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of Transportation
**Federal Railroad
Administration**

ALUMINUM/COLD TEMPERATURE TANK CAR PUNCTURE RESISTANCE TESTS: DATA REPORT

Office of Research and
Development
Washington D.C. 20590

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Transportation Test Center
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16. Abstract

Puncture resistance testing of DOT Type 111 aluminum tank car heads was conducted at the Transportation Test Center (TTC), Pueblo, Colorado. Testing was conducted to determine the puncture resistance of a standard Type 111 aluminum tank car relative to that of DOT Type 112/114 and 105 steel tank car designs. Physical parameters, such as head thickness, jacket or head shield thickness, insulation, and head temperature were evaluated for influence on puncture resistance. Both full scale and one-fifth scale aluminum take heads were tested. Full scale tests were conducted per the procedures described in CFR Title 49, Part 179.105.5. This report presents details of the 6 full scale and the 78 one-fifth scale tank head puncture tests performed by the TTC's Research and Test Department of the Association of American Railroads.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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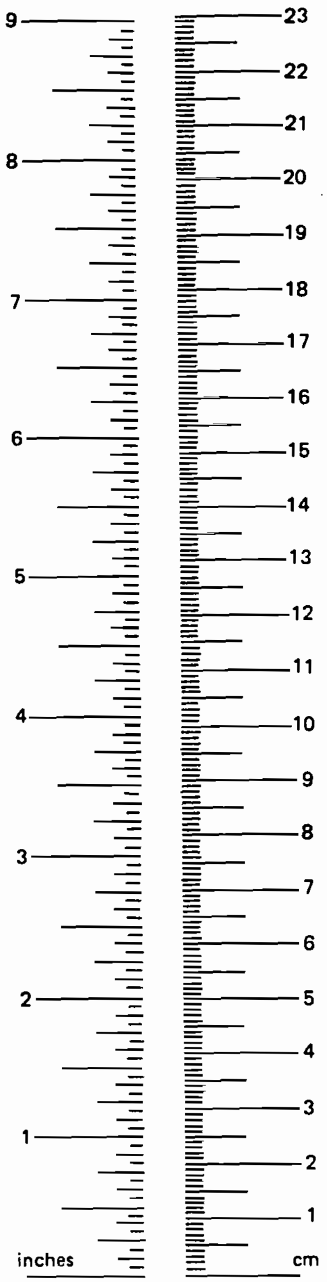
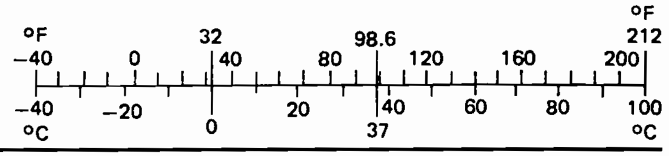
*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

Numerous full scale tests of tank cars were conducted in 1976 at the Transportation Test Center (TTC), Pueblo, Colorado, to establish minimal safety requirements for those series of cars designed to carry flammable liquids and gases. Those tests and results of other studies led to the adoption of performance specifications for the Department of Transportation (DOT) specifications 112/114 tank cars. These specifications are covered in Title 49, Part 179 of the Code of Federal Regulations (49 CFR Part 179). Section 179.105.5 covers tank car head puncture resistance and specifies testing procedures demonstrating puncture resistance. Currently there are no such safety performance standards for DOT 105A500W tank cars carrying poisonous chlorine gas or aluminum tank cars carrying hazardous materials.

1.1 THE CHLORINE TANK CAR PROGRAM

In early 1987, testing was completed at TTC on the determination of the relative puncture resistance of DOT 105 chlorine tank cars compared to DOT 112/114 propane tank cars with head shields. Specifically, testing was modeled around the DOT 105A500W cars and the DOT 112J340W cars. This testing was conducted under Task Order 18 as a joint effort of the Federal Railroad Administration (FRA), Transportation Systems Center (TSC), and the Association of American Railroads (AAR). Three types of tests were conducted in the program under two phases of work effort:

- Phase I - One-fifth scale model drop tests in a laboratory environment.

  Full scale head impact tests on a railroad track.

- Phase II - Full size (actual) tank car impact tests on a railroad track.

The rationale for conducting the three different test head configurations is as follows: (1) to perform a variety of one-fifth scale impact tests with various parameter changes, (2) to perform full scale model impact tests to investigate the relationship between one-fifth scale model and full scale model impact energies, and (3) to perform impact resistance tests on full size (actual) tank cars to correlate results with full scale model tests and to validate the one-fifth scale model testing. Results from the one-fifth scale, full scale, and full size impact tests can be found in TTC engineering sketch files 86-47574-074, 87-47574-093, and 87-47574-104, respectively.

1.2 **THE ALUMINUM TANK CAR PROGRAM**

In July 1983, the National Transportation Safety Board (NTSB) held a public hearing on the safety of hazardous materials in rail yards. As a result of the hearing, NTSB recommended that FRA initiate a program to investigate the vulnerability of aluminum tank cars to being punctured or being subjected to a fire. As part of this program, the NTSB issued Recommendation R-85-64 requesting the FRA to conduct a full testing and evaluation program to develop a head shield to protect DOT specification aluminum tank car heads from puncture. Consequently, Task Order 18 was extended to include puncture resistance testing of aluminum tank car heads, specifically DOT Type 111, in both ambient temperature and specific cold temperature (-20°F and +32°F) conditions. The data described in this report comprise the results of that testing. TSC will review the data collected and will be responsible for the data reduction and analysis.

2.0 BACKGROUND

Testing for tank car head puncture resistance was initiated in 1970 with the RPI-AAR Tank Car Safety Project. An initial part of this investigation provided a thorough review of previous accidents and, with subsequent work, developed some of the test parameters that are used as the basis for present test work and for comparative analysis. (See RPI-AAR Tank Car Safety Project Report RA-05-1-17 for reference.)

Previous engineering studies provide the rationale for the dimensional scaling of the materials, geometry, and forces used in the one-fifth scale model tests relative to full size tank car impacts. The scaling laws for this test are based on the assumption that the head material properties of the one-fifth scale model and the tank car are the same. An additional assumption is that lading in all tests will be water (or a mixture of ethylene glycol and water for the cold temperature tests). Some of the significant variables of the one-fifth scale tests are as follows:

Mass model = mass full scale/125
Length Model = length full scale/5
Pressure Model = pressure full scale

The exact duplication of all scaled conditions in both the one-fifth scale and full scale tests are difficult, or not economically feasible. Table 1 gives a summary of full scale test car variables and dimensions which are the basis for those used in the full scale and one-fifth scale tank heads in this test program. Table 2 shows scaling dimensions utilized in this test program for the one-fifth scale and full scale puncture test.

TABLE 1. SUMMARY OF TEST CAR VARIABLES AND DIMENSIONS

Car Type and Spec.w/Seamless Head	Diameter	Material	"S" (ksi)	Head Thickness Req'd[1]	Head Thickness Actual
DOT 111A60ALW1 or 111A60ALW2	102"	B209-5052, 0 temper	25.0	0.500"	0.588"[2]
DOT 111A60ALW1 or 111A60ALW2	102"	B209-5052, 0 temper	27.0[3]	0.500"	0.588"
DOT 111A100ALW1 or 111A100ALW2	102"	B209-5052, 0 temper	25.0	1.020"	0.938"[2]
DOT 111A100ALW1 or 111A100ALW2	102"	B209-5052, 0 temper	27.0[3]	0.945"	0.938"
DOT 105A500W	102"	A516-70a or TC 128-70	70.9[4]	0.899"	0.813"
DOT 105A500W	102"	TC 128-70	81.0	0.813"	0.813"[2]
DOT 112A340W	120"	A516-70a or TC 128-70	70.9[4]	0.719"	0.688"
DOT 112A340W	120"	TC 128-70	81.0	0.688"	0.688"[2]
DOT 114A340W	120"	A516-70a or TC 128-70	70.9[4]	0.719"	0.688"[2]
DOT 114A340W	120"	TC 128-70	81.0	0.688"	0.688"[2]
DOT 105A300W	102"	A516-70a or TC 128-70	70.9[4]	0.540"	0.688"[2]

[1] - Per 49 CFR based on measured tensile strenth, see 49 CFR 179.100, 179.101 & 179.102 or 179.200, 179.201 & 179.202

[2] - Not used

[3] - Measured tensile strength of aluminum alloy used

[4] - Measured tensile strength of steel used

TABLE 2. SCALING DIMENSIONS
ONE-FIFTH SCALE AND FULL SCALE MODELS

Test Variable	Test Parameter Full Size	Target Dimensions 1/5 Scale/Full Scale	Actual Dimensions 1/5 Scale/Full Scale
Head Thickness:			
Type 111A60ALW1 AC[1]	1/2",5/8"	.100",.125",.188"/NA,.625"	.090",.115",.162"/NA,.619
Type 111A100ALW1 AC	15/16"	.188"/NA	.162"/NA
Type 105A500W CC[2]	13/16"	.163"/NA	.159"/NA
Type 112A340W LPGC[3]	11/16"	.138"/NA	.134"/NA
Tank Diameter:			
Type 111A60/100ALW1 AC	102" I.D.[4]	20.4" I.D./102" I.D.	20.4" I.D./102" I.D.
Type 105A500W CC	102" I.D.	20.4" I.D./NA	20.4" I.D./NA
Type 112A340W LPGC	120" I.D.	24.0" I.D./NA	24.0" I.D./NA
Head Shield Thickness	1/2" 5/8" 3/4"	.100"/.500" NA/.625" .150"/NA	.10"/1/2" Plate NA/5/8" Plate .158"/NA
Insulation Jacket Thickness	11 gage (.125")	.025"/NA	.041"/NA
Insulation Thickness:			
Urethane Foam	4.0"	.8"/NA	0.8"-1.0"/NA
Glass Fiber	4.0"	.8"/4.0"	0.8"-1.0"/4.0"
Ceramic Fiber	.5"	.1"/NA	.1"/NA
Impactor Mass:			
Ram Car	263,000 lbs ±5%	NA/263,000 lbs	NA/265,150 lbs
Drop Hammer	263,000 lbs ±5%	2,104 lbs/NA	2,119 lbs/NA
Reaction Car Weight	263,000 lbs ±5%	NA/263,000 lbs	NA/254,800 lbs
Backup Cars Weight	>480,000 lbs	NA/>480,000 lbs	NA/508,300 lbs

[1] Aluminum Car
[2] Chlorine Car
[3] Liquified Petroleum Gas Car
[4] Inside Diameter

3.0 **OBJECTIVES**

The primary objectives of this program are to:

a. Determine the puncture resistance of a standard (DOT Type 111) aluminum tank car relative to that of DOT Type 112/114 and 105 tank car designs

b. Evaluate the parameters affecting the puncture resistance of an aluminum tank car such as head thickness, jacket or head shield thickness, material type, and insulation conditions

c. Evaluate the effects of cold temperature on tank cars for puncture resistance

SECTION A

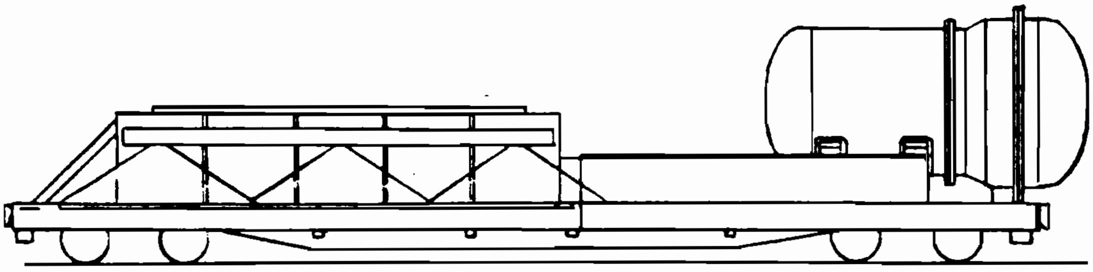
FULL SCALE MODEL TESTS

4.0 TEST IMPLEMENTATION

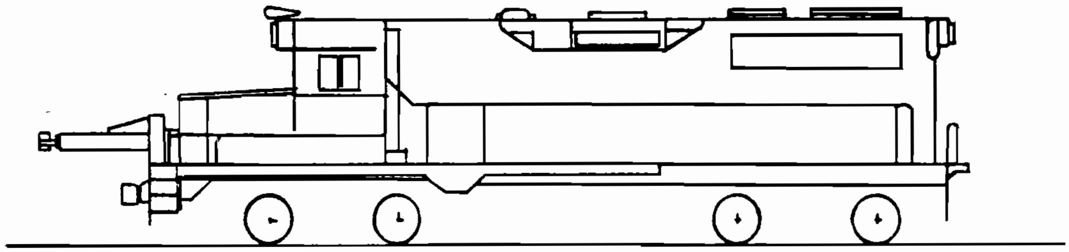
Full scale model impact tests involve a full-sized head assembly, exactly as produced for a commercial tank car, attached to a pressurized tank fixture and mounted to a railroad car. This tank/ car assembly is called the Reaction Car, and it is "backed-up" by three loaded freight cars. The head is then impacted by a specially constructed Impact Car, with a coupler connected to the end of a "beam." The coupler/ram assembly is installed at a preselected height.

The test is designed to resemble the 49 CFR 179.105-5 requirements, except for the differences between the tank volume of a full size tank car and that of the Reaction Car. Figure 1 shows a sketch of the Reaction and Impact Cars, and Figures 2 and 3 show related photographs.

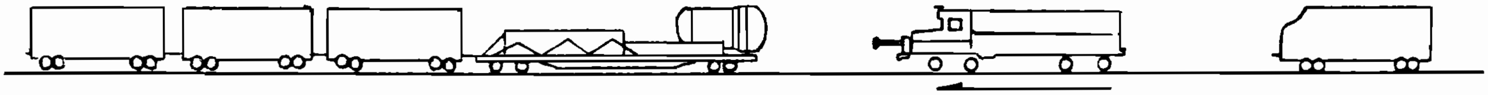
Testing of full scale model heads was performed on the Precision Test Track at the TTC. The track has a constant downward slope from north to south of .8689 percent. The Impact Car is positioned north of, and therefore higher than, the Reaction Car at selected locations and then released. The car accelerates by gravity to develop the desired speed at impact. Figure 4 shows a typical test configuration setup at the impact site.



Reaction Car



Impactor Car



Back-up Cars/Reaction Car

Impactor Car

Positioning
Locomotive

FIGURE 1. FULL SCALE TEST SKETCHES.

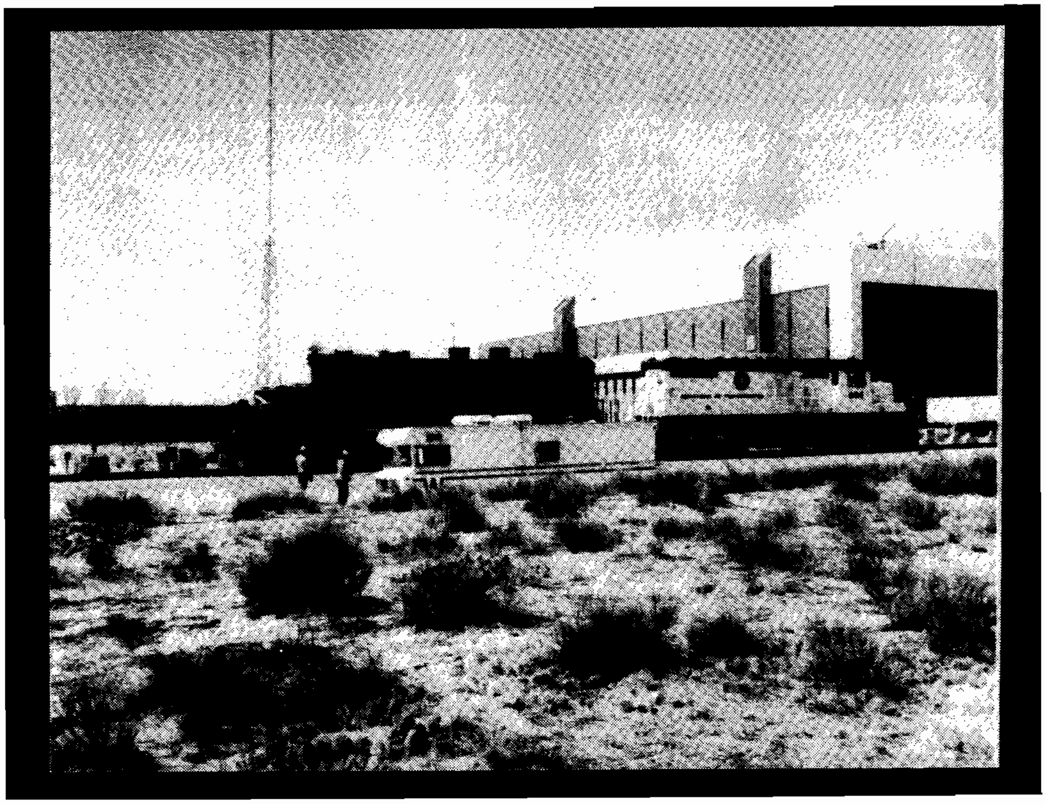


FIGURE 2. IMPACT CAR (LEFT) WITH POSITIONING LOCOMOTIVE.

