bed springs" and responds to local loading. Since pressure is not strongly affected by billet size, to a first approximation the target deflection component of the billet approach will not increase with billet size. The data from the accelerometer records for the 25.6-in.-diam billets of PBX 9404-03 appear to be in support of this point of view.

B. EFFECT OF PANTEX CRADLE

The range of possible mechanical dynamic effects of the Pantex cradle support on the SKID billet contact reactions has been analyzed in detail in Appendix A, section 8. It can be concluded that while the exact effect is uncertain, it must be quite small in numerical magnitude.

Figures 48 through 51 illustrate the result of three limit cradle assumptions for a standard 11-in. billet striking the target at 14 and 45 deg. The curves plotted for the solid line billet conform to the assumption generally made for the results discussed in this report. The solid line billet assumes that the cradle is in the system and couples to the billet in the horizontal direction along a line of action located at the bottom of the cradle. Numerical calculations indicate that this is a maximum cradle effect position. The dotted line billet in Figs. 49 and 51 is the same as the solid line billet except that it

^{*}Maximum billet approach, and the RMS value for normal force reaction were used to determine the target flexibility factor. Both these quantities are obtained directly from the accelerometer records.

is assumed that no cradle is present. The dotted line billet of Figs. 48 and 50 again is the same as the solid line billet except that the cradle is assumed to act at a minimum effect position, analytically determined pursuant to Eq. (33) of Appendix A, section 8.

Figures 48 through 51 all assume the standard billet with a weight of ~23 lb supported by a cradle weighing 6 lb. The large 25.6-in. billets of PBX 9404-03 weighing ~295 lb were supported in a cradle weighing 31 lb. The calculated effect of the cradle on the performance of these large billets is relatively less than that indicated for the standard billet system.

C. SUPERROTATION

At a preimpact angle of 45 deg, many (but not all) billets exhibit the phenomenon of superrotation. Superrotation refers to those instances where the nominal sliding velocity of the contact surface at the end of contact is negative. While it is reasonable to postulate several potential sources for superrotation, current information is insufficient for it to be attributed to any definite single cause or combination of causes. Potential sources of superrotation are listed below:

1. Contact Force Eccentricity

Eccentricity in the contact force reaction is one factor that would cause some level of superrotation. Such an eccentricity could be caused by a buildup of a wedge of wear products as the billet slides along. The calculated effect of contact force eccentricity is illustrated in Figs. 52 and 53. The curves plotted

for the solid line billet conform to the assumption generally made for the results discussed in this report, i.e., that contact force eccentricity is zero. The dotted line billet is the same as the solid line billet except that a large contact force eccentricity is present; the force reaction has been offset from the center of the contact spot by a distance equal to 80% of the contact radius. Note that even this very large value for force offset does not account for the observed magnitude of superrotation.

The calculated effect of assuming a nonzero value for normal force eccentricity is to reduce the drag stress, reduce the coefficient of friction, reduce the fall-off of billet tangential velocity, and reduce the magnitude of calculated superrotation. The accelerometer input curves and the normal pressure and normal billet approach are not affected. Calculated sliding energy fluence is reduced because the calculated drag stress is reduced more than the fall-off in billet sliding velocity.

However, when the same contact force eccentricity assumption is made for all billets, the calculated results for all billets are influenced in the same sense and the comparative billet performance is not changed in any significant way.

2. Tangential Target Motion

A recent standard billet drop of PBX 9011-02 was instrumented with an accelerometer oriented in the tangential direction, located on the abrasive steel target. Another tangential accelerometer was located on the concrete pad. The steel target was bonded to the concrete pad by a sand-loaded, somewhat flexible epoxy

DISPLAY CURVES ARE
 MATERIALS ARE: PBX9404-03
 TARGET SURFACE IS: STD SKID
 DROP HEIGHT IN FEET: 3.50
 PRE-IMPACT ANGLE IN DEGREES: 45.0
 BILLET WEIGHT IN POUNDS: 23.05

SOLID
 PBX9404-03
 STD SKID
 3.50
 45.0
 23.05

DOTTED
 PBX9404-03
 VERT DROP
 2.00
 90.0
 23.18

Fig. 45. Effect of target flexibility for PBX 9404-03.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET HEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	LX04-1
STD SKID	VERT DROP
3.50	2.00
45.0	90.0
25.56	22.94

Fig. 46. Effect of target flexibility for LX 04-1.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	PBX9011-02	PBX9011-02
TARGET SURFACE IS	STD SKID	VERT DROP
DROP HEIGHT IN FEET	3.50	2.00
PRE-IMPACT ANGLE IN DEGREES	45.0	90.0
BILLET WEIGHT IN POUNDS	22.20	22.51

Fig. 47. Effect of target flexibility for PBX 9011-02.

Fig. 48. Cradle in system at 45 degrees, maximum effect versus minimum effect.

Fig. 49. Maximum cradle effect versus no cradle in system at 45 degrees.

DISPLAY CURVES ARE
MATERIALS ARE
TARGET SURFACE IS
DROP HEIGHT IN FEET
PRE-IMPACT ANGLE IN DEGREES
BILLET WEIGHT IN POUNDS

SOLID LX94-1
STD SK10
DOTTED LX94-1
STD SK10
1.25
14.0
23.51

Fig. 50. Cradle in system at 14 degrees, maximum effect versus minimum effect.

DISPLAY CURVES ARE
 MATERIALS ARE
 TARGET SURFACE IS
 DROP HEIGHT IN FEET
 PRE-IMPACT ANGLE IN DEGREES
 BILLET WEIGHT IN POUNDS

SOLID	DOTTED
LX04-1	LX04-1
STD SKID	STD SKID
1.25	1.25
14.0	14.0
23.51	23.51

Fig. 51. Maximum cradle effect versus no cradle in system at 14 degrees.

DISPLAY CURVES ARE	SOLID	DOTTED
MATERIALS ARE	LX34-1	LX34-1
TARGET SURFACE IS	STD SKID	STD SKID
DROP HEIGHT IN FEET	5.00	5.00
PRE-IMPACT ANGLE IN DEGREES	45.0	45.0
BILLET HEIGHT IN POUNDS	22.92	22.92

Fig. 52. Effect of large contact force eccentricity at 45 degrees.

Fig. 53. Effect of large contact force eccentricity at 14 degrees.

adhesive with the trade name Permagil. As luck would have it, superrotation was not present in this particular billet drop. However, the accelerometer mounted on the steel target did exhibit a ringing frequency with a total period of the same approximate duration as the time for billet contact.

The process by which the steel target is bonded to the concrete pad has not been subject to explicit controls. Thus, tangential target motion may be a significant source of superrotation and consequent scatter in the SKID test results reported to date. Further investigation of this problem using tangentially mounted accelerometers is planned.

3. Normal Contact Deformation

Since the calculation for superrotation assumes nominal billet geometry, the contact deformation can result in a small magnitude of superrotation, equivalent to approximately 2% of theoretical pure rolling rotation velocity.

4. Cradle Offset

The cradle reaction can have a small effect on superrotation (compare Figs. 48 and 49 and Figs. 50 and 51). Section VIII-B contains a more detailed discussion of the possible effects of the cradle.

5. A Combination of the Prior Listed Sources

Contact force eccentricity caused by wear products, tangential target motion,

normal contact deformation of the billet and cradle offset may act simultaneously. Also, other sources for superrotation may appear as additional instrumented SKID data accumulates; probably this list is not complete.

Great care was taken in the filtering and calibration of the accelerometer records. Also, the final billet rotation was calculated from Fastax camera records obtained on each drop. Figures A-2 and A-3 in Appendix A, section 9 plot the final rotation velocities for all 45-deg drops in this test series, as calculated from the accelerometer records and as calculated from the Fastax camera records.

The agreement between the accelerometer results and the Fastax camera results is fair. Final rotation velocities determined from the Fastax records tend to be somewhat less than those determined from the accelerometer records, although a significant magnitude of superrotation remains. This result is to be expected since the cradle and cradle support cables are observed to interfere with the billet during rebound. Friction from such interferences would tend to reduce the observed magnitudes for final rotation velocities from the Fastax records.

All results included in this report assume that the accelerometer records are correct.

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Appendix A

Derivations to Reduce Accelerometer Data

CONTENTS

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A-1. SUMMARY OF ANALYSES

The primary derivations are presented in the next following five sections. The equations of motion are derived generally in section 2. The billet is considered to be a single rigid hemisphere with mass properties located at its nominal center of gravity. The cradle is assumed to push against the billet only in the horizontal direction. Accelerometer records are related to billet mass center accelerations in section 3, and the coefficient of friction is defined. Billet mass center accelerations are integrated and are combined to calculate all velocities and displacements of interest. This is described in section 4. The problem of estimating contact area and compensating for observed target "flexibility" is analyzed in section 5. Procedures for the calculation of contact energy fluence and temperature rise are discussed in section 6.

In addition to the above, the SKID drops are characterized by certain defined mechanical motion parameters and apparent material properties. These are described in section 7.

Questions arise concerning the extent to which the cradle reaction can affect the motion of the billet. Calculations have been performed based upon the derivations described in section 8. These calculations show that the effect of the cradle upon the motion of the billet can be no more than second order. This is so regardless of where the cradle is assumed to act in relation to the mass center of billet, or whether or not the cradle is included as part of the system.

Finally, there is an apparent phenomena of superrotation^{*} present for billets dropped against the SKID target at a preimpact angle of 45 deg. Superrotation is discussed in section 9. Tangential target motion is suggested to be an important mechanism accounting for the observed level of superrotation. Wear-induced eccentricity in the contact force reaction also may be involved.

A-2. EQUATIONS OF MOTION

It is assumed that the cradle is supported on a frictionless pivot constrained to translate in a vertical slide. Thus the cradle force reaction always will act in the horizontal direction. Figure A-1 illustrates the system. Four motion equations are of interest.[†]

^{*}When the initial tangential translation velocity of the billet is fully converted into pure rolling, the resulting angular velocity is less than that observed experimentally. The difference is termed superrotation.

