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Conical Shaped Charge Pressed Powder, Metal Liner Jet Characterization and Penetration in Aluminum

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CONICAL SHAPED CHARGE PRESSED POWDER, METAL LINER JET CHARACTERIZATION AND PENETRATION IN ALUMINUM

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Abstract

This work was conducted as part of a Near-wellbore Mechanics program at Sandia National Laboratories. An understanding of the interaction of the perforator jet from an explosive shaped charge with the fluid filled porous sandstone media is of basic importance to the completion of oil wells.

Tests were conducted using the five-head Flash X-ray Test Site to measure the jet tip velocities and jet geometry for the OMNI and CAPSULE Conical Shaped Charge (CSC) oil well perforator jets fired into air. These tests were conducted to generate jet velocity and geometry information to be used in validating the CTH hydrocode modeling/simulation development of pressed powder, metal liner jets in air.

Ten tests were conducted to determine the CSC jet penetration into 6061-T6 aluminum targets. Five tests were conducted with the OMNI CSC at 0.25, 6.0, and 19 inch standoffs from the target. Five tests were conducted with the CAPSULE CSC at 0.60, 5.0, 10.0, and 19 inch standoffs from the target. These tests were conducted to generate jet penetration into homogeneous target information for use in validating the CTH code modeling/simulation of pressed powder, metal liner jets penetrating aluminum targets.

The Flash X-ray radiographs, jet velocities, jet diameters, and jet lengths data for jets fired into air are presented in this report. The jet penetration into aluminum and penetration hole profile data are also presented for the OMNI and CAPSULE perforators. Least Squares fits are presented for the measured jet velocity and jet penetration data.

Acknowledgments

The tests discussed in this report were conducted by John Lanoue and Jerry Brock (1554) at the Flash X-ray Test Site of the Explosive Components Facility. John and Jerry also prepared the Flash X-ray radiographs and pre- and post-test photographs presented in this report.

John Regalbuto (Halliburton , Explosive Products Center) provided the OMNI and CAPSULE conical shaped charge, oil well perforators for this study. John also provided the drawings and other information that were available for these two charges.

Mike Furnish (9332) provided the consultation, comments, and guidance that allowed the successful completion of this task in the overall program.

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CONICAL SHAPED CHARGE PRESSED POWDER, METAL LINER JET CHARACTERIZATION AND PENETRATION IN ALUMINUM

GENERAL BACKGROUND

This work is part of the Advanced Computational Technology Institute (ACTI) program at Sandia National Laboratories (SNL). The goal of this ACTI program is to perform research and development work related to the Near-wellbore Mechanics which includes the explosive shaped charge (CSC) perforator jet and fluid filled porous sandstone media, an interaction which is of basic importance to the completion of oil wells. The work presented in this report is part of the Perforation Induced Damage Team's (PIDT) efforts in this ACTI program. The goal of this team was to describe the state of the near-wellbore environment at a time immediately following the CSC perforator jet penetration of the casing and sandstone media.

Five tests were conducted at SNL's Explosive Components Facility (ECF) using the five-head Flash X-ray Test Site to measure the OMNI and CAPSULE Conical Shaped Charge (CSC), oil well perforator, jet tip velocities and jet geometry. Three tests were conducted with the OMNI CSC and two tests were conducted with the CAPSULE CSC. These tests were conducted to generate jet velocity and geometry information that was used in verifying or validating the CTH hydrocode modeling/simulation of pressed powder, metal liner jets in air.

Ten tests were conducted at the ECF to determine the CSC jet penetration into 6061-T6 aluminum targets. Five tests were conducted with the OMNI CSC at 0.25, 6.0, and 19 inch standoffs from the target. Five tests were conducted with the CAPSULE CSC at 0.60, 5.0, 10.0, and 19 inch standoffs from the target. These tests were conducted to generate jet penetration into homogeneous target information that was used in verifying or validating the CTH code modeling/simulation development of pressed powder, metal liner jets penetrating aluminum targets.

The team goals, project plan, a detailed description of the shaped charges, concrete and sandstone tests conducted as part of the PIDT work are published in references 1-4.

PROBLEM CONFIGURATION

The oil well down hole Conical Shaped Charge (CSC), jet, wellbore, casing, and strata materials configuration of interest are shown in Figure 1. According to Figure 1, the CSC jet must penetrate the following materials:

1. Steel casing (4140 steel),
2. Well completion fluid (8.3 lb/gal.),
3. Casing (Grades L-80, J-55 or similar),
4. Grout, and
5. Sandstone.

The ability to predict the CSC jet damage to the rock formation as illustrated in Figure 2 was of primary importance for this task.

CONICAL SHAPED CHARGE SELECTION

The following CSC's (oil well perforators) were selected for this study:

1. OMNI CSC: 22.7 grams of RDX explosive, 2.0" outside diameter
2. CAPSULE CSC: 15.5 grams of RDX explosive, 1.78" outside diameter

The pressed powder, metal liners for both CSC's are composed of copper, tungsten, tin, graphite, and oil. The explosive for both CSC's is composed of 98.5-99% RDX and 1.0-1.5% wax with a density of 1.65 g/cc. This is very similar to the composition of COMP-A5 explosive (99% RDX, 1% wax, density: 1.65 g/cc).

OMNI CSC PERFORATOR

GENERAL

The OMNI CSC Perforator configuration is shown in Figures 3 through 8. The OMNI cross section geometry is shown in Figure 3. Photographs of the OMNI hardware are shown in Figures 4 through 8. The SE-1 detonator used to initiate the RDX explosive and steel holder ring are shown in Figure 7 with the OMNI CSC. The SE-1 detonator function time is 2.60 microseconds. The assembled hardware ready for testing is shown in Figure 8. The detonator was taped and in contact with the RDX explosive in the OMNI CSC as shown in Figure 8. A summary of the OMNI liner, explosive, tamper housing, jet, and jet parameters are listed in Table I.