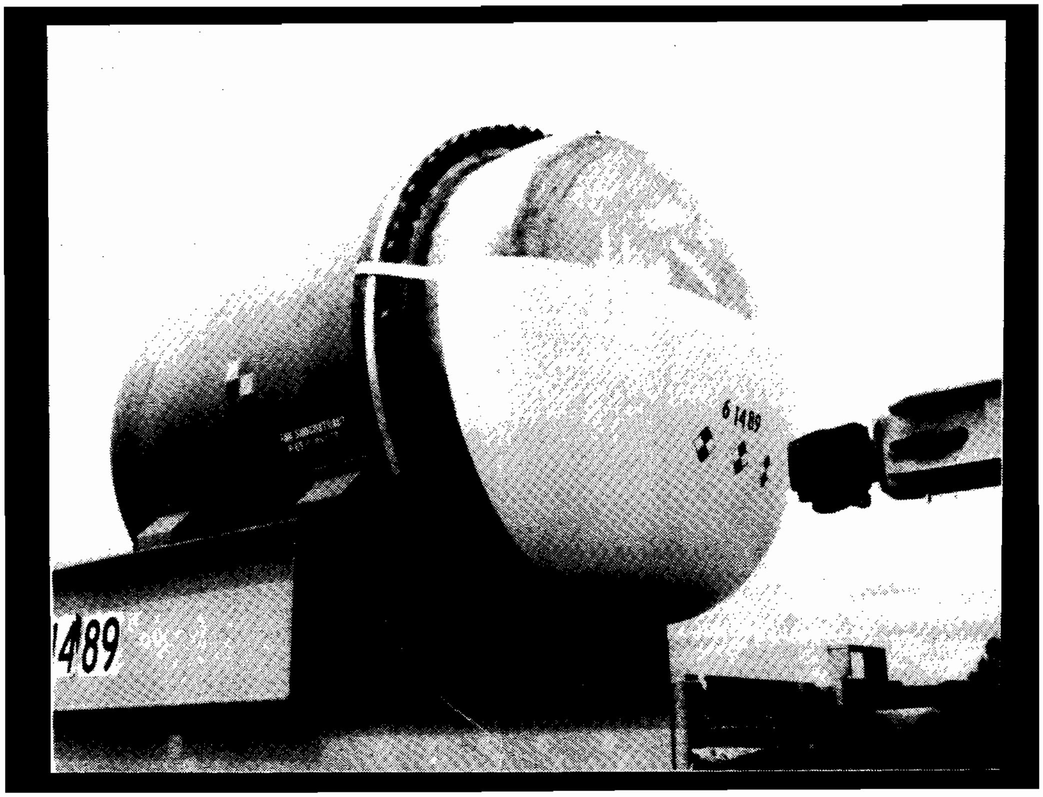


FIGURE 3. REACTION CAR PRESSURE VESSEL.

FIGURE 4. TYPICAL TEST SETUP - FULL SCALE TESTS.

In the full scale model test series, two test configurations were originally planned, but a third single test configuration was later added. The first test series, FA-10, simulated the DOT Type 111 aluminum tank car with a 5/8-inch-thick bare, unprotected head. The second test series, FA-20, simulated the same DOT Type 111 tank car with a 1/2-inch-thick head shield. And the third test, FA-30, simulated the DOT Type 111 tank car with a 5/8-inch-thick head shield. (See Table 3 for Test Matrix 2.)

The original plan was to conduct four impact tests, at varying speeds, for each of the two test series (FA-10 and FA-20) to establish a relationship between dent depth/puncture versus impact speed. The plan was changed, however, when it became apparent early in the testing that the puncture threshold of bare heads (FA-10 series) was very low (3 mph - 5 mph); and that the puncture threshold of 1/2-inch shield-protected heads (FA-20 series) was below the 18 mph minimum puncture speed requirement of 49 CFR 179.105-5.

TABLE 3. TEST MATRIX 2 - FULL SCALE MODEL IMPACT TESTS

Test Series	Car Type and Spec.	Head Thickness (in.)	No. of Heads	Shield Thickness	Pressure (psig)[1]	Insulation Type	Dent Depth (in.)	Test Velocity (mph)	Puncture (Yes/No)
FA-10	111A60ALW1	5/8	3	None	4	None	28.8	5.0	Yes
FA-20	111A60ALW1	5/8	2	1/2"	4	4" G.F.[2]	18.3	17.8	Yes
FA-30	111A60ALW1	5/8	1	5/8"	4	4" G.F.	28	17.5	No[3]

[1] psig = pounds per square inch gage
[2] G.F. = Glass Fiber
[3] Couplers of impact car and reaction car wedged together at impact; may have interfered with ram penetration depth. See Fig. 22 for photograph.

5.0 DESIGN AND FABRICATION

5.1 TEST CARS

Two test vehicles were designed and fabricated to perform this test. Drawings for the Impact Car and for the Reaction Car with pressure vessel can be found in TTC sketch files 84-47574-024 and 84-47574-023, respectively.

The Impact Car vehicle was a donated "scrap" locomotive obtained from the Union Pacific Railroad. A support structure was installed on the mainframe to attach the ram fixture (Figure 5). Total car weight was adjusted to the final test weight of 263,000 lbs ± 2 percent, as specified in 49 CFR 179.105-5. The traction motors were disconnected from the axles to reduce rolling friction.

The Reaction Car vehicle was a 100-ton rated flatcar. Structural steel modifications to the car and mounting arrangement of the pressure vessel were performed at TTC. Fabrication of the pressure vessel was performed by Richmond Tank Car Company, Houston, Texas.

5.2 TANK HEADS

The DOT Type 111 tank heads were a 2:1 ellipsoid of revolution with a 3-inch cylindrical flange extension. Material used was 5/8-inch-thick aluminum conforming to the American Society for Testing and

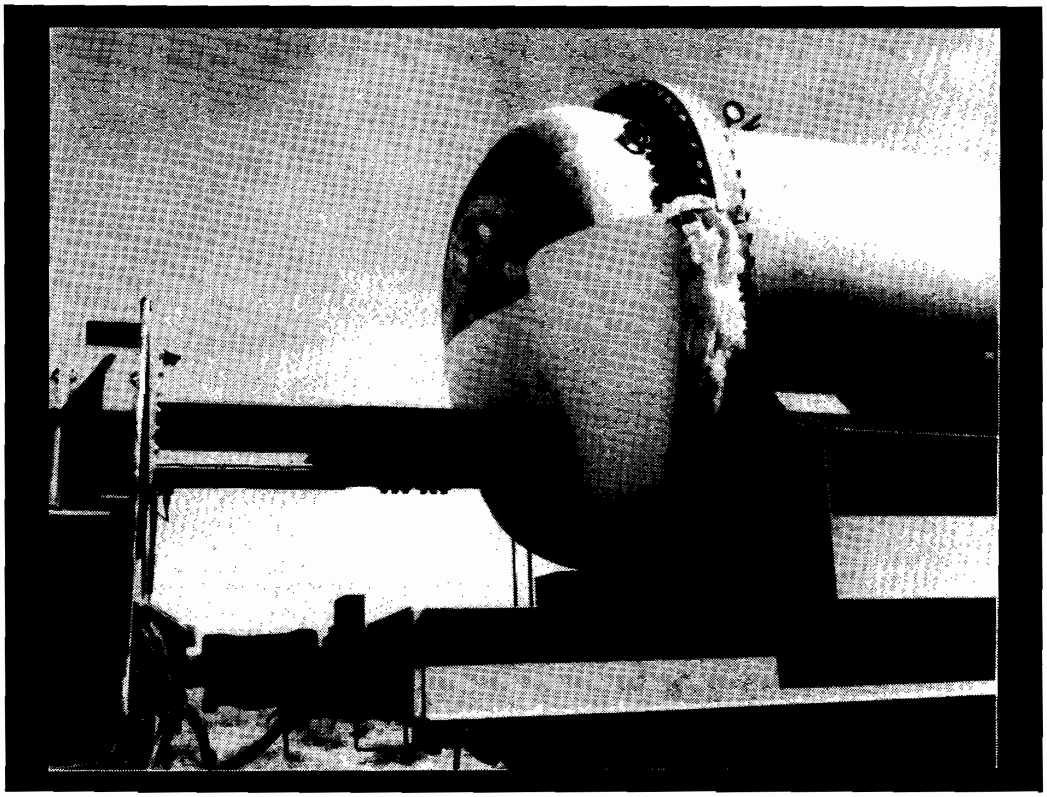


FIGURE 5. IMPACT CAR RAM AFTER IMPACT.

Materials (ASTM) B209,5052 alloy, HO temper. The heads were press formed from standard plate. No heat treatment was allowed after forming. The heads were fabricated to 102-inch inside diameter. The 5/8-inch-thick aluminum plate meets the minimum thickness requirement of 49 CFR 179.200-6 for DOT Specification 111A60ALW1 and 111A60ALW2 tank cars. The minimum plate thickness is calculated by the following formula:

$$t = \frac{Pd}{2SE}$$

where

d = Inside diameter in inches;

E = 1.0 for seamless heads;

P = Minimum required bursting pressure in psi;

S = Minimum tensile strength of plate material in psi (as prescribed in CFR 179.200-7);

t = Minimum thickness of plate in inches after forming.

Therefore, if:

d = 102"

E = 1.0

P = 240 psi

S = 25,000 psi

then

t = (240)(102)/(2)(25,000)(1.0) = 0.500"

In checking the thickness of two random heads at 16 places across each head, the smallest measurement across each head was .588 inches. Therefore, the thickness of the heads was well above the minimum required by the CFR.

5.3 FLANGE ASSEMBLIES

The flanges used were fabricated from 2 1/2-inch-thick aluminum alloy to American Water Works Association (AWWA) Class B pipe flange specifications. They were 102 inch nominal pipe size for DOT Type 111 heads. Gaskets used were 1/8-inch-thick, full-face type fabricated from Garlock No. 77005 asbestos material.

The flanges were welded to a short (3 inch long) 102 inch inside diameter cylindrical section of 5/8-inch aluminum alloy plate with no post weld heat treatment. The flange face was machined flat after welding it to the flange skirt. The tank head was then welded to the flange assembly. Again, no post weld heat treatment was performed on the head/flange assembly.

5.4 HEAD SHIELDS

Head shields were one-half of an ellipsoid, fabricated from a 121 3/8 inch inside diameter (I.D.) tank head, and split into equal halves. Material was AAR TC-128, Grade B (ASTM A612) steel. The head shields were normalized (heat treated) after fabrication.

Material thickness of the shields was either 1/2 inch or 5/8 inch, depending on the test series. The 5/8-inch-thick shield was an addition to the original Test Implementation Plan. An additional test series was created (FA-30) to accommodate the single test run using the 5/8-inch-thick shield.

Attachment brackets, used to hold the head shield in place, were designed to allow the shield to collapse onto the tank head with minimal restraint upon impact.

5.5 INSULATION

Glass fiber insulation blanket was used in the three tests where head shield protection was incorporated. It was applied to the inside surface of the shield using a spray-on adhesive. The insulation material used was manufactured by the Owens-Corning Corporation. It was 4-inch-thick, 1-pound density glass fiber blanket identified as Type At-420, "Tank Car Insulation Blanket."

5.6 RAM/COUPLER ASSEMBLY

The ram consists of a simulated rail car center sill with a coupler and draft gear assembly mounted on one end. The ram is mounted to a structural reaction frame at the front of the Impact Car, with height adjustments in 2-inch increments (Figure 5).

AAR Standard E couplers, catalog No. E60CE, with a Westinghouse Mark 50 draft gear, were used in the coupler assembly. The rotary operation mechanism was removed from the bottom of the coupler, and the knuckle was welded to the coupler body while locked in the engaged position. Couplers were replaced as they became distorted from impact.

6.0 MEASUREMENTS

Two data collection systems were used to process and record the dynamic conditions generated during each test. On the Impact Car, signal outputs were conditioned, digitized, and transmitted to a pulse code modulated (PCM) telemetry system in the Rail Dynamics Laboratory. The data was processed with a DEC PDP1134 computer system and recorded on tape; it was converted to engineering units and tabulated into maximum/minimum and average values with respect to time. A strip chart recorder was also used to monitor the test event. All data was converted to American Standard format using the VAX 11/780 computer for future data analysis by TSC.

Data collection for the Reaction/Backup Cars was conducted with the same Gould DAS 9000 system used for the one-fifth scale model tests. Instrumentation devices were wired directly to the data collection system with drop cabling. The Gould system utilized an IBM PC-XT computer and floppy disks. The Gould data collection system was referred to as the Wayside System. Both data collection systems sample at a rate of 10,000 times per second on each channel.

See Figure 6 for the instrumentation schematic showing measured static and dynamic conditions for the full scale configuration. Also see Table 4, Summary Test Instrumentation, which lists the type of instrumentation used on this project.

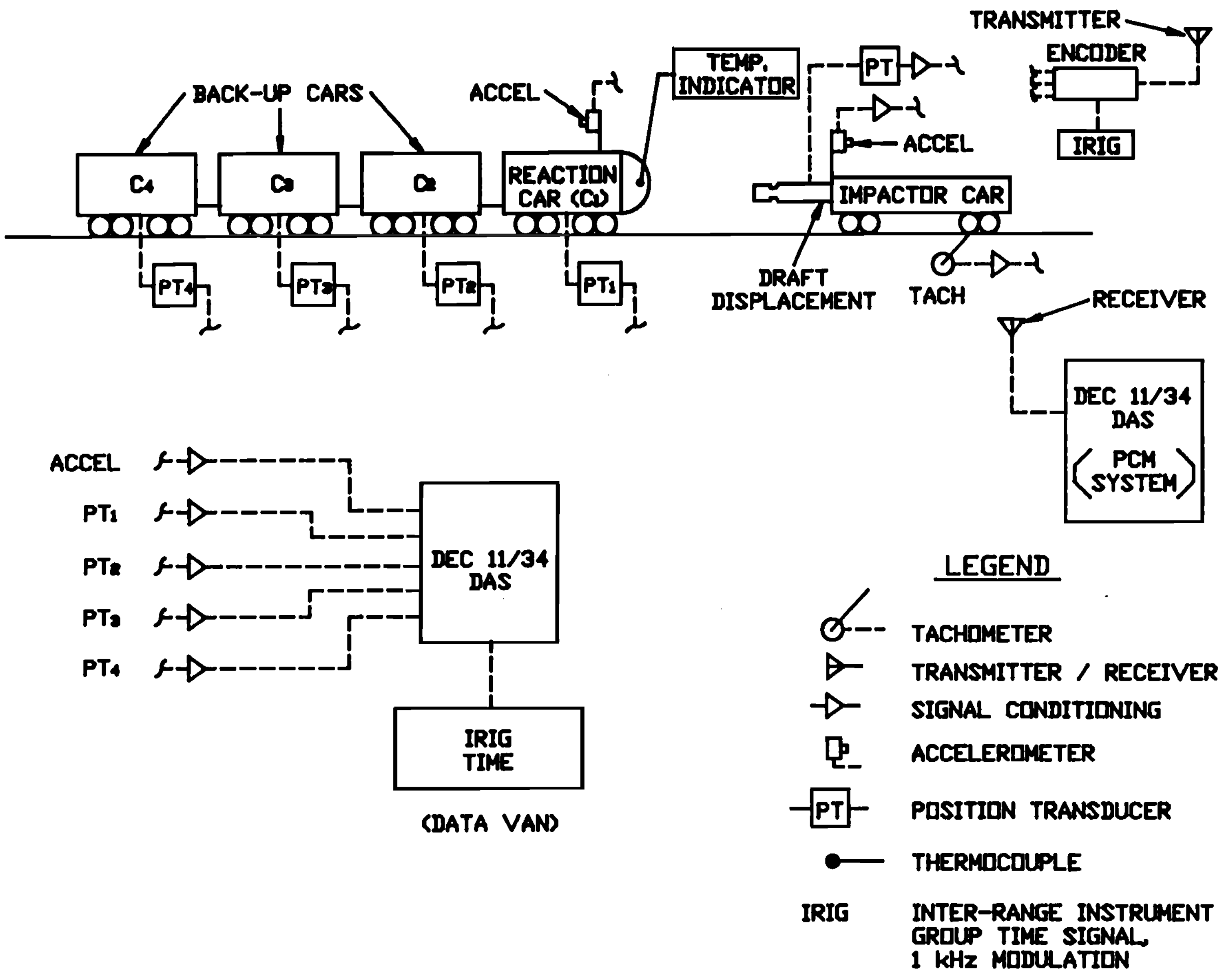


FIGURE 6. FULL SCALE TEST INSTRUMENTATION SCHEMATIC.