[†]In Eqs. (1) and (2), the acceleration of gravity g is not maintained at a constant value. Rather, it is allowed to vary from a value of zero at the beginning of contact to its full theoretical value at the time of maximum billet approach, and then to decline to a value of zero at the conclusion of contact. This procedure avoids the calculation of an erroneous contact normal force reaction at the beginning and end of contact. This in turn compensates a billet model deficiency that would otherwise result in an erroneous calculation for friction factor for large billets striking the target at very low values of normal preimpact velocity.

The cradle horizontal motion is governed by

$$-C = m\ddot{Z} \sin \gamma + m\ddot{X} \cos \gamma + m\epsilon\ddot{\alpha}. \quad (4)$$

Solving Eq. (4) for C and then back-substituting into Eqs. (1), (2) and (3) results in a set of three real symmetric equations for the billet C.G. acceleration.

$$\begin{aligned} a_{11}\ddot{Z} + a_{12}\ddot{X} + a_{13}\ddot{\alpha} &= N - Mg \cos \gamma \\ a_{12}\ddot{Z} + a_{22}\ddot{X} + a_{23}\ddot{\alpha} &= -T + Mg \sin \gamma \\ a_{13}\ddot{Z} + a_{23}\ddot{X} + a_{33}\ddot{\alpha} &= N[(R - a) s + \epsilon] + T[R - (R - a) c] \end{aligned}$$

$$\begin{aligned} a_{11} &= M + ms^2 & a_{12} &= msc \\ a_{22} &= M + mc^2 & a_{13} &= mes \\ a_{33} &= I + me^2 & a_{23} &= mec \\ s &= \sin \gamma & c &= \cos \gamma. \end{aligned} \quad (5)$$

In the Pantex and AWRE^{*} test setups,² the target angle γ is zero. For this case, Eqs. (5) are simplified and may be inverted to yield

$$\begin{aligned} \ddot{Z} + g &= (1/M)N \\ \ddot{X} &= -\left[\frac{me\epsilon}{(I + me^2)M + Im}\right]N - \left[\frac{I + me^2 + mea}{(I + me^2)M + Im}\right]T \\ \ddot{\alpha} &= \left[\frac{(M + m)\epsilon}{(I + me^2)M + Im}\right]N + \left[\frac{(M + m)a + me}{(I + me^2)M + Im}\right]T. \end{aligned} \quad (6)$$

In the LASL test setup,² the cradle mass m is zero and the target tilt angle γ is 45 deg, i.e., $s = c = 1/\sqrt{2}$.

$$\begin{aligned} \ddot{Z} + g/\sqrt{2} &= \left(\frac{1}{M}\right)N \\ \ddot{X} - g/\sqrt{2} &= \left(-\frac{1}{M}\right)T \\ [I + me^2]\ddot{\alpha} &= [(R - a)/\sqrt{2} + \epsilon]N + [R - (R - a)/\sqrt{2}]T. \end{aligned} \quad (7)$$

^{*}In the AWRE test setup, cradle mass m is zero, also.

A-3. ACCELEROMETER DATA RELATED TO BILLET C. G. ACCELERATIONS AND CONTACT FRICTION

In terms of billet translations at the center of rotation, the billet C. G. translations are

$$\begin{aligned}\ddot{Z} &= \ddot{v} \cos \gamma + \ddot{h} \sin \gamma - (R - a) \ddot{\alpha} \sin \gamma \\ \ddot{X} &= -\ddot{v} \sin \gamma + \ddot{h} \cos \gamma - (R - a) \ddot{\alpha} \cos \gamma.\end{aligned}\tag{8}$$

In terms of the accelerometer readings, the center of rotation accelerations are:

$$\begin{aligned}\ddot{v} &= \frac{A_1 + A_2}{2} = A_N \\ \ddot{h} &= A_3 = A_T \\ \ddot{\alpha} &= \left(\frac{A_1 - A_2}{2} \right) \frac{2}{b} = \frac{2}{b} A_R.\end{aligned}\tag{9}$$

Combining (8) and (9) yields billet C. G. accelerations:

$$\begin{aligned}\ddot{Z} &= A_N \cos \gamma + A_T \sin \gamma - \frac{2}{b} A_R (R - a) \sin \gamma \\ \ddot{X} &= -A_N \sin \gamma + A_T \cos \gamma - \frac{2}{b} A_R (R - a) \cos \gamma \\ \ddot{\alpha} &= \frac{2}{b} A_R.\end{aligned}\tag{10}$$

The SKID billet data reported here were obtained at Pantex, where the target angle γ is zero. For this case, Eqs. (10) reduce to

$$\begin{aligned}\ddot{Z} &= A_N = \frac{A_1 + A_2}{2} \\ \ddot{X} &= A_T - \frac{2}{b} A_R (R - a) \\ \ddot{\alpha} &= \frac{2}{b} A_R = \frac{A_1 - A_2}{2} \left(\frac{2}{b} \right).\end{aligned}\tag{11}$$

Only the vertical accelerometers, A_1 and A_2 , were present; the horizontal accelerometer, $A_T = A_3$, was not installed. Thus the first and third of Eqs. (11) can be used to calculate normal and rotational billet motion, while tangential motion must be otherwise estimated.

However, the normal and tangential contact force reactions can be estimated after inverting Eqs. (6). Performing this operation yields the following:

$$N = M (A_N + g)$$

$$T = \left[\frac{(I + me^2)M + Im}{(M + m)a + me} \right] \frac{2}{b} A_R - \left[\frac{(M + m)\epsilon}{(M + m)a + me} \right] N. \quad (12)$$

To calculate T, it is necessary to assume values for the normal contact force eccentricity, ϵ , and the offset of the cradle reaction, e . Then the tangential billet motion can be calculated from Eqs. (6), using values for N and T from Eqs. (12). From Eqs. (6), the horizontal billet C.G. motion is governed by

$$\ddot{X} = - \left[\frac{Me\epsilon}{(I + me^2)M + Im} \right] N - \left[\frac{I + me^2 + mea}{(I + me^2)M + Im} \right] T. \quad (13)$$

In the process represented by Eqs. (11), (12) and (13), the assumption of numerical values for ϵ and e takes the place of the missing horizontal accelerometer data. (See sections A-8 and A-9 for more extended consideration of the influence of assumptions concerning ϵ and e .)

Friction coefficient is defined as the ratio between drag force T and normal force N. From Eqs. (12), this is

$$\begin{aligned} \mu &= T/N \\ &= - \left[\frac{(M + m)\epsilon}{(M + m)a + me} \right] + 2 \left[\frac{\left(\frac{M + m}{M} \right) I + me^2}{(M + m)ab + meb} \right] \left(\frac{A_R}{A_N + g} \right). \end{aligned} \quad (14)$$

It is to be noted that when $A_N \gg g$ and when $\epsilon \rightarrow 0$, the friction coefficient varies directly with the ratio of the input accelerations, as plotted in the graphical results included in the main part of this report (Figs. 4-53).

A-4. INTEGRATION FOR BILLET MOTION AND CONTACT SLIDING VELOCITY

The three arrays of billet C.G. acceleration are numerically integrated for velocity and displacement. The absolute initial velocity of the billet is determined by the drop height:

$$V_0 = \sqrt{2gH}. \quad (15)$$

The initial values for normal and tangential velocity are related to V_0 and the preimpact angle ϕ (see Fig. A-1). The initial rotation velocity is zero. The initial value for

all displacements is zero. The initial values for billet motion are:

$$\dot{Z}(0) = -V_0 \sin \phi$$

$$\dot{X}(0) = V_0 \cos \phi$$

$$\dot{\alpha}(0) = 0$$

$$Z(0) = 0$$

$$X(0) = 0$$

$$\alpha(0) = 0.$$

(16)

The billet mass center motions then become:

$$\dot{Z} = -V_0 \sin \phi + \int_0^t \ddot{Z}(\beta) d\beta$$

$$Z = -V_0 t \sin \phi + \int_0^t d\tau \int_0^\tau \ddot{Z}(\beta) d\beta$$

$$\dot{X} = V_0 \cos \phi + \int_0^t \ddot{X}(\beta) d\beta$$

$$X = V_0 t \cos \phi + \int_0^t d\tau \int_0^\tau \ddot{X}(\beta) d\beta$$

$$\dot{\alpha} = \int_0^t \ddot{\alpha}(\beta) d\beta$$

$$\alpha = \int_0^t d\tau \int_0^\tau \ddot{\alpha}(\beta) d\beta.$$

(17)

Also, the relative sliding motion between the contact surface and the target is of interest. This is calculated by subtracting the tangential surface velocity associated with billet rotation from the forward tangential motion of the billet C. G.; thus,

$$\dot{X}_s = \dot{X} - [R - (R - a) \cos \gamma] \dot{\alpha}$$

$$X_s = X - [R - (R - a) \cos \gamma] \alpha$$

(18)

For the Pantex test setup, $\gamma = 0$ and Eqs. (18) reduce to:

$$\begin{aligned}\dot{X}_S &= \dot{X} - a\dot{\alpha} \\ X_S &= X - a\alpha\end{aligned}\tag{19}$$

A-5. ESTIMATING CONTACT AREA, A FUNCTION OF BILLET NORMAL DISPLACEMENT AND TARGET FLEXIBILITY

So far, equations have been developed to calculate contact force reactions versus time and all pertinent billet motions versus time. Contact stresses must be estimated to calculate energy generation and temperature rise. To estimate contact stress, it is assumed that contact area is proportional to the normal contact displacement, i.e., the billet approach and the diameter of the billet:

$$\begin{aligned}\pi d^2/4 &= \eta K_3 Z D \\ d &= \text{diameter of contact circle,} \\ \eta &= \text{the target flexibility factor,} \\ K_3 &= \text{the area approach factor.}\end{aligned}\tag{20}$$

A simple linear definition for target flexibility factor is based on the assumption that target surface displacement is proportional to billet compression. Then,

$$\eta = Z_B/Z$$

where

$$\begin{aligned}Z &= Z_B + Z_T = \text{billet approach,} \\ Z_B &= \text{billet material displacement,} \\ Z_T &= \text{target surface displacement.}\end{aligned}\tag{21}$$

Two experimental series of billet drops were performed. In the first series, SKID billets were dropped on a smooth rigid target surface; maximum contact circle diameter was measured permitting a direct calculation of the quantity ηK_3 , using Eq. (20). In the second series the billets were dropped on the regular sandy SKID test target surface; maximum contact circle diameter was not measured.