PRESSED POWDER, METAL LINER COMPOSITION AND DENSITY

The pressed powder, metal liners for both CSC's are composed of copper, tungsten, tin, graphite, and oil. The OMNI liner materials, powder mixture weights, weight percents, liner total weight, and calculated composite density parameters are listed in Table II. The density of the composite liner was calculated using the rule of mixtures from the data of Table II. A liner density of 12.07 g/cc was calculated and the details are included in Appendix A. The liner density listed in Halliburton drawing number C462029-5 was 9.7 g/cc. The liner porosity is about 10%.

The OMNI CSC liner density was measured by submerging the liner in water and weighing it to determine the density. The liner was also weighed in air. The volume was derived from the product of the measured density and weight to obtain liner volumes of 3.74 and 3.73 cubic centimeters in two separate measurements. This liner was also weighed at 37.934 and 37.935 grams on two separate measurements. The liner densities measured were 10.15 g/cc for both trials. These data are summarized in Table A1 in Appendix A.

CAPSULE CSC PERFORATOR

The CAPSULE CSC Perforator configuration is shown in Figures 9-14. The CAPSULE cross section geometry is shown in Figure 9. Photographs of the CAPSULE hardware are shown in Figures 10-14. The SE-1 detonator and 3-inch length of 100 grain/ft det cord (PETN explosive, 1.0 g/cc, nylon sheath: O.D. = 0.225 inches) used to initiate the RDX explosive and steel holder ring are shown in Figure 13 with the CAPSULE CSC. The det cord was necessary because this is the typical technique used to shock initiate the RDX explosive through the steel tamper housing of the CAPSULE CSC. The assembled hardware ready for testing is shown in Figure 14. A plastic adapter was used to hold the SE-1 detonator in contact with the PETN explosive in the det cord as shown in Figure 14. The det cord was taped and in contact with the CAPSULE CSC tamper housing as shown in Figure 14.

The length of the det cord from the detonator to the center of the CAPSULE steel housing was 2.0 inches (5.08 cm). The detonation velocity for PETN explosive at a density of 1.0 g/cc was calculated to be 0.642 cm per microsecond. Therefore, the time for the detonation wave to propagate the two inches is 7.9 microseconds. The total function time for the detonator and det cord is 10.5 microseconds. This time will be required for the CTH code modeling/simulation work. This time must be subtracted from the Flash X-ray radiograph times if the detonator and det cord are not included in the modeling/simulation of the CSC.

A summary of the CAPSULE liner, explosive, tamper housing, jet, and jet penetration parameters is listed in Table III. The CAPSULE liner materials, powder mixture weights, weight percents, liner total weight, and calculated composite density parameters are listed in Table II. The density of the composite liner was calculated using the rule of mixtures from the data of Table II. A liner density of 11.47 g/cc was calculated and the details are included in Appendix A. The liner density listed in Halliburton drawing number C212420-5/Rev. C was 9.7 g/cc. The liner porosity is about 10%.

PERFORATOR MODELING/ SIMULATION COMMENTS

Sandia National Laboratories has been involved in the design of conical shaped charge components for more than 40 years (References 5-27). The modeling of full density, homogeneous, CSC liner materials in warhead type CSC's has been well documented with various codes including the CTH code (References 28-33). Generally, very good agreement between code predicted and experimental jet velocities and geometry has been obtained.

The jet that is formed from pressed powder, metal (granular materials) liner is composed of a volume of discontinuous, discrete particles. The modeling of these pressed powder, metal liners using the CTH or other hydrocodes is not well understood and not much documentation of the effect of these materials on jet formation or performance exists. Therefore, the initial CTH code work will be to determine if current CSC liner material equations of state and jet formation models are adequate to predict the velocities and geometry of the CSC jets formed from pressed powder, metal liner jets in air.

Continuum mechanics hydrocodes like CTH may not be the best choice for the modeling/simulation of discontinuous, discrete particle jets formed from pressed powder, metal liners. Discrete particle motion codes or smooth particle aerodynamic codes may be better suited for the modeling/simulation of the jets produced by pressed powder, metal liners.

The jet formed from these types of liners is quite different than the jets formed from the more common anti-tank, warhead, homogeneous metal, high density liners. At large standoffs, jets from warhead type CSC's continuously stretch and the molten metal has ductility so that eventually the jet particulates or breaks up into distinct elongated particles. The pressed powder, metal CSC liners are composed of copper, tungsten, tin, graphite and oil. The composite density is about 9.7 grams per cubic centimeter. The jet formed from these pressed powder, metal liners consists of individual particles that are not bonded together. Therefore, although the jet elongates similarly to warhead CSC jets as it is formed, the jet is not continuous and does not break up into distinct particles at long standoffs as is common for warhead type liners. The relatively slow velocity slug that follows the main high velocity jet that is formed from this type of CSC is not a solid material. This property of the slug is very useful in the oil industry since the slug usually does not plug the hole in the casing to reduce oil production from the well.

CSC JET CHARACTERIZATION/ FLASH X-RAY TESTS

GENERAL

The OMNI CSC, film cassette, and aluminum target for a typical Flash X-ray test are shown in Figure 15. The aluminum target for these tests was located 19 inches from the face of the CSC. The size of the X-ray film inside the aluminum cassettes was 11 by 17 inches. The five Flash X-ray tubes were positioned on an arc configuration with each tube located between 48.125 and 48.25 inches from the jet centerline. The film cassette was located between 5.25 and 6.25 inches from the jet centerline. Therefore, the jet images on the radiographs were magnified by a factor (MF) of about 0.9. The exact magnification factors were as follows:

1. X-ray Tube # 3: MF = 0.902
1. X-ray Tube # 2 and 4: MF = 0.894
1. X-ray Tube # 1 and 5: MF = 0.885

Flash X-ray tests were conducted with the OMNI and CAPSULE CSC's at relatively short times to characterize and measure the following CSC jet parameters:

1. Tip velocity,
2. Diameter, and
3. Length.

The CTH code existing models parameters will be modified to determine if agreement with experimental data can be obtained. The comparison of the CTH code predicted versus experimentally measured jet velocities and geometry will be published in a separate report in the near future.