TABLE 4. SUMMARY - TEST INSTRUMENTATION

Parameter	Measurement Frequency Response	Transducer Type/Manufacturer	Measurement System Accuracy	Comment
Impact Car/ Reaction Car	500 Hz	Strain Gage Accel/ ENDEVCO	±1.55 g	Assume 25 g Range
Impact Car	200 Hz	Tachometer/Air Pax	±.04 mph	20 mph Full Scale Range
Ram Coupler Displacement	12 Hz	Potentiometer/Celesco	±.13 inch	±5 inch Full Scale Range
PCM/Wayside System Event Marker	100 Hz	Photo Cell/Warner	0-4 inch	
Test Car Mass	DC	Track Scale	±.14% ± 35 lbs	
Reaction Car/ Backup Cars	>2 Hz	Potentiometer/Celesco	± 2.1 inch	Assume 250" Full Scale Range
Tank Temperature	DC	Surface Thermocouple/ Omega	±5°F	
Tank Pressure Gage	DC	Test Gage/Omega	±.5 *psig	
Tank Pressure	0-1 kHz	Strain Gage Transducer/ Bell & Howell CEC 1000	±1.8 psig	Assume 100 psig Starting Pressure

* psig = pounds per square inch gage (pressure)

6.1 TEMPERATURE

A thermocouple was attached to the exterior underside of the pressure vessel. Temperature readings were taken prior to impact and recorded on the test log. The tank head temperature varied between 53.1°F and 64.9°F for series FA-10, and 45.8°F and 56.3°F for series FA-20. The temperature of the FA-31 test was 58.9°F. The pressure vessel was normally filled at least 24 hours prior to the test, which allowed the liquid and head to approach ambient temperatures.

6.2 TANK PRESSURE

A pressure gage was mounted on the top of the pressure vessel for visual observation of tank pressure. One pressure transducer was also installed at the top of the tank.

The pressure vessel was filled with water to a 90 percent full condition at ambient pressure in all three series. The pressure transducer was adjusted to a zero reading. The vessel/head assembly was then pressurized to 4 pounds per square inch gage pressure (psig) static, as indicated by the top pressure gage. Dynamic pressure conditions, occurring during the test, were then recorded with the wayside data collection system. Initial, peak, and final test pressures were recorded on the test log.

6.3 IMPACT LOCATION

Impact height was set at 21 inches plus or minus 1 inch above the bottom side of the sill (outside edge of tank) to the center line of the coupler head. Bolt spacings on the ram's structured support frame allow for adjustment in 2-inch increments. Average actual height for the six DOT Type 111 tests was 20 5/8 inches (Figure 7).

6.4 IMPACT ACCELERATION/DECELERATION

The accelerometer for the Impact Car was mounted on the car's mainframe, in the deep web section, where beam flexure reactions are not a problem. The accelerometer for the Reaction Car was mounted on top of the pressure vessel, near the back end.

6.5 DENT SHAPE

A linear profile template was used to measure the formation of the dent at the center of the head profile and the corresponding coupler center line. Dent depth distances were measured between the tank head and template curve along scribed lines, parallel with the tank cylindrical center line. Measurements were taken at 7 1/2-inch increments starting at the tank bottom and progressing to the center (Figures 7 and 8). All measurements taken were noted on the test logs. Maximum dent depth was measured both parallel

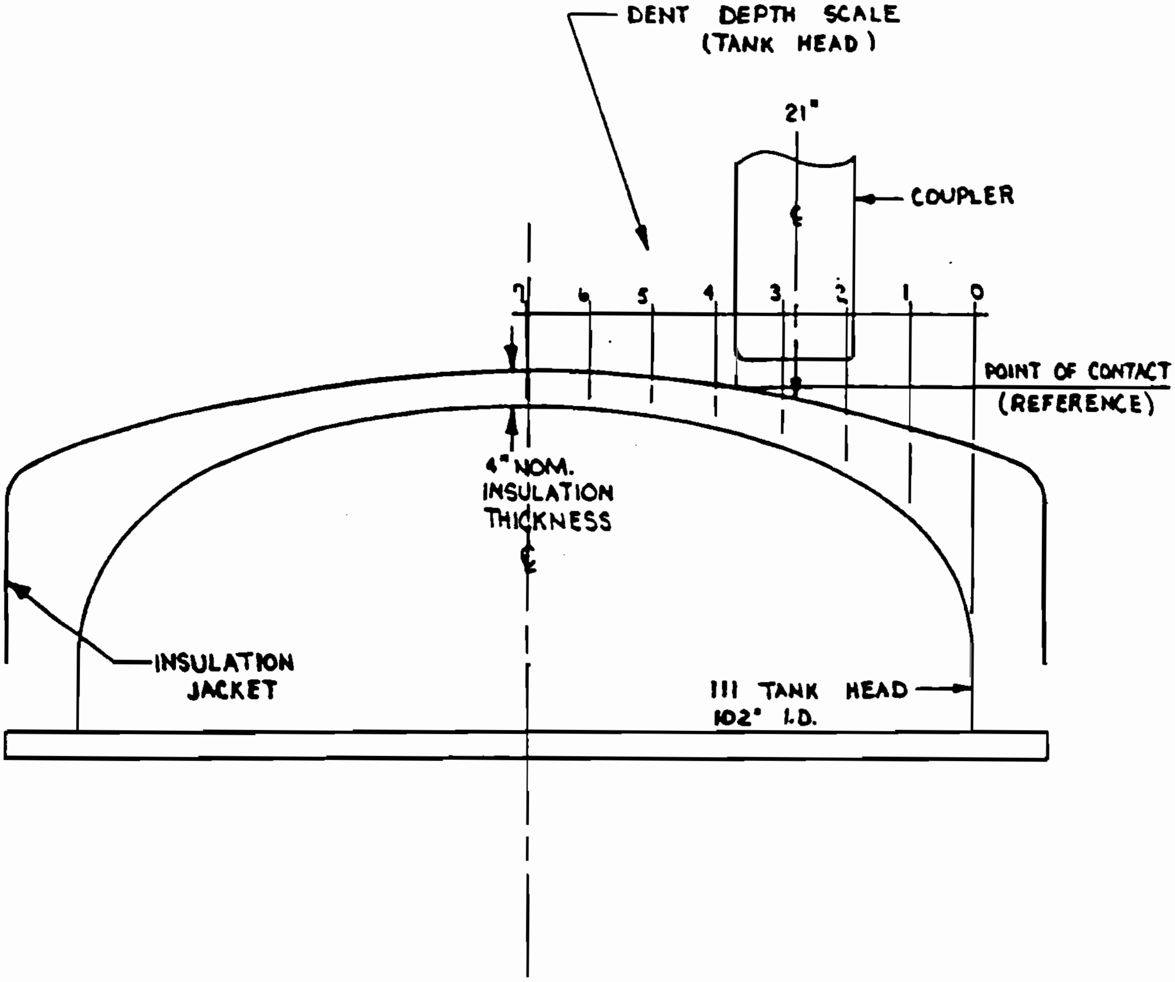


FIGURE 7. FULL SCALE HEAD MEASUREMENT SCALE.

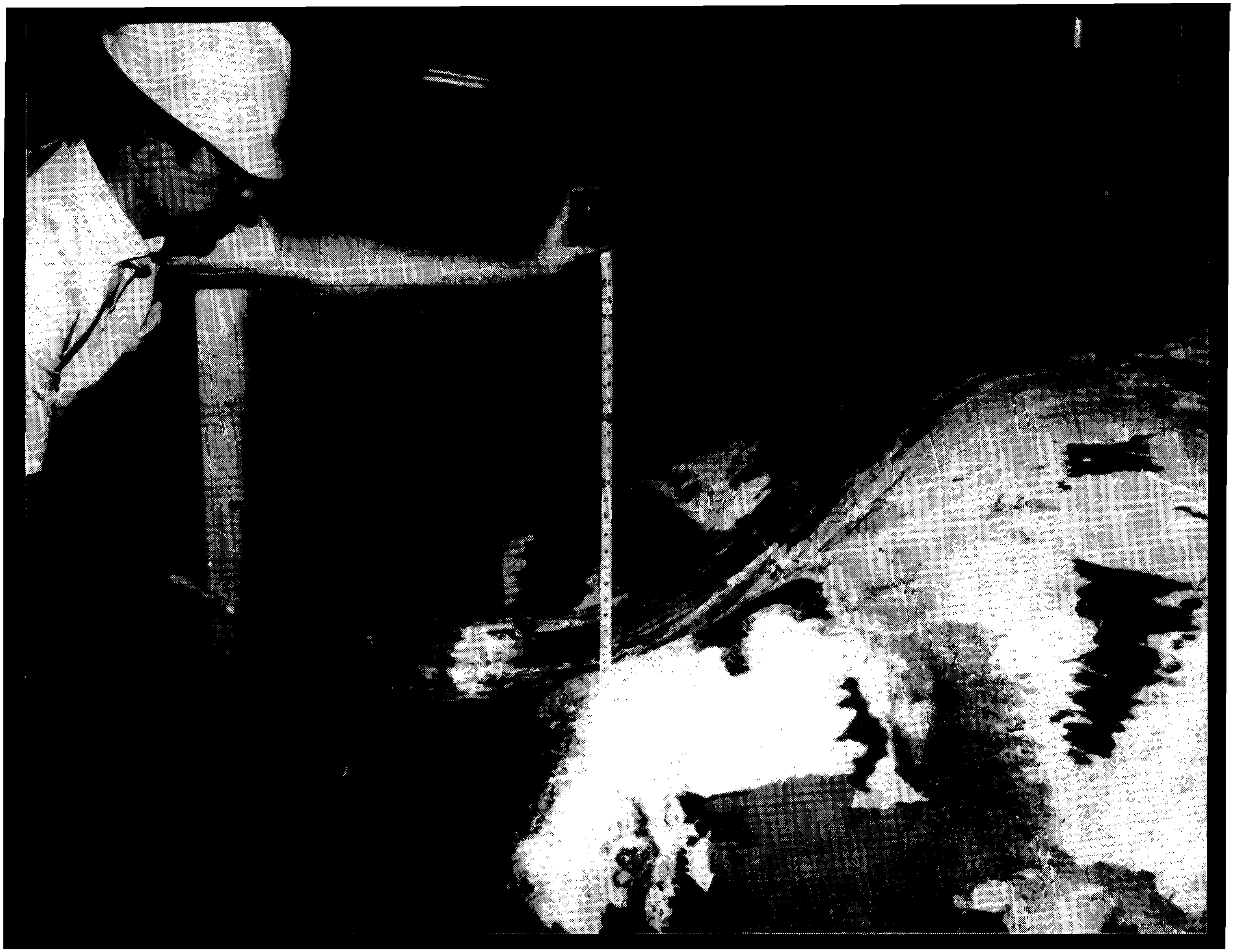


FIGURE 8. FULL SCALE PROFILE TEMPLATE - USED TO MEASURE DENT DEPTH.

to the cylindrical center line, and tangent to the original tank head profile for comparison purposes. The maximum parallel (depth) measurement was used on the dent depth versus impact velocity graphs.

6.6 TANK HEAD THICKNESS

Two random tank heads were checked for proper thickness with an ultrasonic digital thickness gage. Results of these tests can be found in TTC engineering sketch file 87-77506-113. No discrepancies were found. See Table 1 for further reference.

6.7 MASS OF TEST CARS

Cars were weighed on TTC track scales for weights listed on the test logs. See Table 1 for a recap of vehicle test weights. Backup cars were 100-ton rated hopper cars, partially loaded with track ballast material.

6.8 IMPACT VELOCITY

The velocity was measured with a tachometer mounted on the second wheel/axle set at the front of the Impact Car. The average speed reading at moment of impact was used as the "impact speed" and was recorded on the test log.

A backup velocity/measuring system was also used during each test to compare with the tachometer/PCM system. This backup system consisted of two automatic location devices (ALD's) and a timing clock. A target mounted on the Impact Car activated the ALD's, with the elapsed time between the two recorded. Readings between the two systems were within 1 percent of each other.

6.9 DISPLACEMENT OF REACTION/BACKUP CARS

Positions of the Reaction Car and the three backup cars were measured with respect to time using CELESCO Model PT-101-250-A position transducers. Static hand measurements were also taken after final movement to verify final displacement readings, and to record travel distances when the range of the position transducers was exceeded. Final distances were recorded on the test log. Dynamic displacements are recorded on floppy disk files stored in TTC engineering sketch file 87-77506-113.

6.10 PHOTOGRAPHY

Color photographs documenting head assembly construction, test configuration, instrumentation, and dent/puncture formations were taken with a large format camera for each test. Print negatives are on file at the TTC Photography Department. One documentary camera and four high speed cameras were used during each impact. Figure 9 is a schematic layout of the photography used in these tests.