For a given preimpact normal velocity, when the measured contact diameter of the first series was assumed to prevail for the second series, the values of ηK_3 calculated for the second series were significantly less than those of the first series. This result indicates that the regular target surface* is more flexible than the smooth target surface used to measure the size of the contact spot.

In an earlier study,³ a generalized "Meyer" model of the SKID billet was analyzed. In that report, it was indicated that contact area is related to the magnitude of the normal contact reaction,

$$\frac{\pi d^2}{4} = \pi K_2^2 N^{2p} D^{2(1-2p)},$$

where

K_2 = a billet material constant,

p = a billet material constant. (22)

When Eqs. (20) and (22) are equated and the result is ratioed assuming two different target surfaces, a relationship can be derived that can be used to estimate the target flexibility factor, η ;

$$\eta_1 K_3 Z_1 D = \pi K_2^2 N_1^{2p} D^{2(1-2p)},$$

$$\eta_2 K_3 Z_2 D = \pi K_2^2 N_2^{2p} D^{2(1-2p)}.$$

Thus,

$$\eta_1/\eta_2 = (Z_2/Z_1)(N_1/N_2)^{2p}. \quad (23)$$

Values for billet approach Z and normal force reaction N are both ascertained from the accelerometer records. The material constant p is bounded between a value of $1/2$ for "perfectly plastic" material behavior and a value of $1/3$ for linear elastic material behavior.[†] Assuming that the smooth surface is nearly rigid, its value of $\eta \rightarrow 1$ and then the flexibility factor for the rough SKID target surface becomes:

$$\eta_{\text{rough}} = \frac{Z_{\text{smooth}}}{Z_{\text{rough}}} \left(\frac{N_{\text{rough}}}{N_{\text{smooth}}} \right)^{2p}$$

$$1/3 \leq p \leq 1/2 \quad (24)$$

*The regular SKID target is a 1/4-in. steel plate bonded to a 6-in.-deep concrete pad with an epoxied sandy surface layer of about 1/16-in. thickness. The smooth target is a 1-in. steel plate bonded to a 6-in.-deep concrete pad.

†Experimental results indicate that the material behavior is neither elastic nor plastic; it is "in between."

In making use of Eq. (24), the "smooth" and "rough" surface values are the maximum values for approach Z and the rms values for the normal force N, as measured in the two series of tests. The comparison is between the responses of billets of the same size and material striking the target at the same preimpact normal velocity. In reducing the experimental test data, an intermediate value for p was chosen (i.e., $p = 5/12$).

Billets of different size were included in both the smooth target surface test series and the rough, flexible SKID target test series. It was discovered that values of η estimated from Eq. (24) varied with the billet diameter, but remained constant with preimpact normal velocity. Scaling rules relating billet size and deformation were developed in the earlier "Meyer" model study.³ One of these indicates that billet normal approach Z_B should vary directly with billet diameter D. When this scaling rule is combined with the notion that target surface displacement Z_T is a function only of preimpact normal velocity, the observed experimental variation of η with billet size D can be estimated. Equations (21) are restated to yield target surface displacement:

$$Z_T = Z_B(D) \left[\frac{1 - \eta(D)}{\eta(D)} \right]. \quad (25)$$

Billet displacements for any sized billet can be estimated from those observed for 11-in.-diam billets:

$$Z_B(D) = \frac{D}{11} Z_B(11). \quad (26)$$

Equations (25) and (26) can be combined to yield an expression for $\eta(D)$ in terms of $\eta(11)$ and billet diameter D. Since Z_T is assumed not to vary with billet size, Eq. (25) yields

$$Z_B(11) \left[\frac{1 - \eta(11)}{\eta(11)} \right] = Z_B(D) \left[\frac{1 - \eta(D)}{\eta(D)} \right].$$

Further combination with Eq. (26) yields the desired result:

$$\left[\frac{\eta(D)}{1 - \eta(D)} \right] = \frac{D}{11} \left[\frac{\eta(11)}{1 - \eta(11)} \right]. \quad (27)$$

The smooth surface and rough SKID surface billet data leading to numerical definitions for K_3 and $\eta(D)$ are described in detail in Appendix B. The curve fits presented there show that all 11-in. and 25.6-in. billet data can be described fairly well using just two numbers:

$$K_3 = 1.953,$$

$$\eta(11) = 0.652 \rightarrow \eta(25.6) = 0.814.$$

The smooth surface vertical drop data for 6-in. billets appears consistent with a slightly lower value of K_3 , i.e., $K_3 \approx 1.7$. The 6-in. billet target flexibilities,* calculated from Eq. (25), are of the same order of magnitude as those calculated for 11-in. billets. According to Eq. (27), target flexibilities for 6-in. billets should be lower than those calculated for 11-in. billets. The "too low" value for K_3 and the "too high" value for target flexibility may indicate that the "rigid" smooth target is not as "rigid" for 6-in. billets as it is for the larger billets.

A-6. ESTIMATION OF CONTACT PRESSURE, ENERGY FLUENCE, AND TEMPERATURE RISE

Average normal and drag contact stresses are defined by dividing the normal and tangential forces calculated from Eq. (12) by the contact area from Eq. (20):

$$\begin{aligned}\sigma_N &= N/\eta K_3 ZD \\ \sigma_T &= T/\eta K_3 ZD.\end{aligned}\tag{28}$$

The energy generation rates can be defined. These are normal stress multiplied by the normal velocity of approach, and the drag stress multiplied by the tangential sliding velocity calculated from Eqs. (18) or (19):

$$\begin{aligned}\dot{H}_N &= \sigma_N \dot{Z} \\ \dot{H}_T &= \sigma_T \dot{X}_s.\end{aligned}\tag{29}$$

The experimental "record" is complete with the calculation of average contact stress versus time from Eqs. (28) and average energy generation versus time from Eqs. (29). These quantities are the processed result of the accelerometer readings and associated measurements of maximum contact diameter.

A principle objective of this study is to relate the accelerometer records to the observed ignition performance of SKID test billets. To this end, two additional numerical operations were performed: (1) The energy generation rates of Eqs. (29) were integrated with time to calculate values of "energy fluence," and (2) these same energy generation rates were applied to a simple thermal conduction model to calculate surface temperature rise versus time.

"Energy fluence" is defined as the time integration of energy generation, i.e., the integrated flow of generated energy through the center of the contact area considered

* 6-in. billets were dropped vertically upon the standard SKID target to generate data to calculate target flexibility from Eq. (25).

as a control surface. There is a normal fluence, E_N , related to the normal motion of the billet and a sliding fluence, E_T , related to the tangential sliding motion of the billet:

$$E_N = \int_0^t \sigma_N(\beta) \dot{Z}(\beta) d\beta,$$

$$E_T = \int_0^t \sigma_T(\beta) \dot{X}_S(\beta) d\beta. \quad (30)$$

In relating the SKID test ignition performance of different sized billets of PBX 9404-03 and LX 04-1, the sliding fluence E_T from Eqs. (30) and normal pressure σ_N from Eqs. (28) appear to have value as joint criteria for data correlation. This is discussed more fully in section VII of this report.*

Calculated values for temperature rise based on the simple thermal conduction model do not appear to be good basis for data correlation. Similarly, the normal energy fluence E_N does not appear to relate well to the observed data.

A-7. ESTIMATION OF SUMMARY MECHANICAL PARAMETERS

Certain summary normal motion mechanical parameters are calculated pursuant to the "Meyer" model analyses and procedures described in the associated report^{3,6,7} that are concerned with vertical billet drops to a smooth rigid target surface. These are:

- The elastic parameter $E/1 - \nu^2$, based upon maximum billet approach Z_m and the maximum normal force reaction N , measured prior to the time for maximum approach.
- The rms normal flow pressure σ_{rms} , evaluated to the time of maximum approach.
- The impact number $I = V_0 \tau \sin \phi / Z_m$.
- The strain ϵ , strain rate $\dot{\epsilon}$, and strain intensity $\epsilon \dot{\epsilon}$, as defined in Ref. 3.
- The relative time delay RTD, as defined in Ref. 3.
- The coefficient of restitution, CRES.

In addition, an rms coefficient of friction is calculated, based upon ratioing the rms values for normal pressure reaction and drag pressure reaction to the time of maximum approach.

*It appears that the sliding energy fluence accumulated during the initial portion of the contact period while the normal pressure is increasing with time roughly correlates to the observed ignitions of different sized billets and billets of the same size dropped at different preimpact angles.

A-8. EFFECT OF THE PANTEX CRADLE UPON BILLET MOTION

The Pantex cradle is assumed to interact with the billet along a horizontal line of action.* Two principal questions arise:

- (1) Does the cradle affect the billet at all, or will it fall away after the initial contact between the billet and target?
- (2) If the cradle is part of the system, where is its line of action located with respect to the billet mass center?

The answer to the first question is based upon a small deflection interference calculation in which the cradle is assumed to maintain its initial motion, which is then compared to the integrated accelerometer motion of the billet. The horizontal motion of the billet surface at the assumed position of cradle contact is subtracted from the equivalent motion of a cradle that continues to move at initial velocity.

If the differential motion is positive there is no contact, and vice versa. The equation expressing this difference is:

$$A = [t \dot{X}(0) - X(t) - e \alpha(t)] - \left[1 - \frac{a}{R} - \frac{e}{R}\right] [t \dot{Z}(0) - Z(t)] \quad (31)$$

If $A > 0$, the cradle is in contact.