New jet formation and elongation models may have to be developed if necessary. CSC jet models validated by experimental data will be used to model future CSC jet-concrete and CSC jet-sandstone tests.

OMNI FLASH X-RAY TESTS

The X-ray head number, X-ray tube times, jet propagation distances, average jet tip velocities, jet tip diameters, jet tail diameters, and jet lengths are listed in Tables IV, V, and VI for OMNI Tests 1, 2, and 5. The corresponding radiographs are shown in Figures 16-18, respectively. The times listed in Tables IV-VI are measured from the firing set output to the SE-1 detonator. The function time for the detonator is 2.6 microseconds. The jet propagation distances are measured from the initial location of the face of the CSC. The jet tip diameter was measured just aft of the eroding jet tip where the first consistent jet diameter is apparent. The jet tail diameter was measured near the start of the slug position where possible. The jet length was approximated to be the length from the jet tip to the start of the slug position where possible.

CAPSULE FLASH X-RAY TESTS

The X-ray head number, X-ray tube times, jet propagation distances, average jet tip velocities, jet tip diameters, jet tail diameters, and jet lengths are listed in Tables VII and VIII for CAPSULE Tests 3 and 4. The corresponding radiographs are shown in Figures 19 and 20, respectively. The times listed in Tables IV-VI are measured from the firing set output to the SE-1 detonator. The function time for the detonator is 2.6 microseconds. The jet propagation distances are measured from the initial location of the face of the CSC. The jet tip diameter was measured just aft of the eroding jet tip where the first consistent jet diameter is apparent. The jet tail diameter was measured near the start of the slug position where possible. The jet length was approximated to be the length from the jet tip to the start of the slug position where possible.

OMNI AND CAPSULE CSC/ FLASH X-RAY TEST ANALYSIS

The measured jet propagation distance from the initial location of the face of the CSC versus time data are shown in Figure 21 for the OMNI and CAPSULE CSC's. The data for the three OMNI and two CAPSULE CSC Flash X-ray tests are shown in Figure 21. The Least Squares fit for the data of both CSC's are also shown in this figure.

The measured jet tip velocities versus time data are shown in Figure 22 for both the OMNI and CAPSULE CSC's. The average OMNI jet tip velocity is about 0.645 cm per microsecond. The average CAPSULE jet tip velocity is about 0.580 cm per microsecond.

The measured jet length versus time data are shown in Figure 23 for both the OMNI and CAPSULE CSC's. The Least Squares fit for the data of both CSC's are also shown in this figure.

The measured jet tip diameter versus time data are shown in Figure 24 for both the OMNI and CAPSULE CSC's. Data are only shown for OMNI CSC Test 5 and CAPSULE CSC Test 4 since good radiographs were obtained for all five times.

JET PENETRATION INTO ALUMINUM TESTS

GENERAL

Ten tests were conducted at the ECF to determine the CSC jet penetration into 6061-T6 aluminum targets. The aluminum targets consisted of 1.0 inch thick by 6 inch by 6 inch plates as shown in Figure B1 in Appendix B. Five tests were conducted with the OMNI CSC at 0.25, 6.0, and 19 inch standoffs from the target. Five tests were conducted with the CAPSULE CSC at 0.60, 5.0, and 19 inch standoffs from the target. The shortest standoffs of 0.25 inches for the OMNI CSC and 0.6 inches for the CAPSULE CSC are the actual standoffs used in the down hole configurations for the perforators.

These tests were conducted to generate jet penetration into homogeneous target information that was used in validating the CTH code modeling/simulation development of pressed powder, metal liner jets penetrating aluminum targets.

Aluminum was chosen simply because of its relatively low density and because all of the modeling variables are well documented. The CTH code models for jet penetration into a homogeneous material needed to be verified before the code is used to predict jet penetrations into concrete and sandstone targets. The modeling of the concrete and sandstone materials will require much more complicated models.

The CTH code existing models parameters will be modified to determine if agreement with experimental data can be obtained. The comparison of the CTH code predicted versus experimentally measured jet penetration into aluminum will be published in a separate report in the near future. New jet penetration models may have to be developed if necessary.

OMNI JET PENETRATION TESTS

The pre-test OMNI CSC, standoff and aluminum target configurations are shown in Figures B1, B3 and B5 of Appendix B for 0.25, 6.0 and 19 inch standoffs, respectively. The post-test aluminum target plates were aligned to show the jet hole diameters and are shown in Figures B2, B4, and B6-B8.

OMNI JET PENETRATION TESTS/ANALYSIS

The aluminum target depth and jet hole diameter data are listed in Table IX for standoffs of 0.25, 6.0 and 19 inches. As indicated on this table, for a standoff of 0.25 inches, the aluminum slug was embedded in the aluminum plates at depths of 2 to 7 inches. The standoff, total jet penetration, target entrance hole diameter, and the diameter of the last plate penetrated data are listed in Table X for the OMNI CSC. The OMNI jet penetration versus standoff data are shown in Figure 25.

CAPSULE JET PENETRATION TESTS

The pre-test CAPSULE CSC, standoff and aluminum target configurations are shown in Figures C1, C3 and C5 of Appendix C for 0.6, 5.0, 10 and 19 inch standoffs, respectively. The post-test aluminum target plates were aligned to show the jet hole diameters and are shown in Figures C2, C4, and C6-C8.

CAPSULE JET PENETRATION TESTS/ANALYSIS

The aluminum target depth and jet hole diameter data are listed in Table XI for standoffs of 0.6, 5.0 10 and 19 inches. As indicated on this table, for a standoff of 5 inches, the aluminum slug was embedded in the aluminum plates at depths of 1 to 3 inches for Test 9 and at a 1-inch depth for Test 10. The standoff, total jet penetration, target entrance hole diameter, and the diameter of the last plate penetrated data are listed in Table X for the CAPSULE CSC. The CAPSULE OMNI jet penetration versus standoff data are shown in Figure 25.