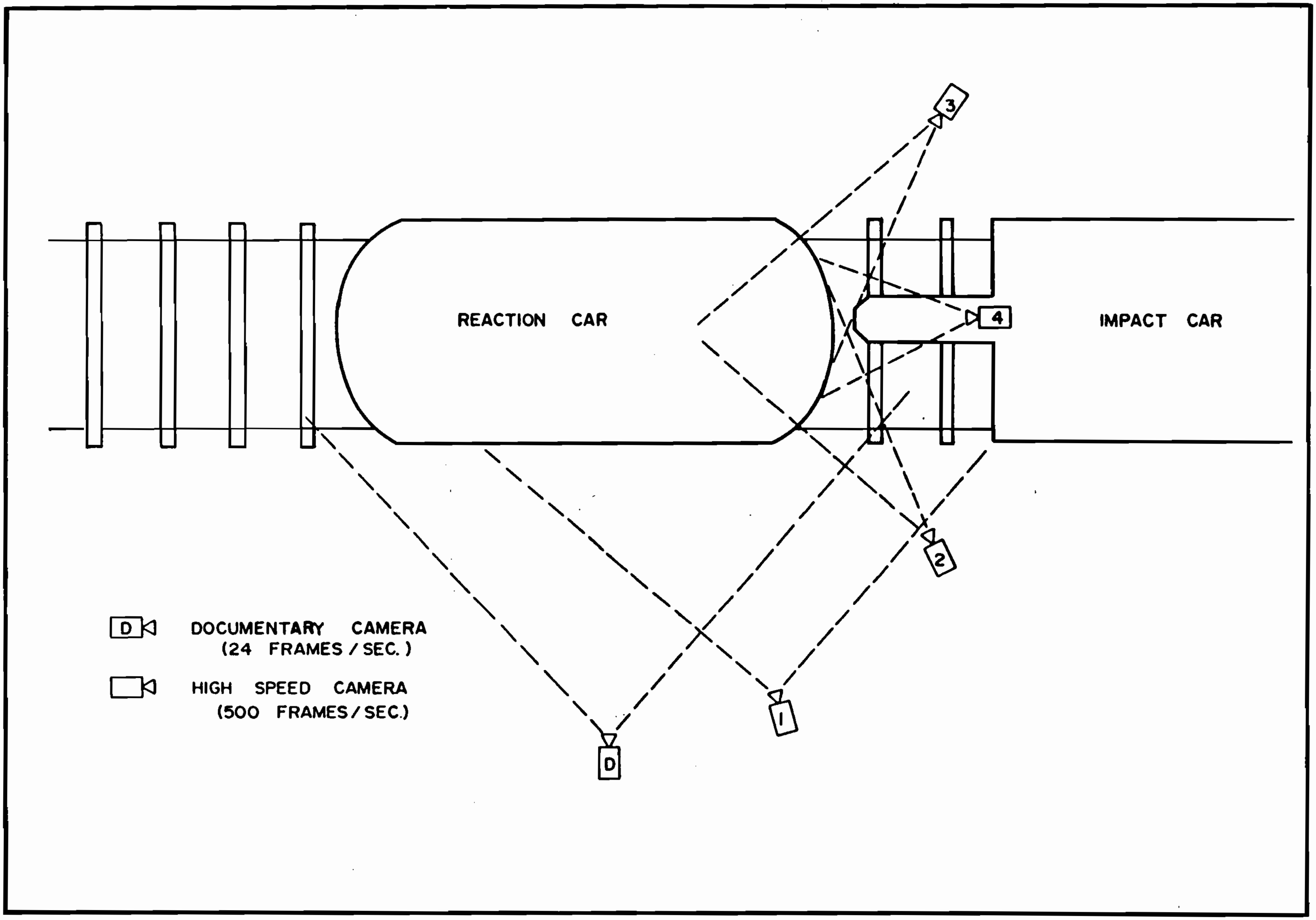


FIGURE 9. PHOTOGRAPHY LAYOUT - FULL SCALE TESTS.

6.11 MATERIAL TESTS

The mill tests and material certification of the raw material were received from ALCOA Aluminum Company and Gulf Railcar, Inc. The certification indicated that the heads were hot formed at 650oF. No heat treatment process was conducted on the heads after the forming operation.

Test samples were taken, before the hot forming process, by the subcontractor from the tank head material in both the parallel and perpendicular rolling directions. The tensile testing, conducted in conformance with ASTM A370 test methods, was performed by W. H. Company, consulting engineers, Houston, Texas.

Tensile tests were also conducted on material samples taken from a selected tank head after impact testing. The samples were prepared at the TTC and tested by Pittsburgh Testing Laboratory. These tests were also performed under ASTM A370 test methods.

Tensile strength tests were nearly the same for pre- and post-test material specimens. However, an exception was the yield strength results from the post-test material which were 30 percent to 40 percent higher than those of the pre-test material. A possible explanation for this is that work hardening of the aluminum material took place during the head press-forming process, without stress relief. Actual material test documents can be found in TTC engineering sketch file 87-77506-113.

The following is a recap of test data for samples taken from tank heads after impact testing:

Mechanical Properties	ASTM B-209 (Alloy 5052, 0 Temper)	Post Test Average of Tank Head Sample
Tensile Strength	25-31 *Ksi	27.6 Ksi
Yield Strength	> 9.5 Ksi	16 Ksi
Elongation in 2 in.	> 19%	35.5%

*Ksi = thousand pounds per square inch

In general, test samples taken perpendicular to the direction of roll gave higher values for tensile and yield strength, with lower percent elongation, than those taken parallel to direction of roll. The difference in yield strength between the two rolled directions was approximately 10 percent. The difference in tensile strength was approximately 3 percent.

7.0 RESULTS - FULL SCALE

The most important result derived from these puncture resistance tests is the relationship of the dent depth, or puncture, with respect to impact velocity; Figures 10 and 11 show these relationships. Figure 10 gives the results of the bare head tests, and Figure 11 gives the results of the shield protected heads.

Dent depths indicated on the charts are the maximum depths, as measured in accordance with Section 6.5 of this report. Table 2 is a summation of test parameters for each test series, and the puncture threshold velocity determined in each of those series.

Of the six full scale aluminum heads tested in this program, only two variables were changed from the baseline bare head configuration: 1) the addition of a head shield with insulation, and 2) the thickness of the head shield.

7.1 DOT TYPE 111 ALUMINUM - BASELINE CONFIGURATION

Test series FA-10 represented the baseline bare head configuration of the full scale tests. The corresponding puncture resistance curves of the three impact tests in this series are presented in Figure 10. The test results show very low puncture resistance for the bare heads.

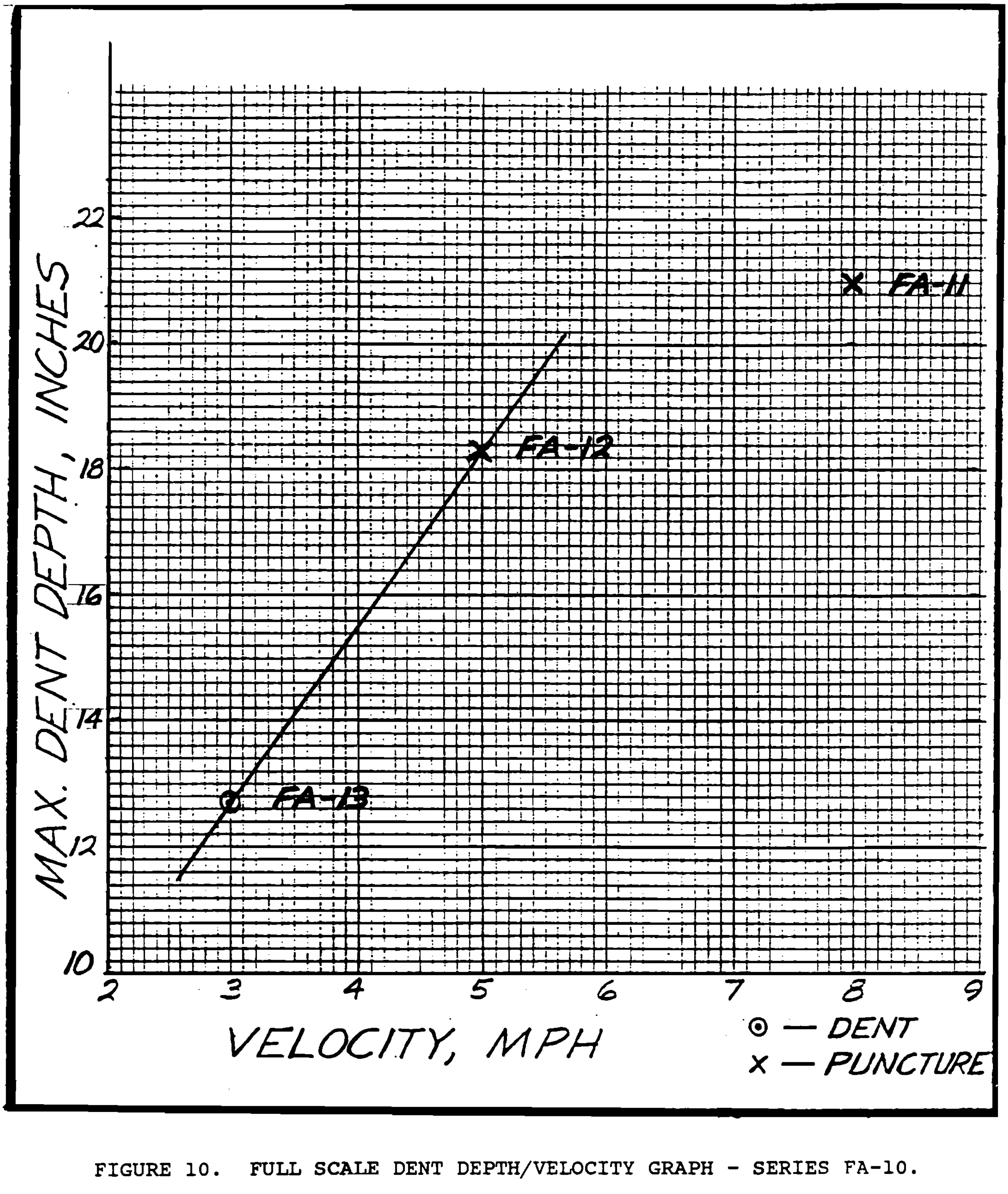


FIGURE 10. FULL SCALE DENT DEPTH/VELOCITY GRAPH - SERIES FA-10.

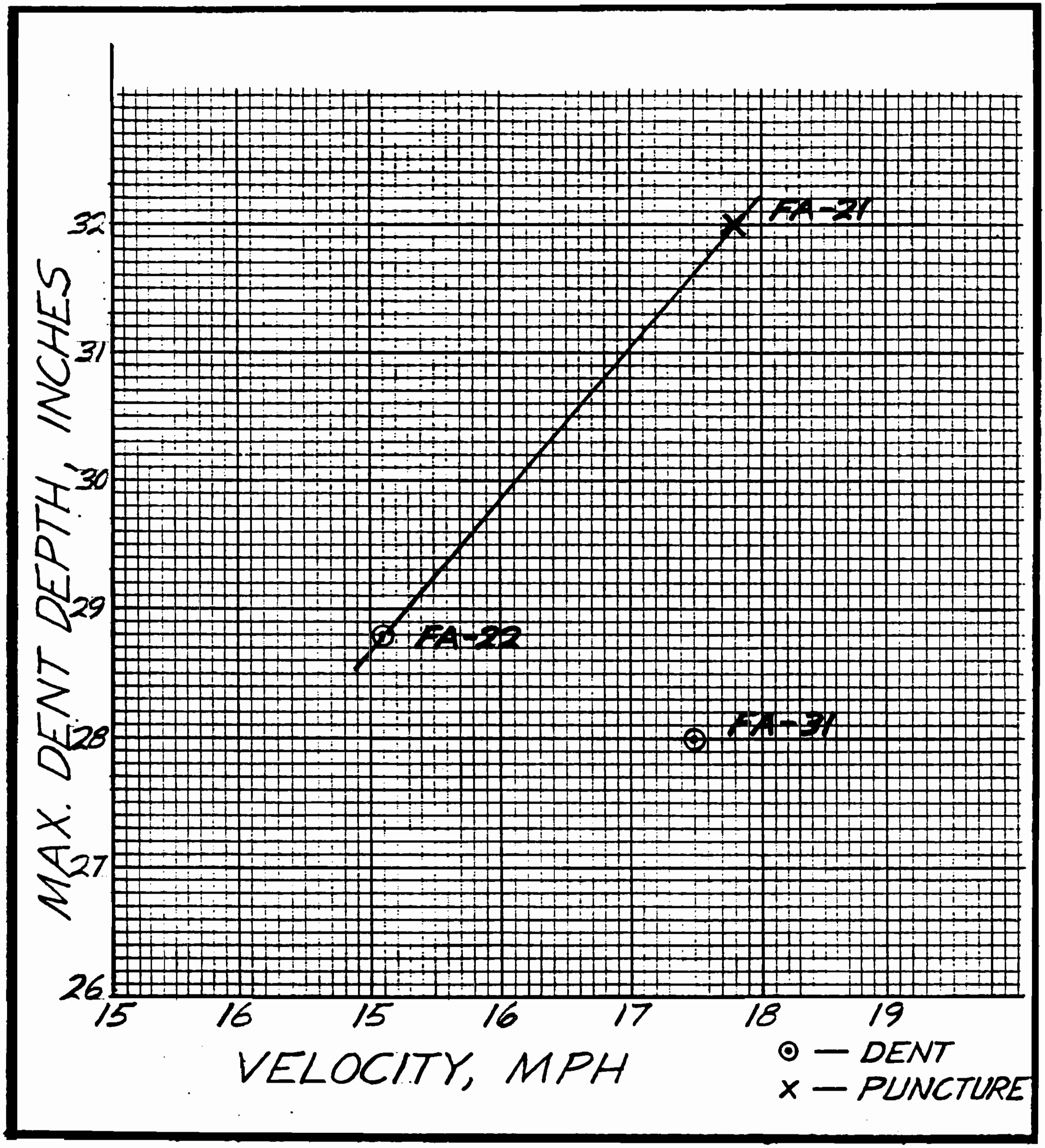


FIGURE 11. FULL SCALE DENT DEPTH/VELOCITY GRAPH - SERIES FA-20 AND FA-30.

7.1.1 **Test No. 1**

In the first test, FA-11, the head was impacted at a speed of 8 mph (Figure 12). As shown in the photograph, a full puncture of the coupler through the head was the result. The head failure was initiated by shearing along the top of the coupler knuckle and top corner of the jaw contact points. A new coupler was installed on the ram prior to this impact test.

In comparison, a full puncture of the coupler occurred at only 4 mph for the one-fifth scale tests of the same configuration and test variables (DA-03).

7.1.2 **Test No. 2**

In the second test, FA-12, the head was impacted at a speed of 5 mph (Figures 13 and 14). These photographs show that full penetration of the coupler did not occur through the head. However, two horizontal shear cracks at the coupler impact area did occur, as shown in Figure 14. This slight puncture of the head would appear to be very near the puncture threshold velocity.

In the related one-fifth scale tests (DA-03), the puncture threshold was just under 1.5 mph. Downward movement of the coupler, combined with compression of the draft gear during impact, may contribute to higher full scale puncture thresholds. The scaled coupler of the drop hammer tests is very rigid.

FIGURE 12. 111 BARE HEAD FA-11 PUNCTURE - IMPACT SPEED 8.0 MPH.

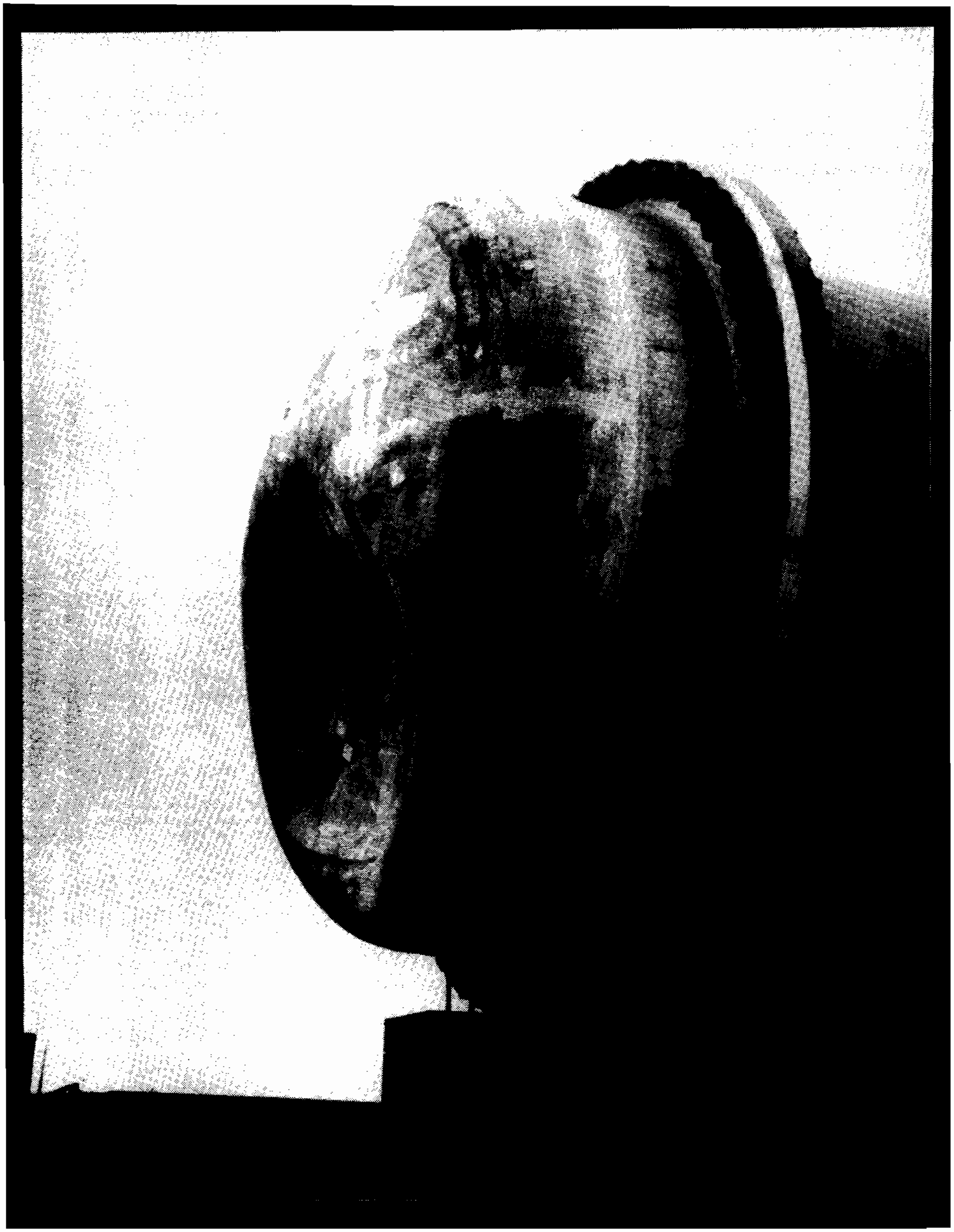


FIGURE 13. 111 BARE HEAD FA-12 PUNCTURE - IMPACT SPEED 5.0 MPH.