The first term on the right expresses the nominal interference in forward horizontal motion between cradle and billet. The second term on the right expresses the tendency of the cradle to fall away from the billet due to differential vertical motion.

The value A has been calculated for each SKID drop. Depending upon initial conditions and assumed cradle line of action, the value A tends to be very slightly negative or positive. Consequently, whether or not the cradle is in the system is uncertain, and question (2) becomes pertinent.

The equation for the contact drag reaction, Eq. (12) of section A-3, is differentiated with respect to cradle position e . Equating the differentiated expression to zero results in an equation that will calculate a minimum effective position.

$$\frac{1}{A_R} \frac{\partial T}{\partial e} = Mm^2e + 2Mm(M+m)ae - I(m^2 + mM) + m(M+m)e \frac{N}{A_R}. \quad (32)$$

Setting the right-hand side to zero leads to

$$e^2 + 2\left(\frac{M+m}{m}\right)ae - \frac{I}{M}\left(\frac{M+m}{m}\right) + \frac{I}{M}\left(\frac{M+m}{m}\right)e \frac{N}{A_R} = 0. \quad (33)$$

*The 11-in.-diam standard SKID billet weighs 23 pounds; its cradle weighs 6 pounds.

Numerically, the term involving the normal force offset ϵ is insignificant, and a drag reaction minimizing the value for e can be found that is geometrically possible.

Further, simple trial and error indicated that assuming a cradle line of action along the nominal bottom edge of the cradle resulted in a value for e that maximized the drag reactions.

For each skid drop, three sets of calculations were performed,* assuming (1) a maximum drag value for e , (2) a minimum drag value for e , and (3) that there is no cradle at all acting in the dynamic system. Figures 48 through 51 are typical of the comparative results. It can be concluded that assumptions regarding the action of the cradle can have no more than a second-order effect on the calculated motion of the billet. Although the precise dynamic effect of the cradle is uncertain, this effect is certain to be insignificant so far as billet motion and contact region energy calculations are concerned.

A-9. NORMAL FORCE CONTACT ECCENTRICITY AND "SUPERROTATION"

All drops to the regular SKID test surface at a preimpact angle of 45 deg have a curve of contact sliding velocity versus time that goes negative toward the end of contact.[†] (For example, see Figs. 52 and 53.) This means that the final billet rotation velocity in relation to its calculated tangential velocity exceeds a theoretical status of "pure rolling."

The equation to follow was derived to estimate a value for final billet rotation velocity. It assumes an instantaneous contact impulse, an effective value for friction coefficient, and a condition of pure rolling at the conclusion of contact.

$$\dot{\theta}_F = \left[\frac{(M + m)a^2}{I / \left(1 + \frac{\epsilon}{a\mu}\right) + (M + m)a^2 + mae} \right] \left(\frac{\sqrt{2gH}}{a} \right) \cos \phi \quad (34)$$

This equation is plotted in Figs. A-2 and A-3, and compared to the experimentally observed values for final rotation velocity. The experimental points plotted on Fig. A-2 directly were integrated from the accelerometer records, while the experimental points plotted on Fig. A-3 are obtained by differentiating the Fastax camera records. The plotted curves cover the reasonable range of possible assumptions regarding action or nonaction of the cradle and magnitude of normal force eccentricity.

*These three cases were calculated for several assumed values of normal force offset, ϵ .

[†]In spite of this, the experimental drag reaction remains unidirectional.

Fig. A-2. Final rotation velocity vs drop height; data from accelerometer records.

Fig. A-3. Final rotation velocity vs drop height; data from Fastax film.

Appendix B

Data Fits for Contact Area and Target Flexibility

CONTENTS

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B-1. SUMMARY

As discussed in detail elsewhere,* the total approach of a SKID test billet consists of two portions: (1) the actual contact deformation of the billet, and (2) deflection of the target surface. It is necessary to separate these components to estimate the contact area. The data used to effect this separation are described here. All data and data fits are variables plotted versus normal preimpact velocity.

Three different target surfaces were used. Maximum contact area was measured in a series of vertical drops³ to a smooth, comparatively rigid steel target surface. Data fits from these data are presented in section B-2. SKID drops were made against the standard SKID target, which proved to be flexible. The data used to estimate the flexibility of the standard target in relation to the vertical drop target are illustrated in section B-3. Also, a special smooth steel target was prepared to measure the change in surface friction compared to the standard target. Data illustrating the flexibility of this special target is included in section B-4.

B-2. RIGID, SMOOTH SURFACE DATA FITS

Figures B-1 through B-7 are a series of four curves each illustrating the data fits for:

1. 25.6-in. billets of PBX 9404-03,
2. 11.0-in. billets of PBX 9404-03,
3. 6.0-in. billets of PBX 9404-03,
4. 11.0-in. billets of LX 04-01,
5. 6.0-in. billets of LX 04-01,
6. 11.0-in. billets of PBX 9011-02, and
7. 11.0-in. billets of assorted materials, including PBX 9011-02 and LX 04-1.

The four curves of each series are data plots versus normal preimpact velocity for:

1. RMS normal force reaction to maximum approach,
2. maximum approach,
3. maximum contact diameter, and
4. area approach constant, K_3 (XK3).

In these curves the plotted line is the fit, while the plotted points are direct experimental data, i.e., the measured contact diameters and the results of analyzing the accelerometer records. The data plotted in these curves are tabulated in Table C-7 of Appendix C. The plotted fit for maximum approach is calculated from the plotted direct data fits for maximum contact diameter and area-approach constant, using Eq. (20), section A-5. For all these drops the target is assumed to be inflexible, i.e., $\eta = 1.0$.

*Section VIII-A, p. and section A-5, p. 74.

Fig. B1. Vertical drop target — PBX 9404-03.

Fig. B2. Vertical drop target—PBX 9404-03.

Fig. B3. Vertical drop target—PBX 9404-03.

Fig. B4. Vertical drop target—LX 04-1.

Fig. B5. Vertical drop target—LX 04-1.

Fig. B6. Vertical drop target—PBX 9011-02.

Fig. B7. Vertical drop target—LX 04-1, PBX 9011-02, LX 09-0, LX 07-1, RX 04-DJ, and RX 04-DS.

The following general results are pointed out: The same set of curve fits applies to LX 04-1 and PBX 9011-02. So far as summary mechanical properties are concerned, no significant difference is observed between these two materials. Furthermore, all materials tested other than PBX 9404-03 and LX 10-0 appear to be represented fairly well by the fits for LX 04-1 and PBX 9011-02. All these materials are illustrated as a group in Fig. B-7. The LX 10-0 data appear to be more like PBX 9404-03. The same average value for area approach constant, $K_3 = 1.953$, is used for both 11-in.-diam and 25.6-in.-diam billets for all materials. This value represents a numerical average of all drops with a preimpact velocity in excess of 100 in./sec. The area-approach constant for the 6-in. billets was significantly less than 1.953 (see Figs. B-3 and B-5).*

B-3. STANDARD SKID SURFACE DATA FITS

Figures B-8 through B-12 are a series of four curves each that illustrate target flexibility data for:

1. 25.6-in. billets of PBX 9404-03,
2. 11.0-in. billets of PBX 9404-03,
3. 11.0-in. billets of LX 04-1,
4. 6.0-in. billets of LX 04-1, and
5. 11.0-in. billets of PBX 9011-02.

The four curves of each series are data plots versus normal preimpact velocity for:

1. RMS normal force reaction to maximum normal approach,
2. maximum normal approach,
3. target flexibility factor, η , and
4. estimated contact diameter.

In these curves the plotted lines are the "rigid" vertical drop data fit just described in section B-2, while the plotted points result from the analysis of the accelerometer records. The plotted points include data from vertical drops to the skid target as well as skid drops at preimpact angles of 14 and 45 deg. Each individual value for η was calculated from the RMS normal force reaction and the maximum normal approach pursuant to Eq. (24) of section A-5. Data plotted on Figs. B-9, B-10, and B-12 were combined[†] to estimate an average value for target flexibility at $\eta(11) = \eta = 0.652$.

If one were so inclined, one could distinguish somewhat different values of η for PBX 9404-03, LX 04-1, and PBX 9011-02. However, this was not done here since the total number of drops for any given material is not large and the differences between materials, if real, are not large.

* See Appendix A-5, p. 74, for a possible explanation of this nonuniform behavior.

† Only data points with preimpact normal velocities in excess of 60 ips were included in the average.

Fig. B8. Standard SKID target — PBX9404-03.

Fig. B9. Standard SKID target — PBX9404-03.

Fig. B10. Standard SKID target — LX04-1.

Fig. B11. Standard SKID target — LX04-1.

Fig. B12. Standard SKID target — PBX9011-02.

The values of η for the large 25.6-in. billets illustrated in Fig. B-8 scatter about an average that is substantially higher than the value of 0.652 chosen for the 11-in.-diam billets. This is to be expected. As discussed in section A-5, a larger billet relatively should deform more in relation to the target. The suggested value of $\eta = 0.814$ calculated from the 11-in. billet average using Eq. (27) is not inconsistent with the data points plotted in Fig. B-8.

The same theory that suggests that values of η increase for large billets also suggests that they decrease for small billets. The data points for the small 6-in. billets, illustrated in Fig. B-11, apparently do not fit this pattern, being of the same order of magnitude as those for the 11-in. billets. However, the value of the area-approach constant, XK3, measured in the vertical drop tests and described in section B-2 also is too low. Taken together, the high value for η and the low value for XK3 indicates that the vertical drop target defined to be rigid is not as rigid for these small billets as it is for the 11-in. and 25.6-in. billets.

B-4. SMOOTH SKID SURFACE DATA FITS

To investigate frictional effects, oblique impact SKID drops to a special smooth steel SKID target were performed. Prior to these drops, it was anticipated that the flexibility characteristics of this target would be equivalent to those of the smooth steel vertical drop target. This did not prove to be the case. The three 45 deg drops and two 14-deg drops illustrated in Fig. B-13 show a level of target flexibility equivalent to that for the standard SKID target. To prove that the flexibility effect is indeed associated with the target and not with the angularity of the drop, a billet was dropped vertically to this target and the result is illustrated in Fig. B-14, i.e., the flexibility effect is associated with the target.