SUMMARY AND CONCLUSIONS

OMNI and CAPSULE conical shaped charge (CSC), oil well perforator measured jet tip velocities and jet geometry (diameters and length) data from Flash X-ray radiographs were presented in Tables IV-VIII. The jet propagation distance versus time data are summarized in Figure 21. The average jet tip velocity versus time data are summarized in Figure 22. The jet length versus time data are summarized in Figure 23. The jet diameter versus time data are summarized in Figure 24.

OMNI and CAPSULE CSC jet penetration into 6061-T6 aluminum target data were presented in Table X for various standoffs. The jet penetration versus standoff data are summarized in Figure 25.

The Flash X-ray, jet characterization data presented can be used to verify or validate computer code modeling/simulation capabilities for pressed powder, metal CSC liners. The jet penetration into a homogeneous, aluminum target data can be used to verify or validate computer code modeling/simulation capabilities for pressed powder, metal CSC liners.

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Tables

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TABLE I. OMNI CSC PARAMETERS/HALLIBURTON (4-5/8-12 SPF-RDX-DP-ZINC)**LINER: (JRC 24 Mixture)**

MATERIAL:	[Cu/W/Sn/Graphite/Oil], [43.19/45.2/11.4/.53/.025 WT%]
INSIDE DIAMETER(in):	1.28
OUTSIDE DIAMETER(in):	1.37
THICKNESS(in):	0.048(APEX) - 0.064(BASE)
APEX ANGLE/INSIDE(degrees):	44
APEX ANGLE/OUTSIDE(degrees):	45.25
APEX RADIUS(in):	0.103
DENSITY(g/cd):	9.7
WEIGHT(g):	37.6

EXPLOSIVE:

TYPE: (SIMILAR TO COMP-A5)	[(98.5 - 99 % RDX, 1 - 1.5 % WAX)] (CLASS 3, TYPE I, E11262)
MOLECULAR COMPOSITION:	C(1.425)H(2.85)N(2.665)O(2.665)
WEIGHT(g):	22.7
DENSITY(g/cc):	1.65
TMD DENSITY (g/cc):	1.757
DETONATION VELOCITY(cm/us):	0.813
DETONATION PRESSURE(Kb):	278
DETONATION ENERGY(Kcal/g):	1408
MELT TEMPERATURE (deg. C):	200 (LLNL REF.)
HEAT OF FORMATION(Kcal/mol):	6.1
GURNEY VELOCITY(cm/us):	0.273
EXPLOSIVE EXPONENT(gamma):	2.92
OXYGEN MASS BALANCE(%):	-25.8
GAS GENERATION(mole/g):	0.0338

TAMPER HOUSING:

MATERIAL:	<u>ZINC</u>	<u>STEEL</u>
THICKNESS(in):	0.420(BASE) - 0.615(DET. END)	
LENGTH(in):	1.73	
INSIDE DIAMETER(in):	1.1(DET. END) - 1.375(BASE)	
OUTSIDE DIAMETER(in):	1.715(DET. END) - 1.86(BASE)	
WEIGHT(g):	160	
DENSITY(g/cc):	6.4	7.83

JET PARAMETERS:

TIP VELOCITY(cm/us):	0.645 Ave.(20 < t < 55 us)
TIP DIAMETER(in):	0.09 (t=20 us) to 0.05 (t = 55 us)
LENGTH(in):	0.97" (t = 20 us) to 7.26" (t = 55 us)

JET PENETRATION:

CONCRETE(API GRADE, 9080 psi):	16.25 inches
CONCRETE(API GRADE, 5685 psi):	17.42 inches
CONCRETE(API SECT.1, 5000 psi):	22.10 inches
RHA:	0.8 cm (0.315 inches)/ZINC TAMPER/SO=91.9cm
RHA	1.2 cm (0.47 inches)/STEEL TAMPER/SO=103cm
ALUMINUM (6061-T6)	9.1" (SO = 0.25"), 13.75" (SO = 6"), 4" (SO = 19")

Table II. Pressed Powder Metal Liner Data

Porosity: 10%/Density: 9.7 g/cc

CSC	Material	Powder Weight (lb)	WT%	Liner Weight (g)	Drawing ** Density (g/cc)	Composite* Density (g/cc)
OMNI	Copper	129.0	43.19	37.6	9.7	12.07
	Tungsten	135.0	45.20			
	Tin	33.0	11.05			
	Graphite	1.59	0.53			
	Oil	<u>0.075</u>	<u>0.025</u>			
	Totals	298.67	99.995			
Capsule	Copper	150.0	49.74	19.5	9.7	11.47
	Tungsten	120.0	39.79			
	Tin	30.0	10.00			
	Graphite	1.50	0.50			
	Oil	<u>0.075</u>	<u>0.025</u>			
	Totals	301.58	100.05			

* - Composite density calculated by "Rule of Mixtures," 10% porosity

** - Drawing No: OMNI/C462029-5/Halliburton

Capsule/C212420-5, Rev. C/Halliburton

TABLE III. CAPSULE CSC PARAMETERS/HALLIBURTON (2.125-DYNA-STAR 6 SPF RDX-DP)**LINER:**

MATERIAL:	(Cu/W/Sn/Graphite/Oil), (49.74/39.79/10/0.5/0.025 WT%)
INSIDE DIAMETER(in):	1.114
OUTSIDE DIAMETER(in):	1.187
THICKNESS(in):	0.051
APEX ANGLE/INSIDE(degrees):	48
APEX ANGLE/OUTSIDE(degrees):	50
APEX RADIUS(in):	0.172
DENSITY(g/cd):	9.7
WEIGHT(g):	19.5
HEIGHT (in):	1.08

EXPLOSIVE:

TYPE: (SIMILAR TO COMP-A5)	(98.5 - 99 % RDX, 1 - 1.5 % WAX), (CLASS 3, TYPE I, E11262
MOLECULAR COMPOSITION:	C(1.425)H (2.85)N(2.665)O(2.665) LLNL REF.
WEIGHT(g):	15.5
DENSITY(g/cc):	1.65 LLNL REF.
TMD DENSITY (g/cc):	1.757
DETONATION VELOCITY(cm/us):	0.813
DETONATION PRESSURE(Kb):	278
DETONATION ENERGY(Kcal/g):	1408
MELT TEMPERATURE (deg. C):	200 LLNL REF.
HEAT OF FORMATION(Kcal/mol):	6.1
GURNEY VELOCITY(cm/us):	0.273
EXPLOSIVE EXPONENT(gamma):	2.92
OXYGEN MASS BALANCE(%):	-25.8
GAS GENERATION(mole/g):	0.0338

TAMPER HOUSING:

MATERIAL:	STEEL
THICKNESS(in):	0.27 (BASE) - 0.27(DET. END)
LENGTH(in):	2.12
INSIDE DIAMETER(in):	0.92(DET. END) - 1.24(BASE)
OUTSIDE DIAMETER(in):	0.92(DET. END) - 1.78(BASE)
WEIGHT(g):	
DENSITY(g/cc):	7.86

JET PARAMETERS:

TIP VELOCITY(cm/us):	0.58 Ave. (20 < t < 65 us)
TIP DIAMETER(in):	0.09" (t = 40 us) to 0.03" (t = 65 us)
LENGTH(in):	2.0" (t = 35 us) to 6.8" (t = 65 us)

JET PENETRATION:

CONCRETE(API GRADE, 5538 psi):	16.61 inches
MILD STEEL:	2.4 inches/SO=0.55 inches
ALUMINUM (6061-T6)	7.75" (SO = 0.6"), 3.25"(SO=5"), 3.5"(SO=10"), 1.2"(SO=19")

TABLE IV. CONICAL SHAPED CHARGE (CSC) JET/FLASH RADIOGRAPH DATA

TEST NO.: 1 DATE: 8/14/96 LINER DENSITY (g/cc): 9.7

CSC: OMNI LINER COMPOSITION: Cu/w/Sn/Graphite/Oil (43.19/45.2/11/4/0.53/o.025)

STANDOFF(in): 19.0 TARGET: Al 6061-T6 JET PENETRATION(in): 4.20

X-RAY HEAD # 3 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 5.25

X-RAY HEADS # 2 & 4 TO JET CENTERLINE DISTANCE(in): 48.25 JET CENTERLINE TO FILM DISTANCE (in): 5.75

X-RAY HEADS # 1 & 5 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 6.25

X-RAY FILM MAGNIFICATION FACTOR (HEAD # 3): 0.903 = $[48.125/(48.125 + 5.25)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 2 & 4): 0.894 = $[48.25/(48.25 + 5.75)]$

X-RAY FILM MAGNIFICATION FACTOR (HEAD S # 1 & 5): 0.885 = $[48.125/(48.125 + 6.25)]$

X-RAY HEAD NO.	t X-RAY TIME (us)	Δt TIME DIFFERENCE (us)	X JET* DISTANCE (in)	ΔX DISTANCE CHANGE (in)	$V=\Delta X/\Delta t$ JET TIP VELOCITY (cm/us)	Dti JET TIP DIAMETER (in)	Dta JET TAIL DIAMETER (in)	Lj JET LENGTH (in)
1.	35.097		4.602			0.18	0.22	4.6
		5.024		1.316	0.665			
2.	40.121		5.918			0.09	0.18	5.9
		14.958		3.779	0.642			
3.	55.079		9.697			0.09	0.14	9.7
		30.142						
4.	ND							
5.	ND							

Vave = 0.654

* - MEASURED DISTANCE MULTIPLIED BY MAGNIFICATION FACTOR

ND - NO DATA

TABLE V. CONICAL SHAPED CHARGE (CSC) JET/FLASH RADIOGRAPH DATA

TEST NO.: 2 DATE: 8/14/96 LINER DENSITY (g/cc): 9.7

CSC: OMNI LINER COMPOSITION: Cu/w/Sn/Graphite (43.19/45.2/11/4/0.53)

STANDOFF(in): 19.0 TARGET: Al 6061-T6 JET PENETRATION(in): 2.0

X-RAY HEAD # 3 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 5.25

X-RAY HEADS # 2 & 4 TO JET CENTERLINE DISTANCE(in): 48.25 JET CENTERLINE TO FILM DISTANCE (in): 5.75

X-RAY HEADS # 1 & 5 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 6.25

X-RAY FILM MAGNIFICATION FACTOR (HEAD # 3): 0.903 = $[48.125/(48.125 + 5.25)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 2 & 4): 0.894 = $[48.25/(48.25 + 5.75)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 1 & 5): 0.885 = $[48.125/(48.125 + 6.25)]$

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X-RAY HEAD NO.	t X-RAY TIME (us)	Δt TIME DIFFERENCE (us)	X JET* DISTANCE (in)	ΔX DISTANCE CHANGE (in)	$V=\Delta X/\Delta t$ JET TIP VELOCITY (cm/us)	D _{ti} JET TIP DIAMETER (in)	D _{ta} JET TAIL DIAMETER (in)	L _j JET LENGTH (in)
1.	20.02		0.903			0.071	0.133	0.90
		5.07		1.243	0.623			
2.	25.09		2.146					2.15
		9.97		2.499	0.637			
3.	35.06		4.645					3.61
		9.85		2.418	0.624			
4.	44.91		7.063					5.28
		10.32		2.584	0.636			
5.	55.23		9.647					7.08

V_{ave} = 0.630

* - MEASURED DISTANCE MULTIPLIED BY MAGNIFICATION FACTOR

TABLE VI. CONICAL SHAPED CHARGE (CSC) JET/FLASH RADIOGRAPH DATA

TEST NO.: 5 DATE: 8/15/96 LINER DENSITY (g/cc): 9.7

CSC: OMNI LINER COMPOSITION: Cu/w/Sn/Graphite/Oil (43.19/45.2/11/4/0.53/0.025)