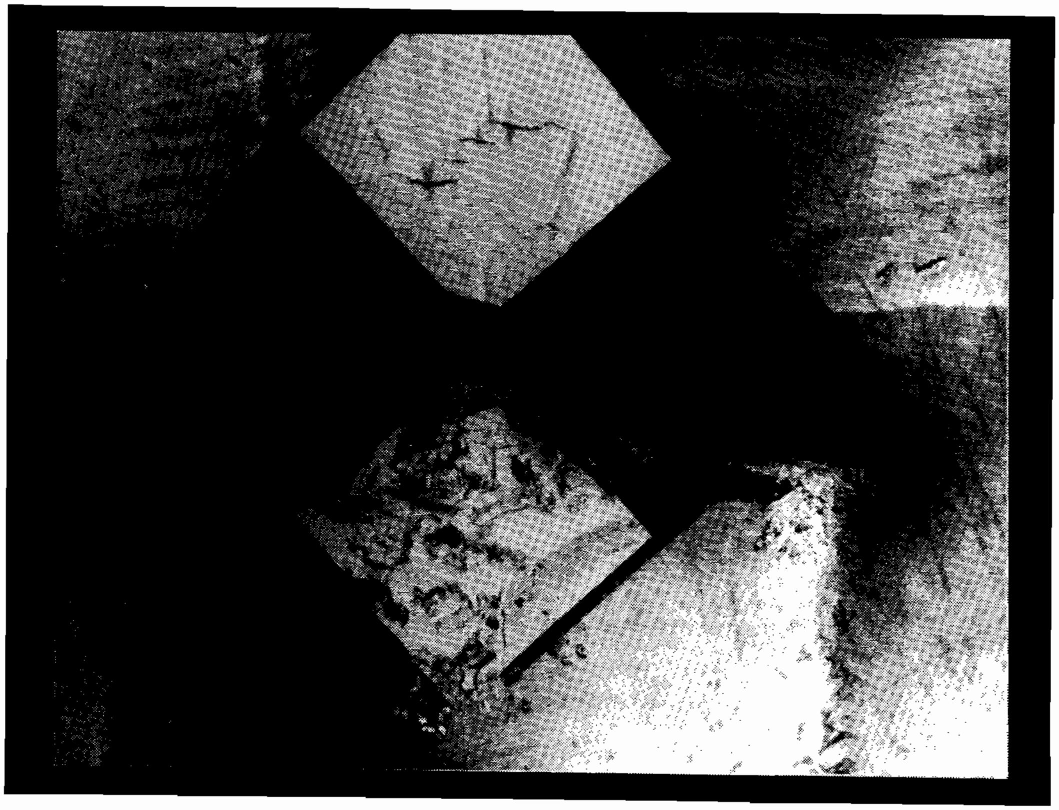


FIGURE 14. FA-12 HEAD PUNCTURE CLOSEUP - TWO HORIZONTAL SHEAR CRACKS.

7.1.3 **Test No. 3**

The third test in the baseline series (FA-13) was conducted at an impact velocity of 3 mph (Figure 15). No puncture occurred in this test. The puncture threshold is therefore between 3 mph and 5 mph.

In the related one-fifth scale test series, the velocity at which no puncture would occur is somewhere below 1.5 mph.

7.2 **DOT SPECIFICATION TYPE 111 ALUMINUM WITH HEAD SHIELD**

Test series FA-20 and FA-30 represented the shield-with-insulation protected configuration of the full scale tests. The corresponding puncture resistance curves of the two impacts in FA-20 and the single impact in FA-30 are presented in Figure 11.

As expected, the test results show much higher puncture thresholds than the bare head configuration. However, the tests in series FA-20, which used the 1/2-inch-thick steel shield, did not perform to the 18 mph minimum requirement of 49 CFR 179.105-5. And the results of the single test in series FA-30, which incorporated a 5/8-inch-thick steel shield, are inconclusive as discussed in Section 7.2.3.

FIGURE 15. 111 BARE HEAD FA-13 DENT FORMATION - IMPACT SPEED 3.0 MPH.

7.2.1 **Test No. 1**

In the first test, FA-21, the head was impacted at a speed of 17.8 mph (Figures 16 and 17). As can be seen in the photographs, a full puncture of the coupler through the shield and head was the result. Also, severe folding and pinching of the aluminum head at the bottom sill area occurred much the same as in the related one-fifth scale tests. The head failure was initiated by shearing along the outside edge of the coupler jaw contact points. There was no evidence of coupler shank bending, as was experienced in a previous test program of steel heads. A new coupler was installed on the ram prior to this test run.

In comparison with the one-fifth scale tests of the same configuration and test variables (DA-07), a crack developed in a weld seam at the bottom sill area during an impact speed of 12 mph. However, there was no puncture in the impact area.

7.2.2 **Test No. 2**

In the second test, FA-22, the head was impacted at a speed of 15.1 mph (see related Figures 18 and 19). As can be seen from the photographs, no puncture occurred in the head. Once again, however, severe deformation of the head in the sill area is evident. A shear line was visible through the head shield along the bottom knuckle edge contact point, and a 1/8-inch separation existed along the shear line on the inside face of the shield.

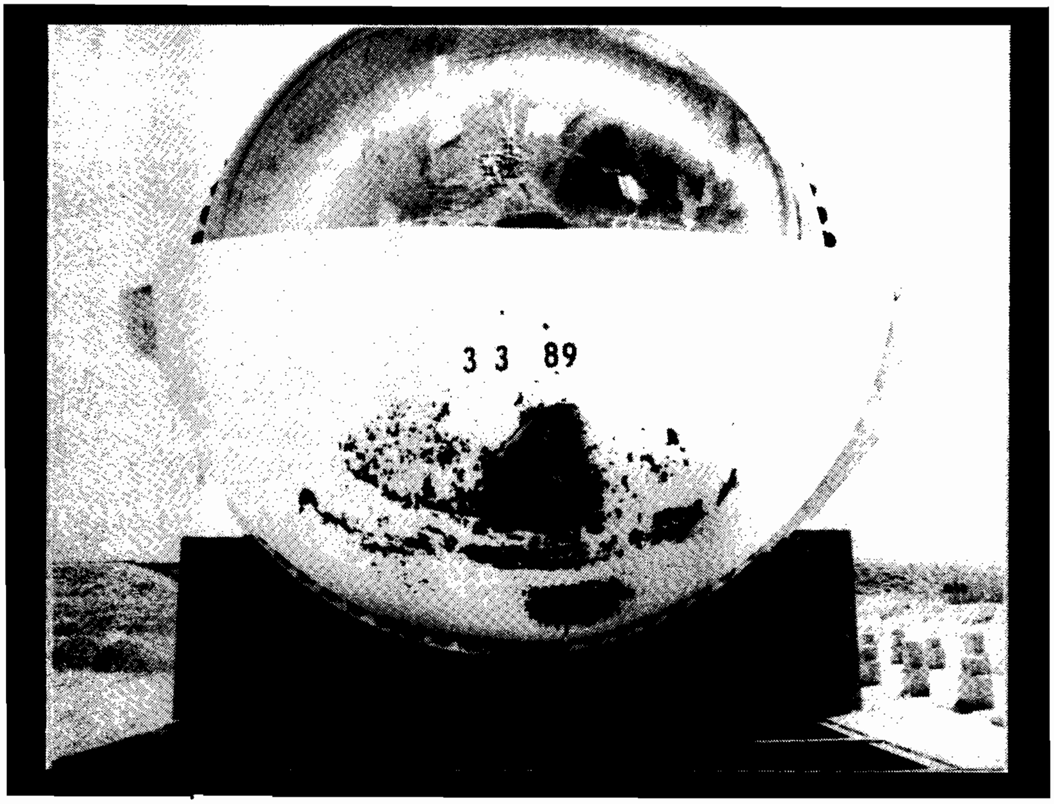


FIGURE 16. 111 SHIELDED HEAD FA-21 PUNCTURE - IMPACT SPEED 17.8 MPH - 1/2"-THICK SHIELD.

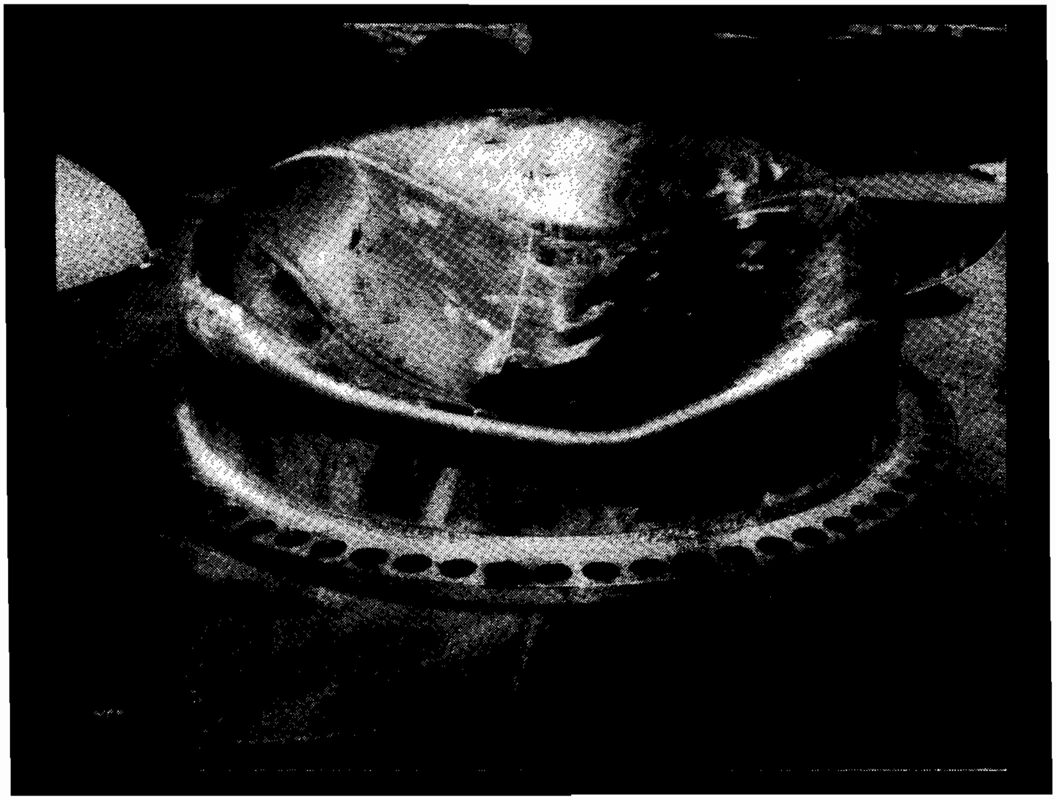


FIGURE 17. FA-21 HEAD, SHIELD REMOVED - NOTE DEFORMATION AT SILL AREA.

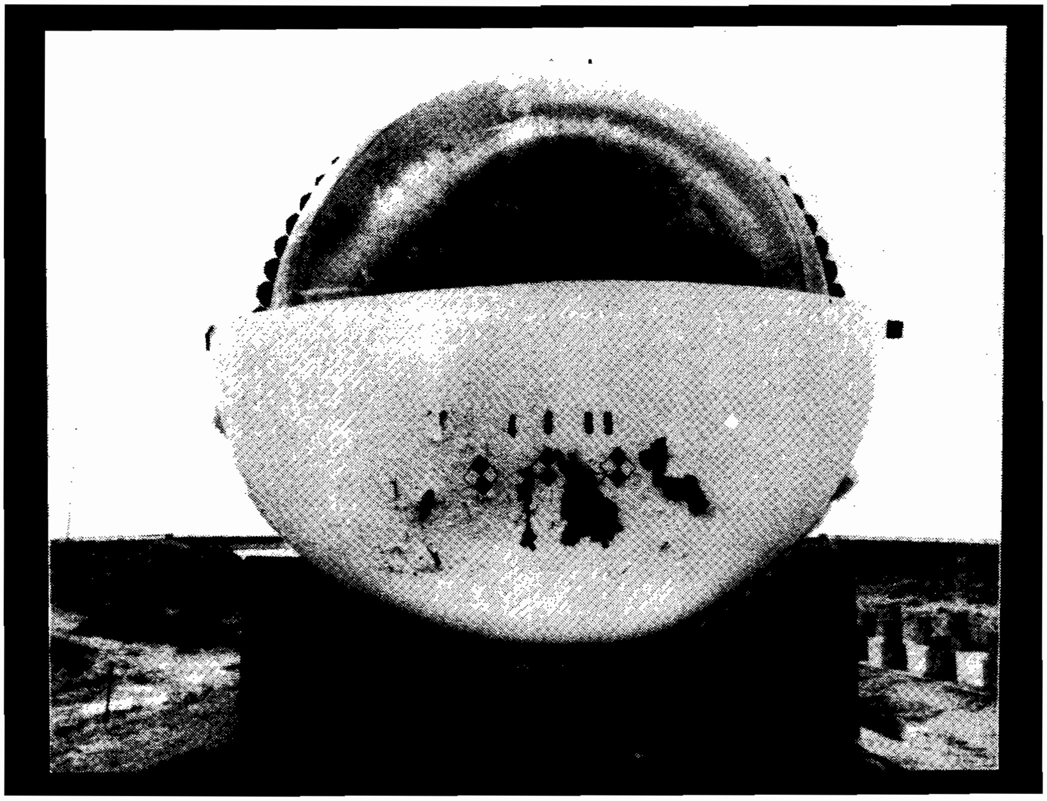


FIGURE 18. 111 SHIELDED HEAD FA-22 DENT FORMATION - IMPACT SPEED 15.1 MPH - 1/2"-THICK SHIELD.