The data reported herein demonstrate the fact of target flexibility, but offer no information as to its source. The flexible smooth steel SKID target is a concrete pad surfaced with a 1-in.-thick steel plate 10 in. square. The more rigid vertical drop target is a concrete pad surfaced with a 1/4-in. steel plate 6 in. square. In both cases, the plate was bonded to the pad with a sand-loaded elastomeric glue bond. It seems reasonable to suppose that uncontrolled variation in bonding is one source of target flexibility.

Since "standard" SKID targets are produced in an equivalent manner, the data of this section are in support of a conclusion that uncontrolled target flexibility is a factor in previously reported SKID test results.

Fig. B13. Smooth steel target—LX 04-1 and PBX 9011-02.

Fig. B14. Smooth steel target vertically dropped LX 04-1 billet.

Appendix C

Data Tabulations

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Table C-1. Composition of reported explosive materials.

	Specific gravity	Vol% HMX	Vol% binder	Binder(s)
LX 04-1	1.86	84.5	15.5	Viton A
LX 07-1	1.86	89.7	10.3	Viton A
LX 10-0 ^a	1.86	94.8	5.2	Viton A
LX 09-0	1.84	91.4	5.8 2.8	DNPA FEFO
PBX 9404-03	1.84	92.4	4.2	TβCP nitrocellulose (12% N)
PBX 9011-02	1.77	85.0	15.0	Estane
RX 04-DJ	1.86	84.5	15.5	crystalline fluorel
RX 04-DS	1.92	82.9	9.9 7.2	Viton A aluminum

Note: DNPA is dinitropropyl acrylate,
FEFO is bis (2 fluoro 2, 2 dinitroethyl) formal,
TβCP is tris-β-chloroethyl phosphate.

^aOnly Table C-10, reproduced from Ref. 3, contains data for these materials.

Table C-2. Explosive material mechanical properties.

Property	Explosive			
	PBX 9404-03	LX 04-1	PBX 9011-02	LX 07-1
Specific gravity	1.836	1.865	1.770	
Poisson's ratio	0.324	0.38	0.35	
Bulk modulus (psi)	1.42×10^6	1.5×10^6	1.39×10^6	
Shear modulus (psi)	0.567×10^7	0.39×10^6	0.463×10^6	
Static shear strength ^a (psi)	750	485	350	
Static tensile strength (psi)	314	300	325	320
Static tensile elongation ^a (min./in.)	2150	4150	3400	3100
Static compressive strength ^a (psi)	1560	1700	1130	
Dynamic compressive strength ^b (psi)	12000	13000	10000	

^aAt 68°C.

^bHopkinson bar data at approximate strain rate of $1000 (\text{sec})^{-1}$.

Table C-3. Comparative Data Tabulation Time (in msec) to Increasing Levels of Energy Fluence for 11-in. Billets

	H (ft)	Angle (deg)	V(1) (ips)	PBX 9404-03	PBX 9404-03 repeat	LX 04-1	RX 04-DJ	PBX 9011-02	PBX 9011-02 repeat	LX 09-0	LX 09-0 repeat	LX 07-1	LX 07-1 repeat
E = 0.5 cal/cm ²	14.1	45	255.375					0.223					
	10.0	45	215.065					0.184					
	7.1	45	181.217			0.217	0.238	0.215					
	5.0	45	152.074			0.301	0.305	0.278					
	3.5	45	127.234	0.243	0.303	0.344		0.319		0.313	0.202	0.252	0.277
	7.1	14	62.00					0.344					
	3.5	14	43.53					0.375					
	1.25	14	26.014			0.669	0.681	0.560	0.745				
	0.88	14	21.827	0.515		0.587	0.845	0.747		0.733		0.811	
E = 1.0 cal/cm ²	14.1	45	255.375					0.318					
	10.0	45	215.065					0.271					
	7.1	45	181.217			0.318	0.327	0.328					
	5.0	45	152.074			0.475	0.460	0.424					
	3.5	45	127.234	0.366	0.433	0.559		0.525		0.453	0.315	0.403	0.424
	7.1	14	62.00					0.485					
	3.5	14	43.53					0.575					
	1.25	14	26.014			1.051	1.080	0.945	1.252				
	0.88	14	21.827	0.851		0.998	1.431	1.260		1.196		1.332	
E = 1.5 cal/cm ²	14.1	45	255.375					0.405					
	10.0	45	215.065					0.355					
	7.1	45	181.217			0.418	0.421	0.449					
	5.0	45	152.074			0.738	0.710	0.631					
	3.5	45	127.234	0.525	0.774	∞		∞		∞	0.458	0.638	0.690
	7.1	14	62.00					0.624					
	3.5	14	43.53					0.785					
	1.25	14	26.014			1.584	1.793	1.482	∞				
	0.88	14	21.827	∞		1.740	∞	∞		∞		∞	

Table C-4. Comparative data tabulation for 25.6-in. billets of PBX 9404-03.

H (in.)	Angle (deg)	V(1) (ips)	H (ft)	95% rising ΔP			75% declining ΔP			End		Time to level of energy fluence (msec)		
				T ₉₅ (msec)	P ₉₅ (psi)	E ₉₅ (cal/cm ²)	T ₇₅ (msec)	P ₇₅ (psi)	E ₇₅ (cal/cm ²)	T _T (msec)	E _T (cal/cm ²)			
22	45	92.085	1.833	0.362	19,004	0.587	1.333	15,003	2.313	2.220	2.442	0.329	0.541	0.777
14.8	45	75.528	1.233	0.397	16,106	0.529	1.408	12,716	1.767	2.30	1.898	0.385	0.698	1.112
7.5	45	53.766	0.625	0.442	15,536	0.354	1.499	12,265	1.218	2.40	1.291	0.584	1.144	∞
7.2	45	52.680	0.600	0.433	16,577	0.242	1.493	13,087	1.108	2.43	1.197	0.445	1.346	∞
5.3	45	45.198	0.442	0.373	18,406	0.246	1.481	14,531	1.117	2.40	1.162	0.634	1.281	∞
3.9	45	38.771	0.325	0.731	15,848	0.312	1.661	12,512	0.793	2.54	0.823	1.022	∞	∞
3.9	14	13.265	0.325	1.324	8,013	0.45	R ^a	R	R	R	R	1.426	R	R
3.0	14	11.643	0.250	1.253	6,679	0.41	2.363	5,273	0.904	3.700	1.074	1.445	2.876	∞
Level of energy fluence $\rightarrow$												0.5	1.0	1.5
(cal/cm ²)														

^aData missing because of reaction.

Table C-5. Instrumented SKID Test Data Summary, Similar to C-10

Drop No.	Material	Diam (in.)	Wt (lb)	Drop ht. (ft)	$V_0 \sin \phi$ (in./sec)	ϵ —	$\dot{\epsilon}$ (sec ⁻¹)	$\epsilon \dot{\epsilon}$ (sec ⁻¹)	σ_{RMS} (psi)	$\frac{E}{1 - \nu^2}$	d_m (in.)	Z_m (in.)	τ (msec)	I	K_3	N_{RMS} (lb)	RTD	CRES
										(psi)								
1	PBX 9404-03	25.6	285.0	1.83	92.1	0.0072	4.24	0.030	16,189	609,635	2.19	0.092	1.695	1.695	1.953	43,236	0.351	0.100
2		25.6	287.0	1.23	75.5	0.0065	3.15	0.020	12,633	541,934	2.08	0.083	2.068	1.872	1.953	30,016	0.468	0.011
3		25.6	291.0	0.63	53.8	0.0047	2.43	0.011	12,860	612,245	1.77	0.060	1.943	1.728	1.953	22,469	0.382	0.013
4		25.6	293.0	0.60	52.7	0.0044	2.46	0.011	14,145	697,390	1.72	0.057	1.807	1.669	1.953	23,888	0.391	0.121
5		25.6	298.0	0.44	45.2	0.0036	2.14	0.008	16,517	855,590	1.55	0.046	1.697	1.651	1.953	22,367	0.293	0.181
6		25.6	296.0	0.33	38.8	0.0034	1.89	0.006	13,839	806,584	1.50	0.044	1.793	1.597	1.953	18,483	0.275	0.205
R ^a 7		25.6	292.0	0.33	13.3	R	R	R	R	R	R	R	R	R	1.953	R	R	R
8		25.6	296.0	0.25	11.6	0.0017	0.54	0.001	5,086	470,724	1.05	0.021	3.105	1.697	1.953	3,361	0.388	0.022
9		11.0	23.5	3.5	127.2	0.0098	15.44	0.151	23,284	998,482	0.98	0.054	0.633	1.498	1.953	14,427	0.131	0.465
10		11.0	23.1	3.5	127.2	0.0101	15.71	0.159	21,468	940,498	1.00	0.056	0.646	1.472	1.953	14,027	0.149	0.523
11		11.0	23.2	0.88	21.8	0.0024	2.79	0.007	12,533	1,273,482	0.48	0.013	0.844	1.424	1.953	1,946	0.052	0.764
12	PBX 9011-02	11.0	21.8	14.1	255.4	0.0244	30.76	0.750	13,791	359,431	1.55	0.134	0.793	1.509	1.953	21,159	0.180	0.426
13		11.0	22.0	10.0	215.1	0.0195	25.61	0.500	15,278	435,373	1.38	0.107	0.763	1.527		18,677	0.214	0.355
14		11.0	22.1	7.1	181.2	0.0168	21.79	0.366	14,872	473,195	1.28	0.092	0.772	1.512		15,709	0.158	0.413
15		11.0	22.2	5.0	152.1	0.0140	18.44	0.258	15,441	545,271	1.17	0.077	0.758	1.500		13,746	0.142	0.498
16		11.0	22.2	3.5	127.2	0.0129	15.17	0.196	12,411	441,888	1.13	0.071	0.852	1.525		10,010	0.178	0.409
17		11.0	21.9	7.1	62.1	0.0076	8.05	0.061	9,269	532,439	0.86	0.042	0.945	1.400		4,736	0.101	0.748
18		11.0	21.8	3.5	43.5	0.0055	5.39	0.030	8,201	501,215	0.74	0.030	1.026	1.469		2,898	0.025	0.744
19		11.0	21.7	1.25	26.0	0.0036	3.18	0.011	6,673	484,501	0.60	0.020	1.142	1.486		1,522	0.168	0.683
20		11.0	21.1	1.25	26.0	0.0038	3.24	0.012	5,946	437,240	0.61	0.021	1.181	1.460		1,468	0.111	0.566
21		11.0	21.9	0.88	21.8	0.0034	2.77	0.009	5,747	478,163	0.58	0.019	1.221	1.433		1,278	0.017	0.867
22		11.0	21.3	5.0	152.1	0.0143	17.01	0.243	13,211	400,797	1.19	0.079	0.840	1.620		11,073	0.345	0.353
23		11.0	21.1	1.25	26.0	0.0035	3.05	0.011	6,828	451,029	0.58	0.019	1.139	1.550		1,432	0.210	0.570
24		11.0	21.3	4.0	192.4	0.0194	24.17	0.468			1.50	0.107	0.804	1.447		16,250	0.192	0.464
25		11.0	20.9	2.0	136.0	0.0135	16.85	0.228			1.20	0.074	0.801	1.468		11,207	0.189	0.490
26		11.0	21.3	1.04	98.1	0.0110	12.36	0.136			1.10	0.061	0.893	1.443		7,420	0.160	0.500
27	LX 04-1	11.0	23.5	7.1	181.2	0.0159	21.15	0.336	17,150	515,527	1.25	0.088	0.753	1.558	1.953	16,736	0.203	0.366
28		11.0	22.9	5.0	152.1	0.0148	17.94	0.266	13,939	454,755	1.21	0.082	0.826	1.541	1.953	12,510	0.153	0.554