STANDOFF(in): 19.0 TARGET: Al 6061-T6 JET PENETRATION(in): 3.75

X-RAY HEAD # 3 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 5.25

X-RAY HEADS # 2 & 4 TO JET CENTERLINE DISTANCE(in): 48.25 JET CENTERLINE TO FILM DISTANCE (in): 5.75

X-RAY HEADS # 1 & 5 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 6.25

X-RAY FILM MAGNIFICATION FACTOR (HEAD # 3): $0.903 = [48.125 / (48.125 + 5.25)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 2 & 4): $0.894 = [48.25 / (48.25 + 5.75)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 1 & 5): $0.885 = [48.125 / (48.125 + 6.25)]$

X-RAY HEAD NO.	t X-RAY TIME (us)	Δt TIME DIFFERENCE (us)	X JET* DISTANCE (in)	ΔX DISTANCE CHANGE (in)	$V = \Delta X / \Delta t$ JET TIP VELOCITY (cm/us)	Dti JET TIP DIAMETER (in)	Dta JET TAIL DIAMETER (in)	Lj JET LENGTH (in)
1.	19.97		0.974			0.09	0.13	0.97
		5.13		1.279	0.663			
2.	25.1		2.253			0.07	0.18	2.25
		9.96		2.528	0.645			
3.	35.06		4.781			0.05	0.11	3.61
		9.86		2.460	0.634			
4.	44.92		7.241			0.05	0.11	5.45
		10.32		2.627	0.647			
5.	55.24		9.868			0.05	0.11	7.26

$V_{ave} = 0.645$

* - MEASURED DISTANCE MULTIPLIED BY MAGNIFICATION FACTOR

TABLE VII. CONICAL SHAPED CHARGE (CSC) JET/FLASH RADIOGRAPH DATA

TEST NO.: 3 DATE: 8/15/96 LINER DENSITY (g/cc): 9.7

CSC: CAPSULE LINER COMPOSITION: Cu/w/Sn/Oil/Graphite (49.74/39.79/10/0.25/0.5)

STANDOFF(in): 19.0 TARGET: Al 6061-T6 JET PENETRATION(in): 1.25

X-RAY HEAD # 3 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 5.25

X-RAY HEADS # 2 & 4 TO JET CENTERLINE DISTANCE(in): 48.25 JET CENTERLINE TO FILM DISTANCE (in): 5.75

X-RAY HEADS # 1 & 5 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 6.25

X-RAY FILM MAGNIFICATION FACTOR (HEAD # 3): $0.903 = [48.125 / (48.125 + 5.25)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 2 & 4): $0.894 = [48.25 / (48.25 + 5.75)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 1 & 5): $0.885 = [48.125 / (48.125 + 6.25)]$

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X-RAY HEAD NO.	t X-RAY TIME (us)	Δt TIME DIFFERENCE (us)	X JET* DISTANCE (in)	ΔX DISTANCE CHANGE (in)	V=ΔX/Δt JET TIP VELOCITY (cm/us)	D _{ti} JET TIP DIAMETER (in)	D _{ta} JET TAIL DIAMETER (in)	L _j JET LENGTH (in)
1.	19.96		ND			ND	ND	ND
		5.06		ND	ND			
2.	25.02		ND			ND	ND	ND
		10.03		ND	ND			
3.	35.05		2.21			0.07	0.16	2.2
		9.82		2.26	0.585			
4.	44.87		4.47			0.07	0.13	4.0
		10.31		2.433	0.599			
5.	55.18		6.903			0.06	0.11	5.75

V_{ave} = 0.592

* - MEASURED DISTANCE MULTIPLIED BY MAGNIFICATION FACTOR

ND - NO DATA

TABLE VIII. CONICAL SHAPED CHARGE (CSC) JET/FLASH RADIOGRAPH DATA

TEST NO.: 4 DATE: 8/15/96 LINER DENSITY (g/cc): 9.7

CSC: CAPSULE LINER COMPOSITION: Cu/w/Sn/Oil/Graphite (49.74/39.79/10/0.25/0.5)

STANDOFF(in): 19.0 TARGET: Al 6061-T6 JET PENETRATION(in): 1.10

X-RAY HEAD # 3 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 5.25

X-RAY HEADS # 2 & 4 TO JET CENTERLINE DISTANCE(in): 48.25 JET CENTERLINE TO FILM DISTANCE (in): 5.75

X-RAY HEADS # 1 & 5 TO JET CENTERLINE DISTANCE (in): 48.125 JET CENTERLINE TO FILM DISTANCE (in): 6.25

X-RAY FILM MAGNIFICATION FACTOR (HEAD # 3): 0.903 = $[48.125/(48.125 + 5.25)]$

X-RAY FILM MAGNIFICATION FACTOR (HEADS # 2 & 4): 0.894 = $[48.25/(48.25 + 5.75)]$

X-RAY FILM MAGNIFICATION FACTOR (HEAD S # 1 & 5): 0.885 = $[48.125/(48.125 + 6.25)]$

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X-RAY HEAD NO.	t X-RAY TIME (us)	Δt TIME DIFFERENCE (us)	X JET* DISTANCE (in)	ΔX DISTANCE CHANGE (in)	$V=\Delta X/\Delta t$ JET TIP VELOCITY (cm/us)	Dti JET TIP DIAMETER (in)	Dta JET TAIL DIAMETER (in)	Lj JET LENGTH (in)
1.	39.93		0.885			0.09	0.11	0.09
		5.08		1.127	0.564			
2.	35.11		2.012			0.07	0.11	2.0
		9.97		2.273	0.579			
3.	45.08		4.285			0.05	0.11	3.6
		9.86		2.152	0.554			
4.	54.94		6.437			0.03	0.11	5.2
		10.31		2.280	0.562			
5.	65.25		8.717			0.03	0.11	6.8