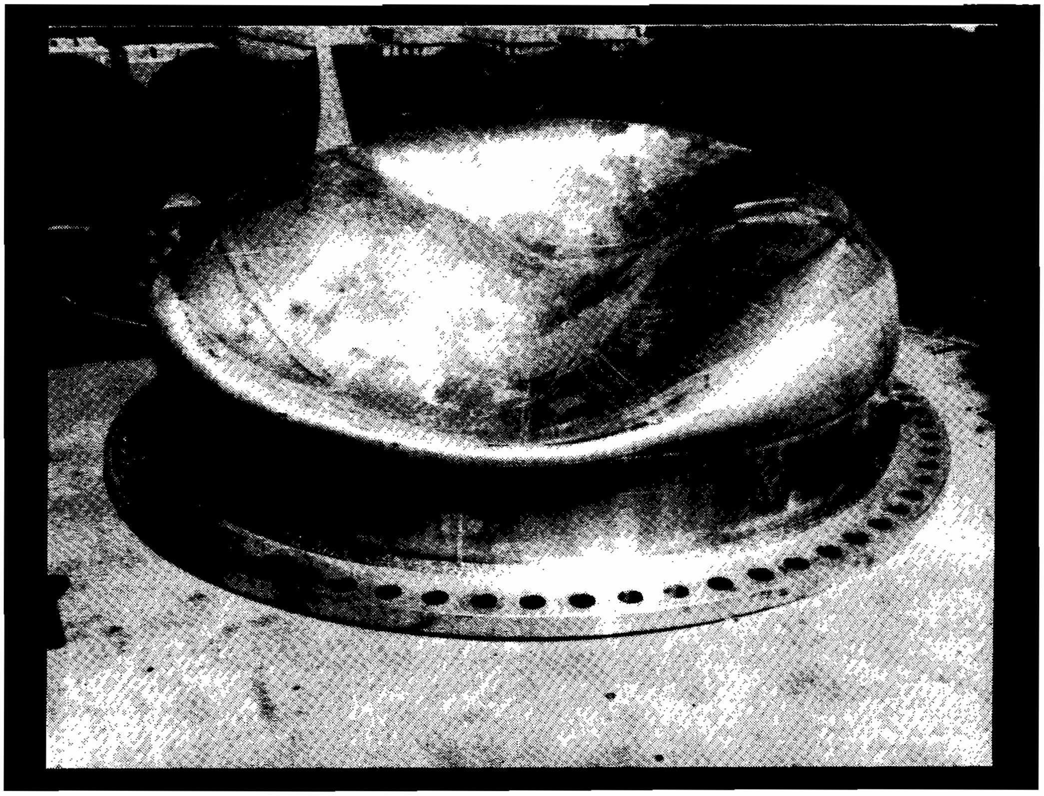


FIGURE 19. FA-22 HEAD, SHIELD REMOVED - NOTE DEFORMATION AT SILL AREA.

This puncture threshold speed of between 15.1 mph and 17.8 mph compares favorably with results in a previous test program on full scale Type 105 steel heads with 1/8-inch-thick jackets. The puncture threshold was near 15.1 mph. The puncture threshold of Type 112/114 steel heads, equipped with 1/2-inch-thick shields, was around 25 mph in the same previous test program.

7.2.3 **Test No. 3**

The third test, FA-31, incorporated a 5/8-inch-thick steel shield because it was now evident that a 1/2-inch shield would not survive the proposed minimum impact speed requirement of 18 mph. This test was conducted at a speed of 17.5 mph (Figures 20 and 21).

No puncture occurred in this test. Deformation at the bottom sill area was again pronounced. However, it was noticed that the coupler knuckles on the Impact Car and Reaction Car were closed prior to and during the impact. After the impact, it was found that the couplers were wedged together and not fully coupled (Figure 22). It was suspected that the couplers' draft gear may have bottomed-out at impact, interfering with ram penetration depth. Therefore, the results may not be accurate and a retest would be recommended.

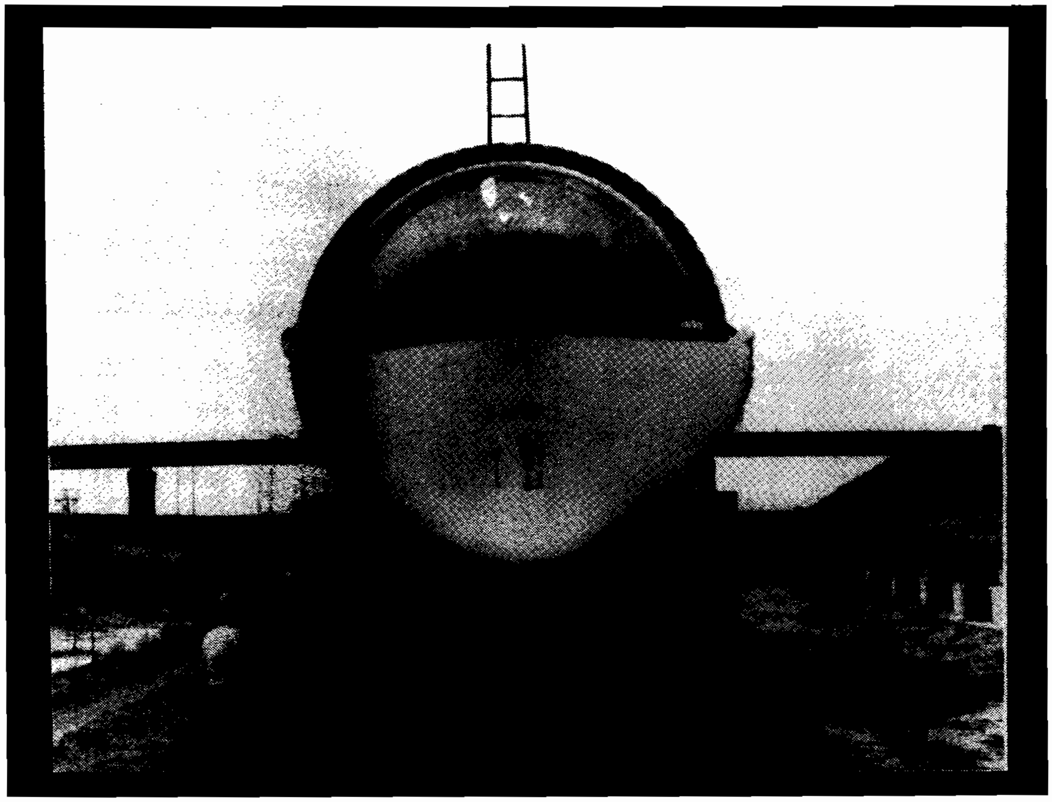


FIGURE 20. 111 SHIELDED HEAD FA-31 DENT FORMATION - IMPACT SPEED 17.5 MPH - 5/8"-THICK SHIELD.

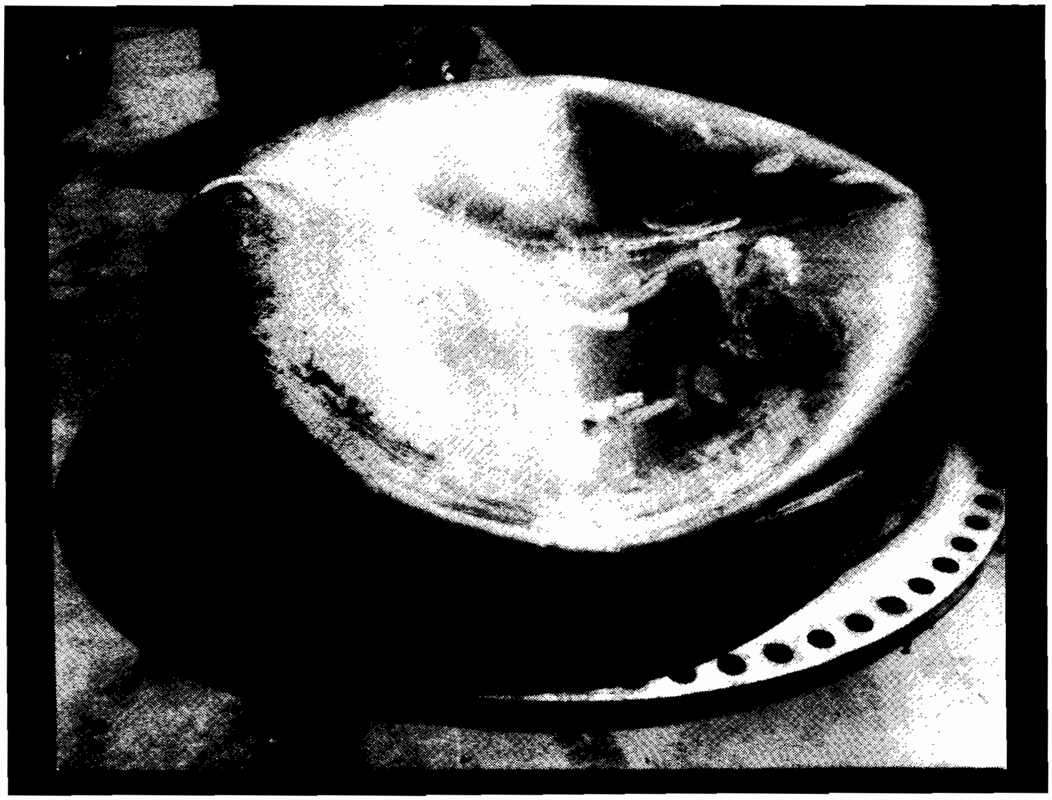


FIGURE 21. FA-31 HEAD, SHIELD REMOVED - NOTE DEFORMATION AT SILL AREA.

FIGURE 22. CLOSED COUPLERS IN FULL SCALE TEST FA-31.

8.0 SUMMARY

This tank car puncture test was composed of six impact tests on full scale DOT Specification, Type 111 aluminum tank heads. All six heads were 5/8-inch-thick 5052 aluminum alloy. Three tests were of a bare head configuration, and three were configured with steel head shields and 4-inch-thick fiberglass insulation. They were conducted according to the requirements specified in the CFR, Title 49, Part 179.105.5 for steel tank cars. The one exception is that the internal pressure was reduced from 100 psi to a nominal 4 psi for aluminum.

For the bare aluminum head configuration, the head punctured at a minimum speed of 5 mph. There was no puncture at 3 mph. The threshold puncture velocity is estimated to be near 4 mph.

For the two aluminum heads protected by 1/2 inch-thick shields, one punctured at 17.8 mph, but there was no puncture at 15.1 mph. The puncture threshold velocity is estimated to be near 16.5 mph.

The test of the aluminum head protected by a 5/8-inch-thick steel shield was not considered valid. Although the head survived a 17.5 mph impact, it was noted that the couplers of the Impact and the Reaction Cars had wedged together and did not fully couple. This may have interfered with the ram penetration depth. A retest of this configuration would be recommended.

SECTION B

ONE-FIFTH SCALE MODEL TESTS

9.0 **TEST IMPLEMENTATION**

There were 15 different test configurations conducted in this one-fifth scale drop tower test program. They were divided into two major groups: (1) ambient temperature conditions, and (2) cold temperature conditions. In all, combinations of seven different test condition variables were tried. They were as follows:

a. Head Diameter (DOT car type)
b. Head Thickness
c. Head Materials (steel or aluminum)
d. Head Protection
e. Insulation Material (used with jacket or shield)
f. Head Temperature
g. Internal Head Pressure

The original plan was to perform an impact on six head assemblies for each of the 15 test series, resulting in a total of 90 impacts. However, the number of impacts in some series was reduced from the planned six when it became apparent that the puncture velocities were extremely low (e.g., 1.5 mph to 2 mph) or very high (above 18 mph). Velocities above 18 mph would risk damage to the fixture tank vessel. Table 5 is the test matrix for Ambient Temperature Tests, and Table 6 is the test matrix for Cold Temperature Tests.

During the course of testing, two significant changes were made from the original test plan. In Matrix 1, test series 4, the 1/2-inch-thick aluminum heads (actual scaled thickness = .100 inch) were changed from a bare head configuration to one with head shield protection. The reason for this change was an extremely low puncture threshold velocity, less than 1.5 mph. The second major change was the addition of eight cold temperature impact tests in Matrix 3. The tests were divided into three additional test series to study an unexpected increase in puncture resistance of cold temperature heads versus ambient temperature heads. Another concern was that rounding of the simulated coupler, due to repeated impacts in Test Matrix 1, may have significantly decreased the severity of the impacts in Test Matrix 3. The coupler was reprofiled for each of the three additional series.

TABLE 5. TEST MATRIX 1 - AMBIENT TEMPERATURE ONE-FIFTH SCALE DROP TOWER IMPACT TESTS

Test Series	Car Type & Spec.	Head Thickness (in.)	No. of Heads	Shield (S)/ Jacket (J) Thickness	Pressure (psig)[1]	Insulation Type	Dent Depth (in.)	Test Velocity (mph)	Puncture (Yes/No)
DA-01	112A340W	11/16	7	1/2" S	100	1/2" Fiber	5.1	10.5	Yes
DA-02	105A500W	13/16	6	1/8" J	100	4" Foam	4.5	13.0	Yes
DA-03	111A60ALW1	5/8	3	None	4	None	2.1	<1.5	Yes
DA-04	111A60ALW1	1/2	4	3/4" S	4	4" G.F.[2]	56.5	16.0	No[3]
DA-05	111A60ALW1	15/16	5	None	4	None	.9	1.5	Yes
DA-06	111A60ALW1	5/8	6	1/8" J	4	4" G.F.	4.1	5.0	Yes
DA-07	111A60ALW1	5/8	4	1/2" S	4	4" G.F.	5.7	12.0	No[3]
DA-08	111A60ALW1	1/2	3	1/2" S	4	4" G.F.	6.1	12.0	No

[1] psig = pounds per square inch gage

[2] G.F. = Glass Fiber

[3] Failure occurred as crack at pinched perimeter flange weld/sill area; visible leakage. See Fig. 44 for a typical example.

TABLE 6. TEST MATRIX 3 - COLD TEMPERATURE
ONE-FIFTH SCALE DROP TOWER IMPACT TESTS

Test Series	Car Type & Spec	Head Thickness (in.)	No. of Heads	Shield (S)/ Jacket (J) Thickness	Head Temp (°F)	Pressure (psig)[1]	Insulation Type	Dent Depth (in.)	Test Velocity (mph)	Puncture (Yes/No)
DC-01	111A60ALW1	5/8	4	None	+32	4	None	2.7	1.6	Yes
DC-02	111A60ALW1	5/8	4	None	-20	4	None	3.0	2.5	Yes
DC-03	111A60ALW1	5/8	5	1/2" S	-20	4	4" G.F.[2]	6.4	13.0	No[3]
DC-04	105A500W	13/16	5	1/8" J	+32	20	4" Foam	6.8	18.0	No
DC-05	105A500W	13/16	5	1/8" J	-20	20	4" Foam	6.9	18.0	No
DC-06	112A340W	11/16	5	1/2" S	+32	40	1/2" Fiber	5.5	14.0	Yes
DC-07	112A340W	11/16	4	1/2" S	-20	10	1/2" Fiber	6.5	18.0	No
ADDITIONAL IMPACT TESTS										
DC-03A	111A60ALW1	5/8	3	1/2" S	-20	4	4" G.F.	5.7	13.0	Yes
DC-05A	105A500W	13/16	3	1/8" J	-20/ +37	100/20	54" Foam	4.3	13.0	Yes
DC-07A	112A340W	11/16	2	1/2" S	-20/-1	10	1/2" Fiber	6.8	18.0	No[3]

[1] psig = pounds per square inch gage

[2] G.F. = Glass Fiber

[3] Failure occurred as crack at pinched perimeter flange weld/sill area; visible leakage. See Fig. 44 for a typical example.

10.0 **FABRICATION**

The drop test fixture was transferred from Socorro, New Mexico, to the TTC as a government furnished property item (Figure 23). The fixture was modified to fit in to the Components Test Laboratory (CTL) for controlled environmental conditions. The modified drop fixture has a maximum drop height of 18.5 feet with the DOT 105 head assembly and can develop a 25 mph theoretical free fall velocity at impact.

Fabrication of the pressure vessel assembly, impact mass, and one-fifth scale coupler ram was accomplished. Fabrication of head assemblies was by A. Gunthard Company, Ennis, Texas, under subcontract. Drawings on modifications to the drop tower and fabrication of the head assemblies/pressure vessels can be found in TTC engineering sketch file 87-77506-112.