Table C-5. (continued)

Drop No.	Material	Diam (in.)	Wt (lb)	Drop ht. (ft)	$V_0 \sin \phi$ (in./sec)	ϵ	$\dot{\epsilon}$ (sec ⁻¹)	$\epsilon \dot{\epsilon}$ (sec ⁻¹)	σ_{RMS} (psi)	$\frac{E}{1 - \nu^2}$ (psi)	d_m (in.)	Z_m (in.)	τ (msec)	I	K_3	N_{RMS} (lb)	RTD	CRES
29	LX 04-1	11.0	23.6	3.5	127.2	0.0121	15.56	0.188	15,290	594,562	1.09	0.067	0.779	1.486	1.953	11,844	0.166	0.459
30		11.0	23.5	1.25	26.0	0.0038	3.32	0.013	6,801	528,853	0.61	0.021	1.159	1.425		1,739	0.051	0.800
31		11.0	23.5	0.88	21.8	0.0029	2.69	0.008	8,096	661,796	0.53	0.016	1.073	1.473		1,501	0.115	0.661
32		11.0	22.3	7.1	181.2	0.0166	20.94	0.348	14,846	430,790	1.28	0.092	0.795	1.573		14,922	0.371	0.448
33		11.0	22.3	5.0	152.1	0.0136	17.15	0.233	15,416	491,835	1.15	0.075	0.791	1.612		12,329	0.368	0.410
34		11.0	23.3	1.25	26.0	0.0032	2.96	0.009	8,848	576,397	0.56	0.017	1.073	1.601		1,638	0.301	0.547
35		11.0	23.5	2.5	152.1	0.0152	17.95	0.273			1.28	0.082	0.834	1.541		12,638	0.221	0.491
36		11.0	22.6	4.0	192.4	0.0163	23.40	0.382			1.30	0.089	0.695	1.495		18,933	0.208	0.493
37		11.0	21.1	2.0	136.0	0.0122	16.77	0.204			1.20	0.067	0.727	1.475		12,280	0.175	0.484
38		11.0	22.4	1.0	96.2	0.0106	12.08	0.128			0.90	0.058	0.875	1.447		7,828	0.143	0.586
39		6.0	3.8	1.98	135.3	0.0144	31.39	0.452			0.71	0.043	0.457	1.437		3,619	0.125	0.480
40		6.0	3.8	1.13	102.0	0.0126	24.20	0.305			0.60	0.038	0.520	1.405		2,439	0.134	0.448
41	LX 09-0, C	11.8	28.6	3.5	127.2	0.0111	14.47	0.161	17,967	728,594	1.12	0.065	0.765	1.490		14,668	0.150	0.446
R ^b 42	LX 09-0, A	11.8	28.4	3.5	127.2	0.0101	14.46	0.146	21,482	902,594	1.07	0.060	0.701	1.491		16,112	0.144	R
43	LX 09-0, C	11.8	28.3	2.5	107.5	0.0107	12.52	0.134	13,828	609,782	1.10	0.063	0.857	1.456		11,231	0.183	0.356
44	LX 09-0, A	11.8	28.3	2.5	107.5	0.0102	11.75	0.120	14,442	587,887	1.07	0.060	0.865	1.552		10,344	0.249	0.250
R ^c 45	LX 09-0, C	11.8	28.2	0.88	21.8	0.0028	2.52	0.007	8,164	684,251	0.57	0.017	1.128	1.467		1,715	0.114	R
46	LX 09-0, A	11.8	28.6	0.88	21.8	0.0028	2.57	0.007	8,612	759,218	0.57	0.017	1.103	1.438		1,856	0.048	0.757
47	LX 09-0	11.0	22.9	3.5	127.2	0.0103	15.25	0.157	20,062	801,942	1.01	0.057	0.677	1.517		12,976	0.114	0.444
48	LX 09-0	11.0	22.7	3.5	127.2	0.0094	15.10	0.142	23,721	978,792	0.96	0.052	0.623	1.532		13,857	0.197	0.476
49	LX 09-0	11.0	22.9	0.88	21.8	0.0030	2.83	0.008	7,706	710,625	0.55	0.017	1.069	1.400		1,575	0.018	0.821
50	LX 07-1	11.0	23.1	3.5	127.2	0.0115	15.51	0.178	16,688	665,309	1.06	0.063	0.739	1.492		12,136	0.121	0.492
51	LX 07-1	11.0	23.1	3.5	127.2	0.0106	15.70	0.166	19,757	835,735	1.02	0.058	0.676	1.473		13,596	0.113	0.555
52	LX 07-1	11.0	23.1	0.88	21.8	0.0031	2.82	0.009	7,206	637,948	0.56	0.017	1.112	1.408		1,519	0.056	0.788
53	RX 04-DJ	11.0	22.8	7.1	181.2	0.0147	21.97	0.322	20,125	686,524	1.20	0.081	0.670	1.500		18,936	0.180	0.469
54	RX 04-DJ	11.0	22.3	5.0	152.1	0.0127	18.62	0.236	18,777	717,116	1.12	0.070	0.683	1.485		15,267	0.122	0.540
55	RX 04-DJ	11.0	22.6	1.25	26.0	0.0036	3.34	0.012	7,258	597,869	0.60	0.020	1.092	1.417		1,752	0.039	0.764
56	RX 04-DJ	11.0	22.6	0.88	21.8	0.0034	2.82	0.010	5,888	498,143	0.58	0.019	1.216	1.409		1,350	0.054	0.728

^aExplosive reacted at 1.74 msec.^bExplosive reacted at 0.89 msec.^cExplosive reacted at 1.26 msec.

Table C-6. Summary Tabulation for all Reported Instrumented SKID Test Data, Additional Information