Vave = 0.565

* - MEASURED DISTANCE MULTIPLIED BY MAGNIFICATION FACTOR

ND - NO DATA

TABLE IX. CONICAL SHAPED CHARGE(CSC) JET HOLE PROFILE IN ALUMINUM

CSC NAME: OMNI

DATE: 10/14 - 15/96

SO = CSC STANDOFF FROM ALUMINUM TARGET

<u>JET HOLE DIAMETER (in)</u>				
ALUMINUM TARGET DEPTH (in)	TEST # 6 SO=0.25"	TEST # 7 SO=6.0"	TEST # 1 SO=19"	TEST # 5 so=19"
0	0.48	0.58	0.4 - 0.8	0.3 - 0.8
1	0.42	0.27	0.18 - 0.27	0.25 - 0.32
2	0.38 (slug)	0.27	0.19 - 0.27	0.25
3	0.33 (slug)	0.25	0.18 - 0.24	0.25
4	0.25 (slug)	0.23		
5	0.22 (slug)	0.22		
6	0.21 (slug)	0.19		
7	0.19 (slug)	0.16		
8	0.27	0.15		
9	0.25 - 0.34	0.14		
10		0.14		
11		0.13-0.17		
12		0.34-0.42		

TABLE X. CONICAL SHAPED CHARGE (CSC) JET PENETRATION IN ALUMINUM

DATE: 10/14 - 15.96

<u>JET HOLE DIAMETER (in)</u>				
CSC	STANDOFF (in)	JET PENETRATION (in)	TARGET ENTRANCE	LAST PENETRATED PLATE
OMNI	0.25	9.1	.48	0.25 - 0.34
OMNI	6.0	13.75	0.58	0.34 - 0.42
OMNI	19.0	4.2	0.3 - 0.8	0.31
OMNI	19.0	2.0	0.4 - 0.8	0.18 - 0.24
OMNI	19.0	3.75	2 holes/.24-.5	2 holes/.2 - .3
CAPSULE	0.60	7.75	0.4 - 0.55	0.25 - 0.27
CAPSULE	5.0	3.25	0.2 - 0.5	0.2
CAPSULE	10.0	3.5	0.35 - 0.6	0.14
CAPSULE	19.0	1.25	0.2 - 0.3	0.15
CAPSULE	19.0	1.10	3 holes/ —	0.12

TABLE XI. CONICAL SHAPED CHARGE(CSC) JET HOLE PROFILE IN ALUMINUM

CSC NAME: CAPSULE

DATE: 10/15/96

ALUMINUM TARGET DEPTH (in)	JET HOLE DIAMETER (in)				
	TEST # 8 SO=0.60 "	TEST # 9 SO=5.0"	TEST # 10 SO=10"	TEST # 3 SO=19"	TEST # 4 SO=19"
0	0.4 - 0.55	0.2 - 0.5	0.35 - 0.6	2 holes/ 0.2 - 0.3	3 holes/ -----
1	0.33	0.25- 0.35*	0.2-0.3 *	0.15	.05,.06,.1
2	0.26 (slug)	0.26 *	0.18		
3	0.21 (slug)	0.24 *	0.25		
4	0.15 (slug)				
5	.1- .2(slug)				
6	.1- .2(slug)				
7	0.25 - 0.27				

SO = CSC STANDOFF FROM ALUMINUM TARGET

* - SLUG EMBEDDED IN TARGET

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Figures

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FIGURE 1. NEAR WELLBORE MECHANICS/PERFORATION INDUCED DAMAGE PROBLEM CONFIGURATION

FIGURE 2. SHAPED CHARGE DAMAGE TO FORMATION CONFIGURATION

FIGURE 3. OMNI CSC PERFORATOR GEOMETRY

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Figure 4. OMNI CSC Side Configuration

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Figure 5. OMNI CSC Liner and Tamping Configuration

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Figure 6. OMNI CSC Liner and Tamping Configuration

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Figure 7. OMNI CSC, DE-1 Detonator and Holder Ring

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Figure 8. Assembled OMNI CSC, SE-1 Detonator and Holder Ring

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STEEL HOUSING

RDX EXPLOSIVE (15.5 g)

LINER [Cu/W/Sn/Oil/G(50/40/9/0.03/1)]

STANDOFF HOUSING/STEEL

FIGURE 9. CAPSULE CSC PERFORATOR GEOMETRY

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Figure 10. Assembled CAPSULE CSC

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Figure 11. CAPSULE CSC Liner, Tamping Housing and Standoff Cap

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Figure 12. CAPSULE CSC Liner, Tamping Housing and Standoff Cap

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Figure 13. CAPSULE CSC, SE-1 Detonator, Detcord and Holder Ring

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Figure 14. Assembled CAPSULE CSC, SE-1 Detonator,
Detcord and Holder Ring

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Figure 15. CSC, Holder Ring, X-Ray Film and Aluminum Target Configuration

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Figure 16. Test 1/OMNI CSC Flash X-Ray Radiograph

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Figure 17. Test 2/OMNI CSC Flash X-Ray Radiograph

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Figure 18. Test 5/OMNI CSC Flash X-Ray Radiograph

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Figure 19. Test 3/CAPSULE CSC Flash X-Ray Radiograph

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Figure 20. Test 4/CAPSULE CSC Flash X-Ray Radiograph

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Figure 21. Distance versus Time/Flash X-Ray Data

Figure 22. CSC Jet Tip Velocity versus Time

SANDIA FLASH X-RAY DATA

Figure 23. CSC Jet Length versus Time

Figure 24. CSC Jet Tip Diameter versus Time

FIGURE 25. CSC JET PENETRATION IN ALUMINUM VERSUS STANDOFF

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Appendix A

Calculation of the Pressed Powder, Metal Liner Composite Densities

AI.	OMNI CSC Liner Composite Density Calculation, based on total powder mixture weight	75
AI.	CAPSULE CSC Liner Composite Density Calculation, based on total powder mixture weight	76