10.1 **TANK HEADS**

Tank heads were a 2:1 ellipsoid of revolution with 2-inch-straight flange extensions. Material used for the Type 112 and Type 105 steel tank heads was ASTM A612 (AAR TC-128, Grade B). It was purchased in standard thickness sheets and then machined by Blanchard grinding to .163 inch thickness for the Type 105 heads, and .138 inch thickness for the Type 112 heads. Material used for

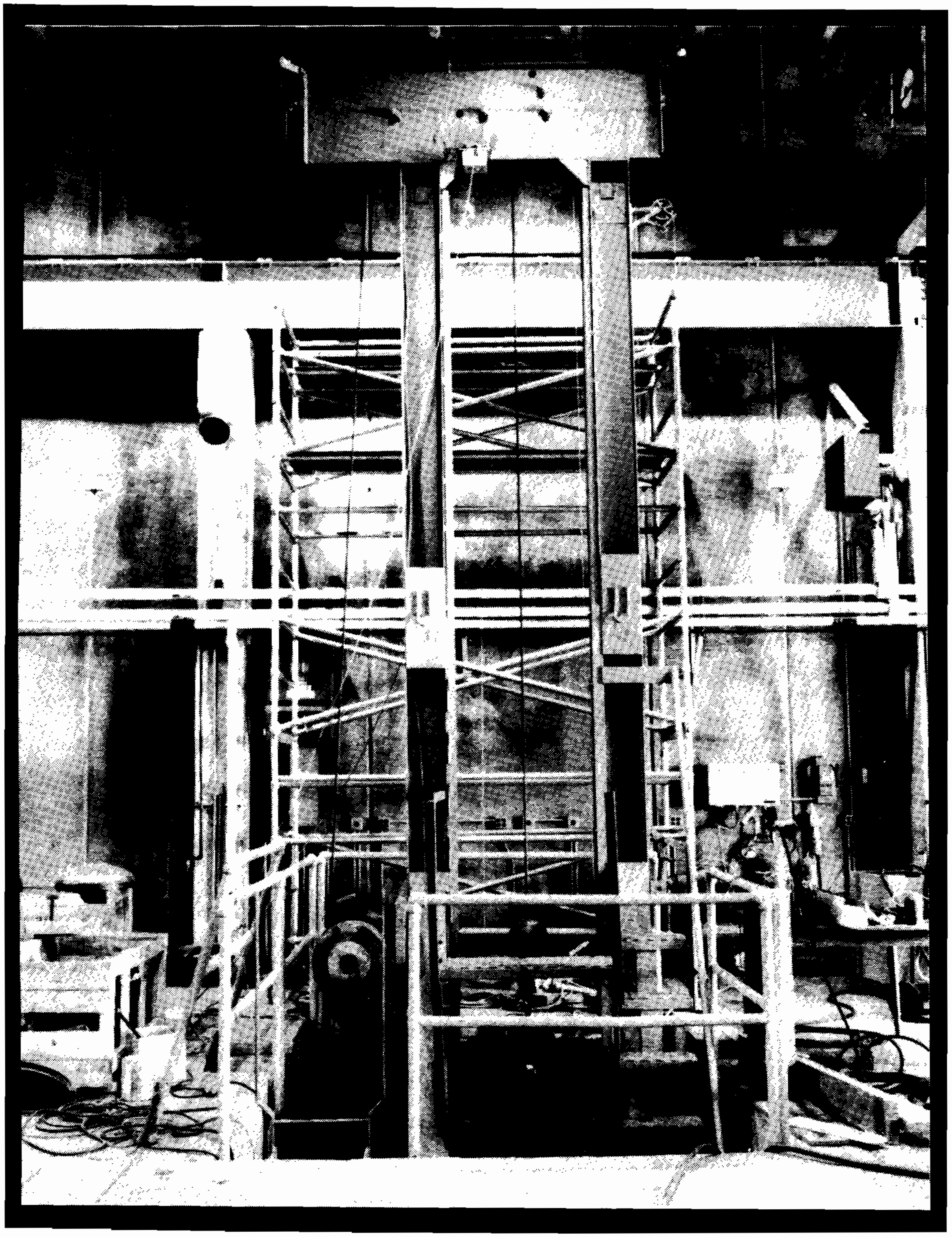


FIGURE 23. ONE-FIFTH SCALE DROP TEST FIXTURE - COMPONENTS TEST LABORATORY.

the Type 111 aluminum tank heads was ASTM B209, Alloy 5052, HO temper. It was purchased in the required thicknesses of .100, .125, and .190 inch, and no grinding was required.

The heads were all press formed with heat, but below normalizing temperatures of steel and annealing temperatures of aluminum. The steel heads were normalized after forming in accordance with 49 CFR 179.100-8. The aluminum head material was annealed prior to forming, as specified in ASTM B597. Marmon pipe clamps with sheet metal type flanges were used to attach the tank heads to the pressure vessel.

10.2 INSULATION JACKETS

Insulation jackets were a 2:1 ellipsoid of revolution, the same size as the scale model DOT Type 112 tank heads, with 1-inch-straight flange extensions. The material was .025-inch-thick steel, conforming to ASTM A366 specifications. The insulation jackets were hot press formed using the same DOT 112 head form.

10.3 HEAD SHIELDS

Head shields were one-half of an ellipsoid of revolution type head, made from the same press form as the DOT 112 heads. The material was .105-inch-thick steel, conforming to ASTM A606 specifications.

Test series 4 of Matrix 1 was changed from bare .100-inch-thick aluminum heads to those protected by .150-inch-thick steel shields. The shields were cut from existing one-fifth scale propane tank car heads (DOT Type 112/114), left over from the previous Chlorine Tank Car Puncture Resistance Test Program. Material was ASTM A366 steel. The shields were added after it was discovered that bare aluminum heads had an extremely low puncture velocity threshold (below 2 mph).

10.4 INSULATION

Three types of insulation materials were used in the ambient and cold temperature test matrices. Tables 4 and 5 show the insulation materials used in each series of tests. The insulation materials are described as follows:

Foam - Product used was Isofoam R-0990 two component polyurethane foam system. The material is designed for a 2 pound/cubic foot (pcf) density under controlled environmental conditions. Samples taken previously from insulation jacket assemblies at the impact zone area had densities ranging from 3.7 pcf to 4.4 pcf. The higher densities are attributed to the narrow space between the head and shield (.8 inches), inhibiting the free expansion of the foam.

Ceramic Fiber - Material used was on hand at the TTC. The blanket was approximately .100 inch thick. It was formerly used in thermal insulation tests for tank cars and the manufacturer and material density is not known.

Glass Fiber - Material used was an Owens Corning building insulation grade. It was .8 inches thick and 1 pcf density.

11.0 MEASUREMENTS

Figure 24 shows the instrumentation schematic of the setup used to measure the static and dynamic conditions at the drop test fixture. Table 7 lists the type of instrumentation used on this project.

Static conditions were recorded on the test log. Dynamic conditions were collected with a Gould DASA 9000 system at a rate of 10,000 samples/second using an IBM PC-XT computer. The data was stored on floppy disks and converted to ASCII format for data analysis. The original disks can be found in TTC engineering file 87-77506-112.

11.1 TEMPERATURE

A thermocouple was attached to the exterior side of the tank head, under any jackets, shields, and insulation systems installed. Temperature readings were taken prior to impact and recorded on the test log. For the ambient temperature tests (Test Matrix 1), temperatures varied from a low of 63°F to a high of 74°F. For the cold temperature tests (Test Matrix 3), temperatures were within ±3F° of the target temperature listed in the Test Matrix.

In the cold temperature tests, liquid carbon dioxide was expanded through a 50/50 water/glycol solution to obtain the desired liquid temperature. Figure 25 is a schematic of the system, and Figures 26 and 27 show related photographs. The

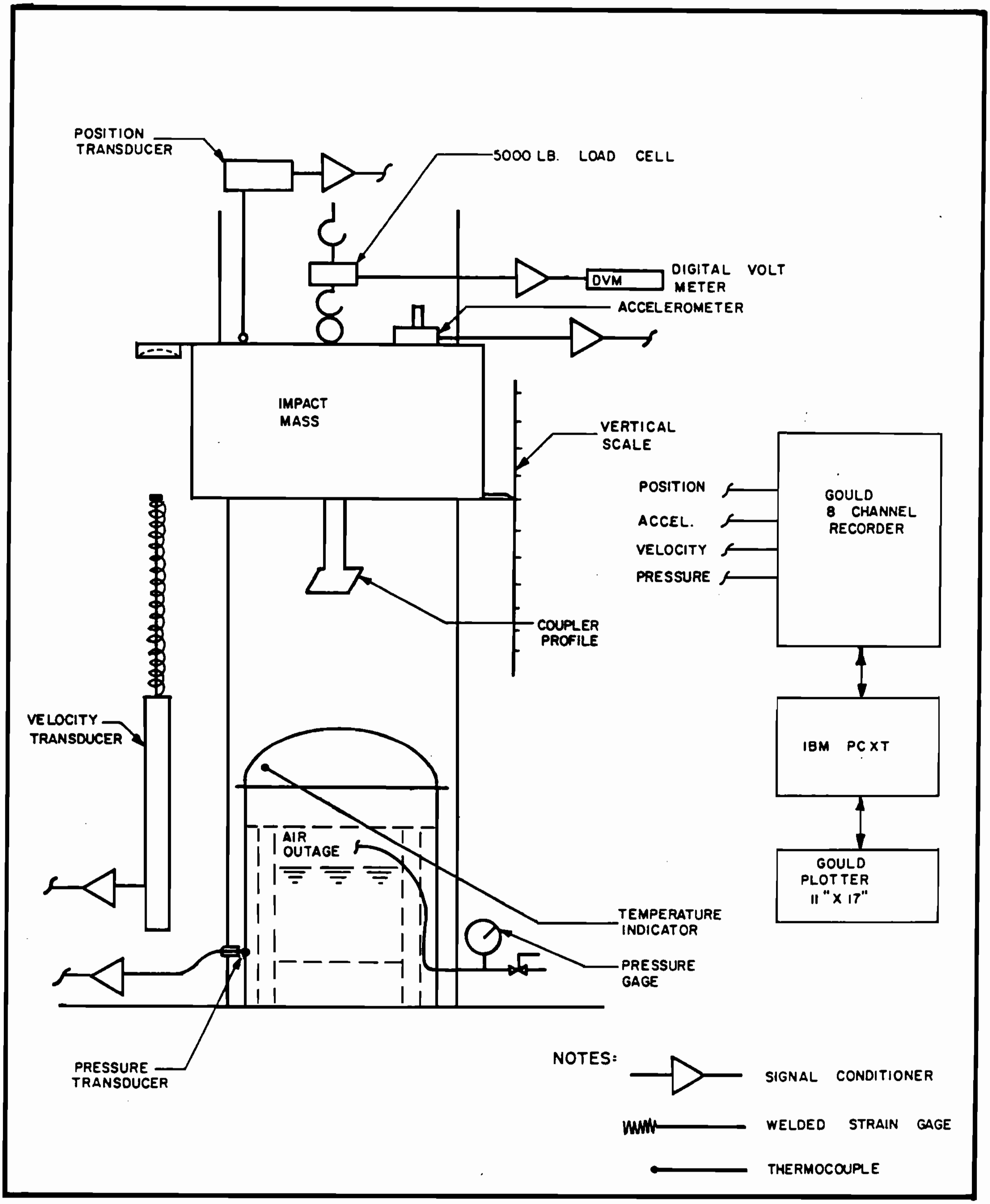


FIGURE 24. ONE-FIFTH SCALE TEST INSTRUMENTATION SCHEMATIC.

TABLE 7. SUMMARY - TEST INSTRUMENTATION

Parameter	Measurement Frequency Response	Transducer Type/Manufacturer	Measurement System Accuracy	Comment
Impactor Mass, Static		Scale/Dillon	±10 lbs	
Tank Temperature, Static		Surface Thermocouple/ Omega	±5^{o}F	
Tank Pressure Gage, Static		Test Gage/Omega	±.5*psig	
Tank Pressure, Dynamic	0-1 kHz	Strain Gage Transducer/ Bell & Howell CEC 1000	±1.8 psig	
Impactor Position, Dynamic	2 Hz	Potentiometer/Celesco	±1 inch	Assume 100" Drop
Impactor Position, Static		Steel Tape/-----	±1/16 inch	
Impactor Final Velocity, Dynamic	0-5 kHz	Velocity/Schaevitz	±1.74%	
Impactor Acceleration, Dynamic	0-1 kHz	Piezoelectric Accel/ B&K	±4.2 g	

* psig = pounds per square inch gage (pressure)

The above table is the result of an error analysis based on manufacturers' specifications and TTC calibration for equipment used on this test program. In most dynamic measurements, the largest source error is the resolution of the Gould Transient Recorder (1 part in 127). All accuracies were calculated by the combined error (rms) method.

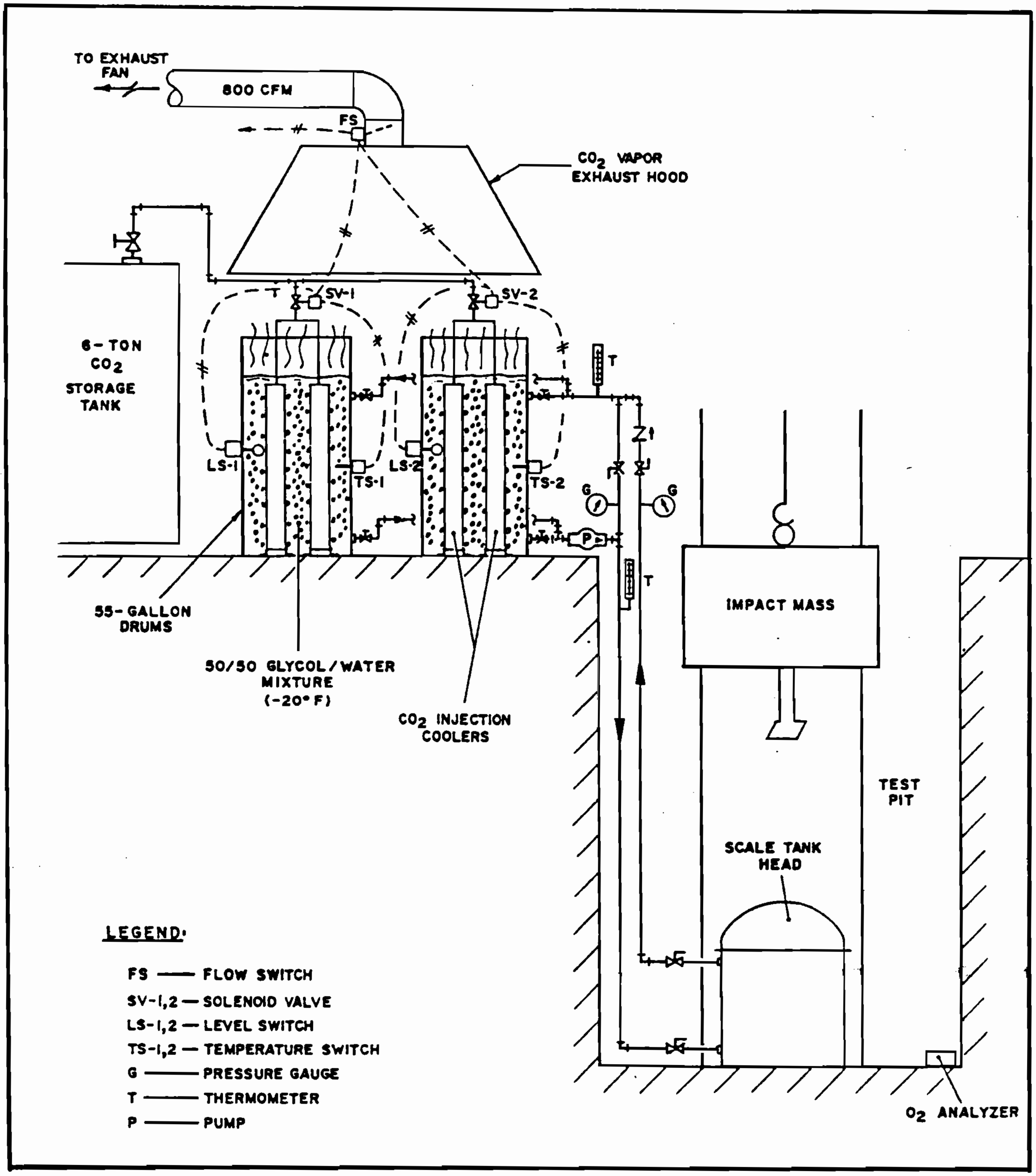


FIGURE 25. ONE-FIFTH SCALE CHILLED LIQUID SYSTEM FOR LOW TEMPERATURE TESTS.