Drop No.	Material	Tar- get	Tar- get flex. η	ϕ (deg)	$V_0 \cos \phi$ (in./sec)	Max. approach			95% rise time			75% decline time			End of sliding			End of impact			
						f_{rms} —	σ_τ (psi)	E_τ (c/cm ²)	τ_{95} (msec)	σ_{95} (psi)	E_{95} (c/cm ²)	τ_{75} (msec)	σ_{75} (psi)	E_{75} (c/cm ²)	τ_{s0} (msec)	σ_{s0} (psi)	E_{s0} (c/cm ²)	τ_T (msec)	E_T (c/cm ²)	θ_F (sec ⁻¹)	
1	PBX 9404-03	STD	0.814	45	92.1	0.379	8,229	2.426	0.362	19,004	0.587	1.333	15,003	2.313	1.784	6,342	2.428	2.220	2.442	7.93	
2				45	75.5	0.370	1,839	1.897	0.397	16,106	0.529	1.408	12,716	1.767	2.300	0	1.898	2.300	1.898	5.61	
3				45	53.8	0.356	5,101	1.285	0.442	15,536	0.354	1.499	12,265	1.218	2.400	0	1.291	2.400	1.291	4.09	
4				45	52.7	0.325	8,199	1.178	0.433	16,577	0.242	1.493	13,087	1.108	2.430	0	1.197	2.430	1.197	4.02	
5				45	45.2	0.338	10,925	1.149	0.373	18,406	0.246	1.481	14,531	1.117	1.982	5,708	1.159	2.400	1.162	3.77	
6				45	38.8	0.325	10,282	0.808	0.731	15,848	0.312	1.661	12,512	0.793	2.235	3,592	0.822	2.540	0.823	3.13	
7				14	53.2	R	R	R	1.324	8,013	0.450	R	R	R	R	R	R	R	R	R	
8				14	46.7	0.395	1,720	1.051	1.253	6,679	0.410	2.363	5,273	0.904	3.700	0	1.074	3.700	1.074	0.93	
9			0.652		45	127.2	0.359	25,406	1.653	0.343	27,436	0.909	0.713	21,660	1.672	0.711	21,654	1.674	1.050	1.756	30.40
10					45	127.2	0.360	24,877	1.456	0.352	25,903	0.698	0.776	20,449	1.494	0.724	21,772	1.480	1.100	1.591	31.56
11	14	87.5			0.285	16,800	0.990	0.630	16,328	0.675	1.089	12,890	1.268	1.550	0	1.465	1.550	1.465	4.79		
12	PBX 9011-02	45			255.4	0.384	13,946	2.624	0.355	16,906	1.215	0.822	13,347	2.640	0.879	11,466	2.639	1.500	2.716	58.54	
13		45			215.1	0.437	14,969	2.547	0.293	17,979	1.139	0.787	14,194	2.547	0.762	15,014	2.547	1.300	2.663	52.11	
14		45			181.2	0.416	15,301	2.070	0.350	17,321	1.097	0.833	13,674	2.072	0.796	14,662	2.071	1.370	2.225	46.03	
15		45			152.1	0.369	16,873	1.622	0.332	17,750	0.686	0.858	14,013	1.636	0.845	14,442	1.636	1.430	1.699	35.65	
16		45			127.2	0.402	12,588	1.318	0.404	14,332	0.723	0.918	11,314	1.318	0.899	11,686	1.318	1.450	1.363	29.70	
17		14			248.7	0.308	12,530	2.457	0.696	12,424	1.740	1.167	9,808	2.909	1.850	0	3.399	1.850	3.399	13.11	
18		14			174.6	0.365	10,138	1.972	0.723	9,827	1.360	1.309	7,759	2.367	1.950	0	2.699	1.950	2.699	11.06	
19		14			104.3	0.417	7,699	1.219	0.737	7,930	0.735	1.443	6,261	1.477	2.200	0	1.716	2.200	1.716	8.13	
20		14			104.3	0.362	7,024	0.943	0.750	7,229	0.505	1.362	5,707	1.078	2.100	0	1.289	2.100	1.289	6.65	
21	14	87.5			0.446	7,629	0.968	0.871	7,284	0.633	1.562	5,751	1.206	2.500	0	1.485	2.500	1.485	7.89		
22	SMTH	45			152.1	0.163	10,359	1.000	0.280	17,002	0.398	0.646	13,423	0.865	1.500	0	1.174	1.500	1.174	14.57	
23		SMTH			14	104.3	0.157	6,449	0.508	0.557	7,838	0.246	1.195	6,188	0.529	2.400	0	0.786	2.400	0.786	3.03
24					STD	90	0												1.35		
25					90	0													1.37		
26					90	0													1.48		
27		LX 04-1	0.652	45	181.2	0.399	16,200	2.222	0.293	20,723	0.870	0.760	16,360	2.255	0.793	14,863	2.224	1.280	2.304	42.40	
28	LX 04-1	45		152.1	0.353	14,295	1.572	0.283	15,133	0.451	0.988	11,947	1.599	0.933	12,835	1.594	1.450	1.686	36.93		

Table C-6 (continued)

Drop No.	Material	Tar- get	Tar- get flex. η	ϕ (deg)	$V_0 \cos \phi$ (in./sec)	Max. approach			95% rise time			75% decline time			End of sliding			End of impact		
						f_{rms} —	σ_τ (psi)	E_τ (c/cm ²)	τ_{95} (msec)	σ_{95} (psi)	E_{95} (c/cm ²)	τ_{75} (msec)	σ_{75} (psi)	E_{75} (c/cm ²)	τ_{s0} (msec)	σ_{s0} (psi)	E_{s0} (c/cm ²)	τ_F (msec)	E_F (c/cm ²)	θ_F (sec ⁻¹)
29	LX 04-1	STD	0.652	45	127.2	0.323	16,884	1.303	0.449	18,382	0.746	0.863	14,512	1.341	0.981	9,870	1.348	1.300	1.353	25.87
30				14	104.3	0.390	8,937	1.127	0.798	8,620	0.675	1.515	6,805	1.454	2.300	0	1.717	2.300	1.717	8.17
31				14	87.6	0.388	9,461	1.078	0.646	9,637	0.576	1.320	7,608	1.291	2.000	0	1.529	2.000	1.529	6.36
32		SMTH		45	181.2	0.120	13,448	0.964	0.298	19,384	0.379	0.626	15,303	0.816	1.450	0	1.237	1.450	1.237	14.44
33				45	152.1	0.122	11,943	0.858	0.277	19,852	0.339	0.602	15,672	0.721	1.400	0	1.064	1.400	1.064	11.59
34				14	104.3	0.173	7,365	0.694	0.290	10,467	0.179	0.968	8,264	0.641	2.400	0	1.039	2.400	1.039	3.23
35				90	0														1.400	
36		STD		90	0														1.20	
37				90	0														1.27	
38				90	0														1.500	
39				90	0														0.780	
40				90	0														0.880	
41	LX 09-0,C			45	127.2	0.306	19,351	1.328	0.389	21,379	0.514	0.845	16,878	1.398	0.972	10,874	1.402	1.280	1.415	24.67
42	LX 09-0,A			45	127.2	0.282	23,925	1.455	0.377	25,280	0.697	R	R	R	R	R	R	R	R	R
43	LX 09-0,C			45	107.5	0.317	14,803	0.957	0.484	17,505	0.413	0.887	14,803	0.976	1.145	4,113	1.004	1.380	1.005	19.56
44	LX 09-0,A			45	107.5	0.340	12,100	1.240	0.389	17,350	0.592	0.814	13,697	1.220	1.290	0	1.264	1.290	1.264	18.38
45	LX 09-0,C			14	87.5	0.310	9,259	0.913	0.709	9,991	0.493	R	R	R	R	R	R	R	R	R
46	LX 09-0,A			14	87.5	0.296	11,080	0.869	0.757	10,659	0.488	1.425	8,415	1.133	2.050	0	1.293	2.05	1.293	4.63
47	LX 09-0			45	127.2	0.355	21,040	1.423	0.300	23,213	0.450	0.760	18,326	1.446	0.773	17,476	1.448	1.100	1.491	29.01
48	LX 09-0			45	127.2	0.364	23,815	1.758	0.271	27,471	0.805	0.688	21,688	1.790	0.701	20,637	1.772	1.080	1.881	31.17
49	LX 09-0			14	87.5	0.348	10,671	0.879	0.820	10,325	0.602	1.398	8,151	1.157	2.050	0	1.360	2.050	1.360	6.17
50	LX 07-1			45	127.2	0.407	18,321	1.551	0.383	19,689	0.936	0.824	15,544	1.565	0.773	17,302	1.557	1.250	1.620	30.31
51	LX 07-1			45	127.2	0.349	22,866	1.491	0.360	23,473	0.786	0.803	18,531	1.525	0.777	19,653	1.521	1.150	1.595	30.33
52	LX 07-1			14	87.5	0.342	9,731	0.819	0.828	9,486	0.519	1.435	7,489	1.072	2.100	0	1.261	2.100	1.261	5.96
53	RX 04-DJ			45	181.2	0.382	21,305	2.148	0.314	24,202	0.922	0.742	19,107	2.167	0.732	19,131	2.166	1.180	2.305	44.52
54	RX 04-DJ			45	152.1	0.267	21,122	1.466	0.379	22,407	0.750	0.804	17,690	1.597	1.200	0	1.626	1.200	1.626	28.96
55	RX 04-DJ			14	104.3	0.341	9,817	1.014	0.816	9,547	0.674	1.378	7,537	1.287	2.050	0	1.532	2.050	1.532	7.04
56	RX 04-DJ			14	87.5	0.386	7,899	0.842	0.890	7,745	0.544	1.503	6,115	1.044	2.150	0	1.224	2.150	1.224	6.50

Table C-7. Smooth target vertical drop data summary.