Table

A1.	OMNI and CAPSULE CSC Perforator Liner Measured Densities.....	77
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AI. OMNI CSC Liner Composite Density Calculation

A. Based on total powder mixture weight of 298.665 lb

From the "Rule of Mixtures"

$$\rho_t = (\rho_c M_c + \rho_w M_w + \rho_s M_s + \rho_g M_g + \rho_o M_o) / M_t$$

where,

M = Powder mixture weight, ρ = density

$M_t = 298.665$ lb, $\rho_t =$ g/cc

$M_c = 129$ lb, $\rho_c = 8.8$ g/cc

$M_w = 135$ lb, $\rho_w = 19.2$ g/cc

$M_s = 33$ lb, $\rho_s = 7.2$ g/cc

$M_g = 1.59$ lb, $\rho_g = 1.64$ g/cc

$M_o = 0.075$ lb, $\rho_o = 0.91$ g/cc

$$\rho_t = [8.8(129) + 19.2(135) + 7.2(33) + 1.64(1.59) + 0.91(0.075)] / 298.665$$

$$\rho_t = 13.284 \text{ g/cc, } 0\% \text{ porosity}$$

$$\rho_t = 12.07 \text{ g/cc, } 10\% \text{ porosity}$$

AII. Capsule CSC Liner Composite Density Calculation

A. Based on total powder mixture weight of 301.58 lb

From the "Rule of Mixtures":

$$\rho_t = (\rho_c M_c + \rho_w M_w + \rho_s M_s + \rho_g M_g + \rho_o M_o) / M_t$$

where,

M = Powder mixture weight, ρ = density

$M_t = 301.58$ lb, $\rho_t =$ g/cc

$M_c = 150$ lb, $\rho_c = 8.8$ g/cc

$M_w = 120$ lb, $\rho_w = 19.2$ g/cc

$M_s = 30$ lb, $\rho_s = 7.2$ g/cc

$M_g = 1.5$ lb, $\rho_g = 1.64$ g/cc

$M_o = 0.075$ lb, $\rho_o = 0.91$ g/cc

$$\rho_t = [8.8(150) + 19.2(120) + 7.2(30) + 1.64(1.5) + 0.91(.075)] / 301.58$$

$$\rho_t = 12.74 \text{ g/cc, } 0\% \text{ porosity}$$

$$\rho_t = 11.47 \text{ g cc, } 10\% \text{ porosity}$$

Table A1. OMNI and CAPSULE CSC Perforator Liner Measured Densities

Parameter	OMNI Liner Trial 1	OMNI Liner Trial 2	CAPSULE Liner Trial 1	CAPSULE Liner Trial 2
Weight (g)	37.9338 (37.6)	37.93467 (37.6)	11.52187 (19.5)	11.52176 (19.5)
Density (g/cc)	10.15 (9.7)	10.15 (9.7)	(9.7)	(9.7)
Derived Volume	3.74	3.73		

() - Halliburton drawing values

Density calibration sphere: 1.47 g/cc (measure reference values: Trial 1 was 1.469 g/cc,
Trial 2 was 1.486 g/cc)

OFHC copper control (Literature reference): 8.92 g/cc (Laboratory measure value was 8.9 g/cc)

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Appendix B

OMNI CSC Jet Penetration of Aluminum Test Photographs

Pre-Test CSC and Target Configurations, Post-Test Target Hole Configurations

Figures

B1. Pre-Test OMNI CSC/0.25 inch Standoff.....	81
B2. Post-Test OMNI CSC/0.25 inch Standoff.....	83
B3. Pre-Test OMNI CSC/6.0 inch Standoff.....	85
B4. Post-Test OMNI CSC/6.0 inch Standoff.....	87
B5. Pre-Test OMNI CSC/19 inch Standoff.....	89
B6. Post-Test 1 OMNI CSC/19 inch Standoff.....	91
B7. Post-Test 2 OMNI CSC/19 inch Standoff.....	93
B8. Post-Test 5 OMNI CSC/19 inch Standoff.....	95

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Figure B1. Pre-Test OMNI CSC/0.25 Inch Standoff

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Figure B2. Post-Test OMNI CSC/0.25 Inch Standoff

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Figure B3. Pre-Test OMNI CSC/6.0 Inch Standoff

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Figure B4. Post-Test OMNI CSC/6.0 Inch Standoff

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Figure B5. Pre-Test OMNI CSC/19 Inch Standoff

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Figure B6. Post1 OMNI CSC/19 Inch Standoff

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Figure B7. Post-Test 2 OMNI CSC/19 Inch Standoff

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Figure B8. Post-Test 5 OMNI CSC/19 Inch Standoff

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Appendix C

CAPSULE CSC Jet Penetration of Aluminum Test Photographs

Pre-Test CSC And Target Configurations, Post-Test Target Hole Configurations

Figures

C1. Pre-Test CAPSULE CSC/0.6 inch Standoff	99
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C4. Post-Test CAPSULE CSC/5.0 inch Standoff	105
C5. Pre-Test CAPSULE CSC/10 inch Standoff	107
C6. Post-Test CAPSULE CSC/10 inch Standoff	109
C7. Post-Test 3 CAPSULE CSC/19 inch Standoff	111
C8. Post-Test 4 CAPSULE CSC/19 inch Standoff	113

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Figure C1. Pre-Test CAPSULE CSC/0.6 Inch Standoff

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Figure C2. Post-Test CAPSULE CSC/0.6 Inch Standoff

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Figure C3. Pre-Test CAPSULE CSC/5.0 Inch Standoff

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Figure C4. Post-Test CAPSULE CSC/5.0 Inch Standoff

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Figure C5. Pre-Test CAPSULE CSC/10 Inch Standoff

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Figure C6. Post-Test CAPSULE CSC/10 Inch Standoff

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Figure C7. Post-Test 3 CAPSULE CSC/19 Inch Standoff

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Figure C8. Post-Test 4 CAPSULE CSC/19 Inch Standoff

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