Drop No.	Material	Billet		Drop height (ft.)	V ₀ (in./sec)	ϵ	$\dot{\epsilon}$ (sec) ⁻¹	$\epsilon\dot{\epsilon}$ (sec) ⁻¹	σ_{rms} (psi)	E/1 - ν^2 (psi)	d _m (in.)	Z _m (in.)	τ (msec)	I	K ₃	N _{rms} (lb)	RTD	CRES
		Diam (in.)	Wt (lb)															
1	PBX 9404-03	25.6	286	0.92	92.1	0.0064	4.04	0.025	16797	610180	2.25	0.082	1.578	1.777	1.898	47763	0.493	0.029
2	PBX 9404-03	25.6	296	0.50	68.0	0.0048	3.05	0.014	16729	674379	1.97	0.062	1.587	1.740	1.917	36038	0.401	0.069
3	PBX 9404-03	25.6	294	0.09	29.0	0.0027	1.37	0.003	15147	630776	1.20	0.034	1.946	1.652	1.292	12707	0.332	0.090
4	PBX 9404-03	25.6	292	0.04	19.6	0.0020	0.78	0.001	12598	567992	1.01	0.025	2.545	1.966	1.23	6811	0.489	0.002
5	PBX 9404-03	11.0	23.2	2.0	136.0	0.0093	17.22	0.161	21017	802501	1.15	0.51	0.541	1.436	1.844	18719	0.075	0.59
6	PBX 9404-03	11.0	23.1	1.0	96.2	0.0058	11.25	0.065	18628	998697	1.05	0.032	0.512	1.554	2.484	13483	0.160	0.518
7	PBX 9404-03	11.0	22.2	1.0	96.2	0.0059	11.32	0.066	17394	917944	1.05	0.032	0.579	1.545	2.438	12818	0.210	0.510
8	PBX 9404-03	11.0	23.1	0.50	68.0	0.0049	8.48	0.041	19788	923060	0.81	0.027	0.579	1.458	1.735	8648	0.049	0.630
9	PBX 9404-03	11.0	23.2	0.12	34.0	0.0031	4.22	0.013	12188	722130	0.65	0.017	0.735	1.464	1.768	3376	0.115	0.640
10	PBX 9404-03	11.0	22.8	0.12	34.0	0.0031	4.25	0.013	12233	739286	0.65	0.017	0.721	1.455	1.789	3445	0.099	0.670
11	PBX 9404-03	6.0	3.75	4.0	192.4	0.0177	44.48	0.786	14292	311986	0.77	0.053	0.398	1.442	1.463	5734	0.120	0.450
12	PBX 9404-03	6.0	3.75	2.0	136.0	0.0117	32.18	0.376	15765	477215	0.66	0.035	0.364	1.409	1.622	4834	0.039	0.56
13	PBX 9404-03	6.0	3.75	1.0	96.2	0.0092	23.39	0.215	13740	478219	0.57	0.028	0.395	1.371	1.535	3156	0.114	0.60
14	PBX 9404-03	6.0	3.76	0.50	68.0	0.0066	16.10	0.106	13956	507559	0.47	0.020	0.412	1.408	1.455	2165	0.028	0.71
15	PBX 9011-02	11.0	21.0	8.0	272.0	0.0192	33.82	0.650	17196	436911	1.67	0.105	0.566	1.463	1.89	32116	0.117	0.500
16	PBX 9011-02	11.0	21.4	8.0	272.0	0.0188	33.10	0.622	16458	431377	1.72	0.103	0.568	1.494	2.044	31776	0.119	0.500
17	PBX 9011-02	11.0	22.1	4.0	192.4	0.0155	24.07	0.373	13365	393115	1.52	0.086	0.646	1.453	1.929	20573	0.148	0.450
18	PBX 9011-02	11.0	21.1	4.0	192.4	0.0135	24.40	0.329	17346	573280	1.43	0.074	0.552	1.433	1.972	24367	0.094	0.560
19	PBX 9011-02	11.0	21.9	2.0	136.0	0.0101	16.76	0.169	14293	532455	1.30	0.055	0.601	1.475	2.178	16716	0.118	0.520
20	PBX 9011-02	11.0	22.6	2.0	136.0	0.0110	16.98	0.186	13236	472578	1.30	0.060	0.695	1.457	2.003	14848	0.148	0.520
21	PBX 9011-02	11.0	22.4	1.0	96.2	0.0069	11.48	0.079	13863	638045	1.11	0.038	0.604	1.523	2.305	11558	0.107	0.500
22	PBX 9011-02	11.0	22.2	1.0	96.2	0.0069	11.50	0.079	13535	646796	1.13	0.038	0.600	1.520	2.403	11650	0.133	0.540
23	PBX 9011-02	11.0	22.3	0.12	34.0	0.0043	4.15	0.038	4961	280057	0.84	0.024	1.046	1.490	2.111	2219	0.092	0.670
24	PBX 9011-02	11.0	21.3	0.12	34.0	0.0044	4.15	0.044	4822	261298	0.83	0.024	1.063	1.490	2.027	2123	0.106	0.640
25	LX 04-1	11.0	22.6	8.0	272.0	0.0200	34.01	0.682	17300	431592	1.69	0.110	0.589	1.454	1.857	32926	0.157	0.505
26	LX 04-1	11.0	22.6	8.0	272.0	0.0200	34.01	0.682	17300	431592	1.69	0.110	0.589	1.454	1.857	32926	0.157	0.505
27	LX 04-1	11.0	22.1	4.0	192.4	0.0161	23.61	0.381	12656	341130	1.52	0.089	0.682	1.482	1.863	19155	0.194	0.420
28	LX 04-1	11.0	21.9	4.0	192.4	0.0155	24.16	0.374	15159	399682	1.43	0.085	0.640	1.447	1.716	20747	0.141	0.480
29	LX 04-1	11.0	22.9	2.0	136.0	0.0113	17.36	0.196	14200	472303	1.30	0.062	0.651	1.425	1.941	17069	0.078	0.520
30	LX 04-1	11.0	23.5	2.0	136.0	0.0119	16.55	0.197	11738	373062	1.34	0.065	0.717	1.494	1.965	13741	0.163	0.490
31	LX 04-1	11.0	23.5	1.0	96.2	0.0078	11.21	0.087	11945	453709	1.15	0.043	0.698	1.56	2.196	10310	0.140	0.460
32	LX 04-1	11.0	23.6	1.0	96.2	0.0076	11.13	0.084	12308	491238	1.15	0.042	0.679	1.571	2.271	10608	0.264	0.470
33	LX 04-1	11.0	23.3	0.12	34.0	0.0042	4.14	0.017	7121	317868	0.73	0.023	1.011	1.492	1.653	2429	0.109	0.590
34	LX 04-1	11.0	23.3	0.12	34.0	0.0043	4.13	0.017	7096	297792	0.72	0.024	1.036	1.497	1.573	2338	0.131	0.500
35	LX 04-1	6.0	3.8	4.0	192.4	0.0171	42.89	0.732	12559	301581	0.83	0.051	0.398	1.495	1.760	5559	0.184	0.420
36	LX 04-1	6.0	3.8	2.0	136.0	0.0123	30.21	0.372	11899	340698	0.71	0.037	0.406	1.501	1.796	3974	0.137	0.460
37	LX 04-1	6.0	3.8	1.0	96.2	0.0094	21.65	0.203	10967	344767	0.60	0.028	0.433	1.481	1.676	2617	0.192	0.500
38	LX 04-1	6.0	3.8	0.50	68.0	0.0070	15.20	0.106	9836	354463	0.52	0.021	0.457	1.491	1.697	1767	0.235	0.500
39	LX 10-0	11.0	22.8	2.0	136.0	0.0100	16.84	0.168	16114	585368	1.26	0.055	0.593	1.469	2.065	17840	0.106	0.560
40	LX 10-0	11.0	23.2	1.0	96.2	0.0062	11.21	0.069	18139	806132	1.03	0.034	0.556	1.560	2.209	12389	0.263	0.500
41	LX 09-0	11.0	23.0	2.0	136.0	0.0105	17.02	0.178	15228	548938	1.26	0.058	0.615	1.453	1.969	16282	0.106	0.530
42	LX 09-0	11.0	22.8	2.0	136.0	0.0106	17.23	0.182	15605	543916	1.24	0.059	0.617	1.435	1.878	16352	0.109	0.520
43	LX 09-0	11.0	22.7	1.0	96.2	0.0080	11.50	0.092	11091	460791	1.16	0.044	0.693	1.521	2.193	9409	0.206	0.460
44	LX 09-0	11.0	22.4	1.0	96.2	0.0084	11.76	0.098	11527	426243	1.11	0.046	0.717	1.487	1.897	9303	0.163	0.450
45	LX 07-1	11.0	22.8	2.0	136.0	0.0111	16.85	0.187	13655	459973	1.28	0.061	0.658	1.468	1.918	14916	0.165	0.520
46	LX 07-1	11.0	22.7	2.0	136.0	0.0123	17.48	0.215	13272	395106	1.26	0.068	0.705	1.415	1.672	14546	0.149	0.510
47	LX 07-1	11.0	22.7	1.0	96.2	0.0081	11.61	0.094	11232	462639	1.15	0.044	0.695	1.507	2.129	9451	0.136	0.510
48	LX 07-1	11.0	22.5	1.0	96.2	0.0081	11.56	0.093	11582	456545	1.13	0.044	0.698	1.513	2.053	9279	0.141	0.510
49	RX 04-DJ	11.0	22.6	4.0	192.4	0.0151	23.92	0.361	15330	430178	1.46	0.083	0.629	1.462	1.838	21724	0.126	0.490
50	RX 04-DJ	11.0	22.6	4.0	192.4	0.0147	23.70	0.348	15289	439663	1.47	0.081	0.621	1.476	1.905	21792	0.115	0.490
51	RX 04-DS	11.0	24.1	2.0	136.0	0.0109	16.63	0.181	13046	491032	1.35	0.060	0.653	1.487	2.180	15647	0.157	0.500
52	RX 04-DS	11.0	24.1	2.0	136.0	0.0096	16.34	0.157	14415	627507	1.35	0.053	0.588	1.514	2.463	16720	0.150	0.500
53	RX 04-DS	11.0	24.1	1.0	96.2	0.0081	11.80	0.095	12541	516258	1.13	0.044	0.685	1.482	2.052	10440	0.123	0.530
54	RX 04-DS	11.0	24.1	1.0	96.2	0.0075	11.79	0.083	11971	630089	1.20	0.041	0.634	1.483	2.499	11255	0.133	0.510

Table C- 8. Nomenclature

Symbol		Appendix A Section Ref.
V_0	Preimpact velocity	
d_m	Maximum contact diameter	
Z_m	Maximum billet approach	
τ	Compression time to Z_m	
I	Impact No.	A-7
K_3	Area-approach constant	A-5
N_{rms}	rms force reaction	A-7
σ_{rms}	rms flow stress	A-7
$E/1 - \nu^2$	Elastic parameter	A-7
E	Young's modulus	A-7
ν	Poisson's ratio	A-7
ϵ	Apparent contact strain	A-7
$\dot{\epsilon}$	Apparent contact strain rate	A-7
ξ	$\xi = \epsilon \dot{\epsilon}$	A-7
RTD	Relative time delay	A-7
CRES	Coefficient of restitution	A-7
ϕ	Preimpact angle	A-2
η	Target flexibility	A-5
f_{rms}	rms friction coefficient	A-7
σ_τ	Normal pressure at Z_m	A-6
E_τ	Energy fluence at Z_m	A-6
τ_{95}	Rise time to 95% peak normal pressure	
σ_{95}	Pressure at 95% peak normal pressure	
E_{95}	Energy fluence at 95% peak normal pressure	
τ_{75}	Time after pressure decline to 75% peak normal pressure	
σ_{75}	Pressure after pressure decline to 75% peak normal pressure	
E_{75}	Energy fluence after pressure decline to 75% peak normal pressure	
τ_{s0}	Time where sliding velocity goes to zero	
σ_{s0}	Pressure when sliding velocity goes to zero	
E_{s0}	Energy fluence when sliding velocity goes to zero	
τ_T	Time at end of impact	
E_T	Energy fluence at end of impact	
$\dot{\theta}_F$	Final billet rotation velocity	

Distribution

LRL Internal Distribution

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