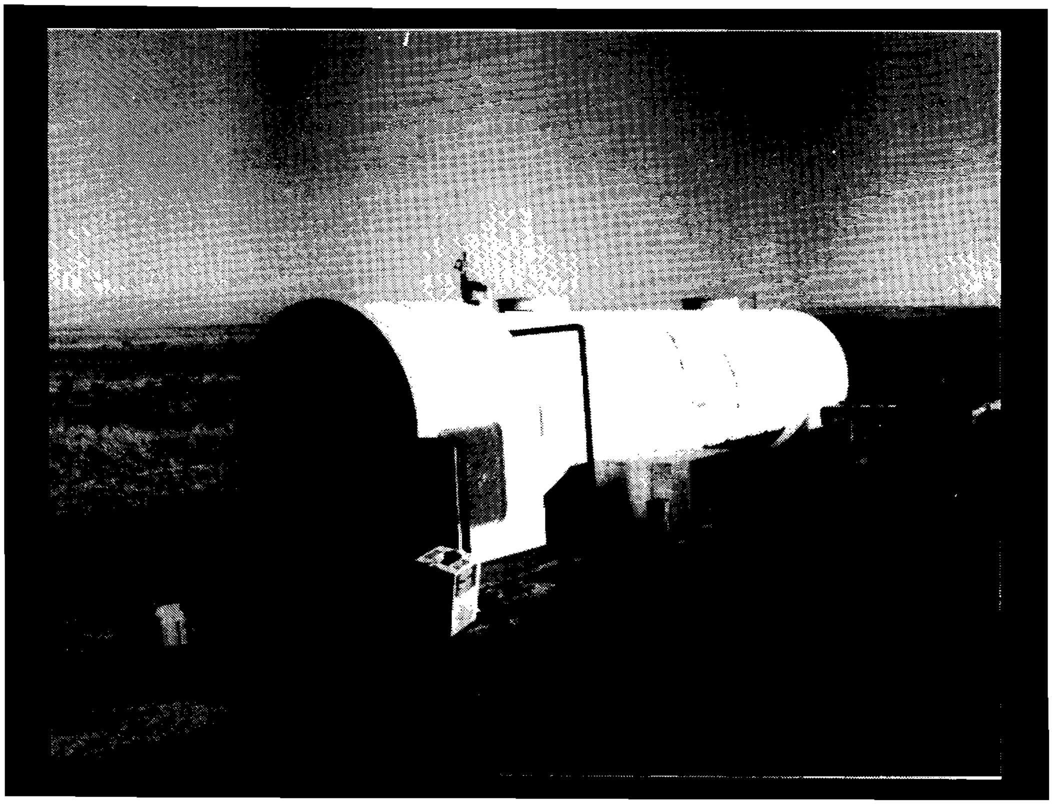


FIGURE 26. CO_2 STORAGE TANK FOR CHILLED SYSTEM.

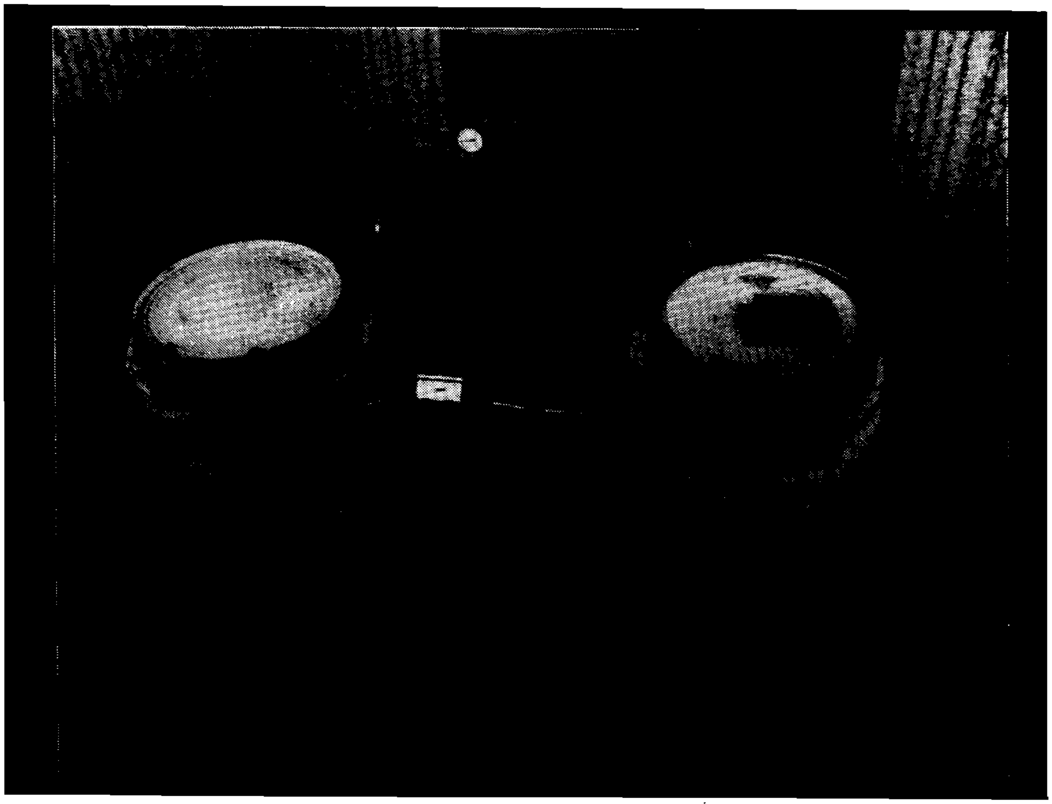


FIGURE 27. CO_2 LIQUID INJECTION SYSTEM.

chilled liquid was circulated through the model tank vessel until the head temperature dropped to that specified in Test Matrix 3. The tank vessel and head were insulated during the chill down cycle, and removed just prior to impact testing (Figures 28 and 29).

11.2 TANK PRESSURE

The pressure vessel assemblies for the two different sized heads incorporated an inverted, cylindrical container inside. This container entrapped air during the liquid filling procedure and was sized to provide a 10 percent air to water volume ratio within the pressure vessel and below the head (Figure 24). All air was purged from the vessel, except for that within the inverted container. Once the 10 percent air outage was established, the pressure within the vessel assembly was adjusted by adding compressed air to the inverted container through an external air fitting. Test pressures for each series of impacts were in accordance with those specified in Test Matrices 1 and 2. Static pressure readings were taken prior to, and immediately after, each impact. They were recorded in the test log.

11.3 IMPACT LOCATION

The impact location was set at 4.2 inches from the sill, or perimeter of head, to the center line of the coupler. The coupler location for the two different sized head/vessel assemblies was

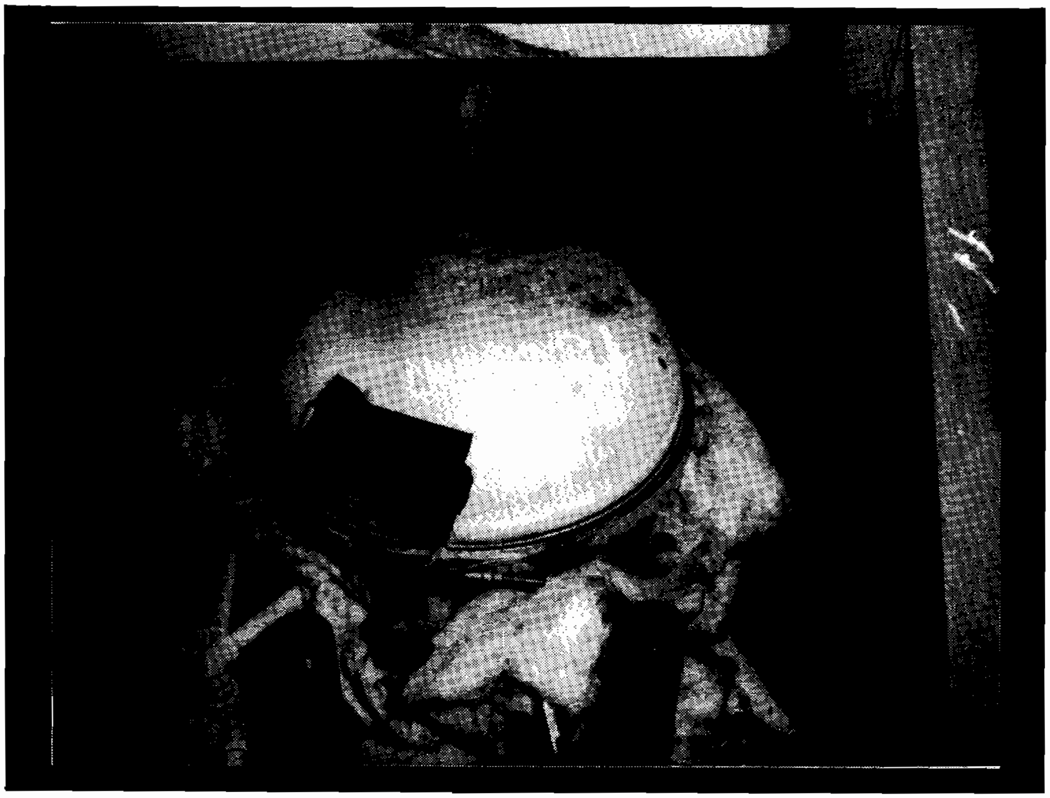


FIGURE 28. ONE-FIFTH SCALE 111 HEAD AT -20°F.

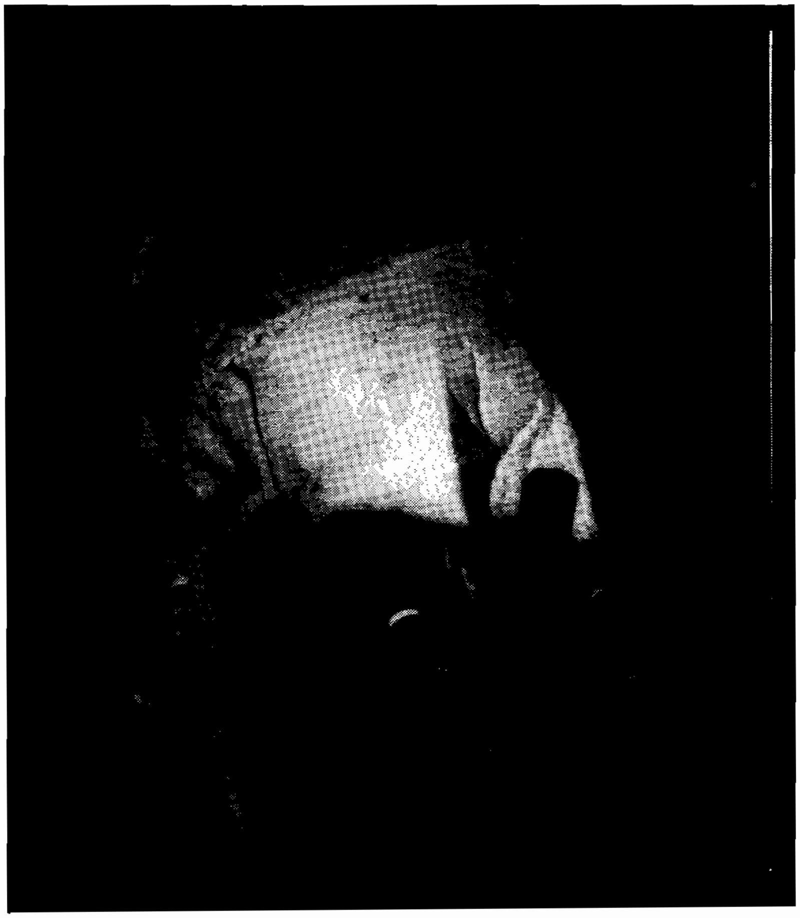


FIGURE 29. ONE-FIFTH SCALE HEAD DURING CHILL DOWN ROUTINE.

adjusted by dropping a plumb bob (weight) from the coupler center line to the impact point. The impact point was found by using the tank head template (Figures 30-32).

11.4 **IMPACT ACCELERATION/DECELERATION**

Impact mass velocity with respect to time was calculated and compared with three different measuring devices. The devices were (1) B & K piezoelectric accelerometer, (2) Celesco Model PT-101-250-A position transducer, and (3) Schaevitz Model 7L 20VT-Z velocity transducer. Signal outputs from those devices were collected with a Gould DASA 9000 system, at a sampling rate of 10,000 samples/ second. Movement of the velocity transducer just before impact triggered the data collection system.

11.5 **DENT SHAPE**

A flat profile template was used to measure the formation of the dent at the center of the head profile and corresponding coupler center line (Figures 30 and 32). Dent depth distances were measured between the tank head and template curve, and along scribed lines parallel with the cylindrical center line of the tank and head assembly. These scribed lines were 1 1/2 inches apart and were numbered starting at the tank bottom and progressing to the tank center. All measurements taken were noted on the test logs. Maximum dent depth was also measured and recorded on the test log for use in the dent depth/velocity curves.

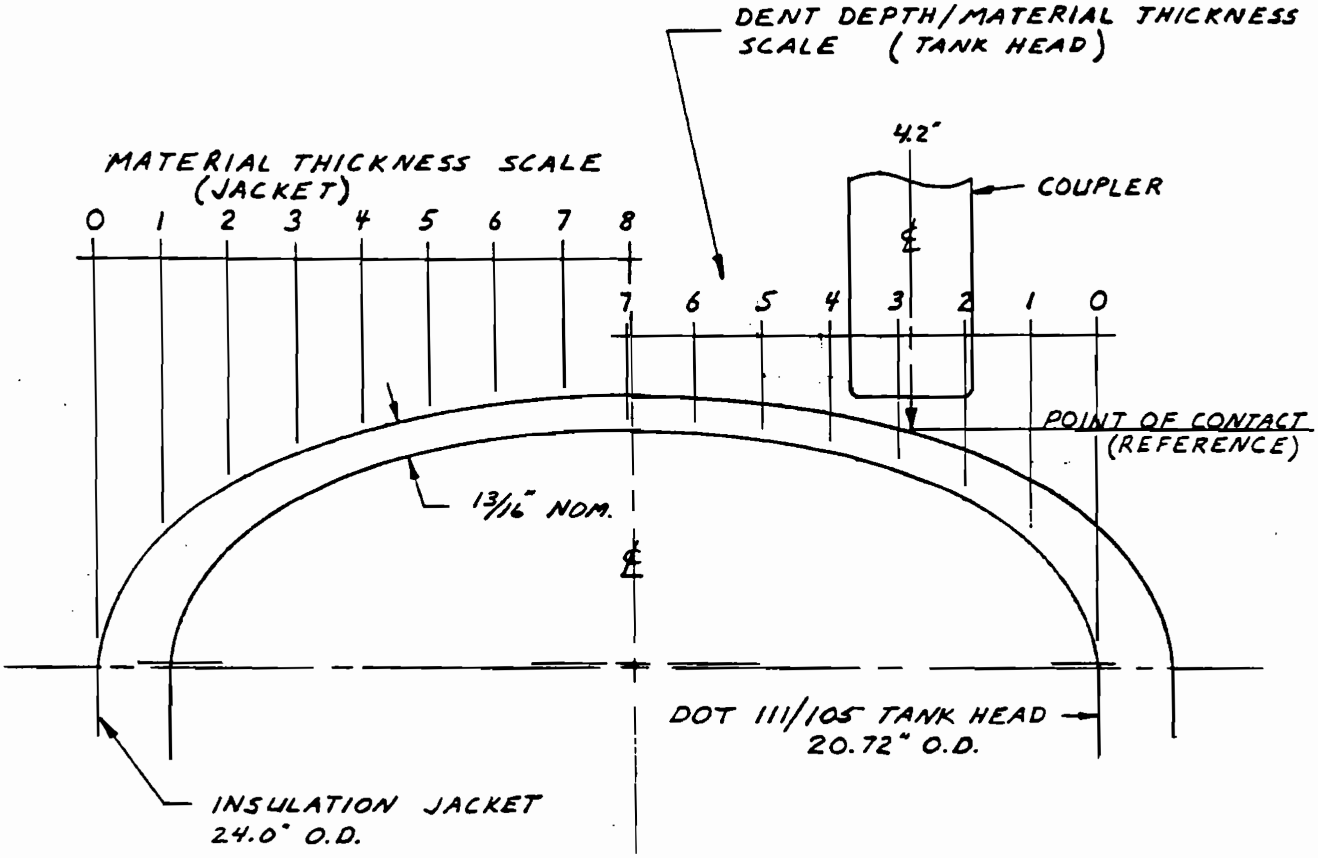


FIGURE 30. ONE-FIFTH SCALE HEAD MEASUREMENT SCALE.

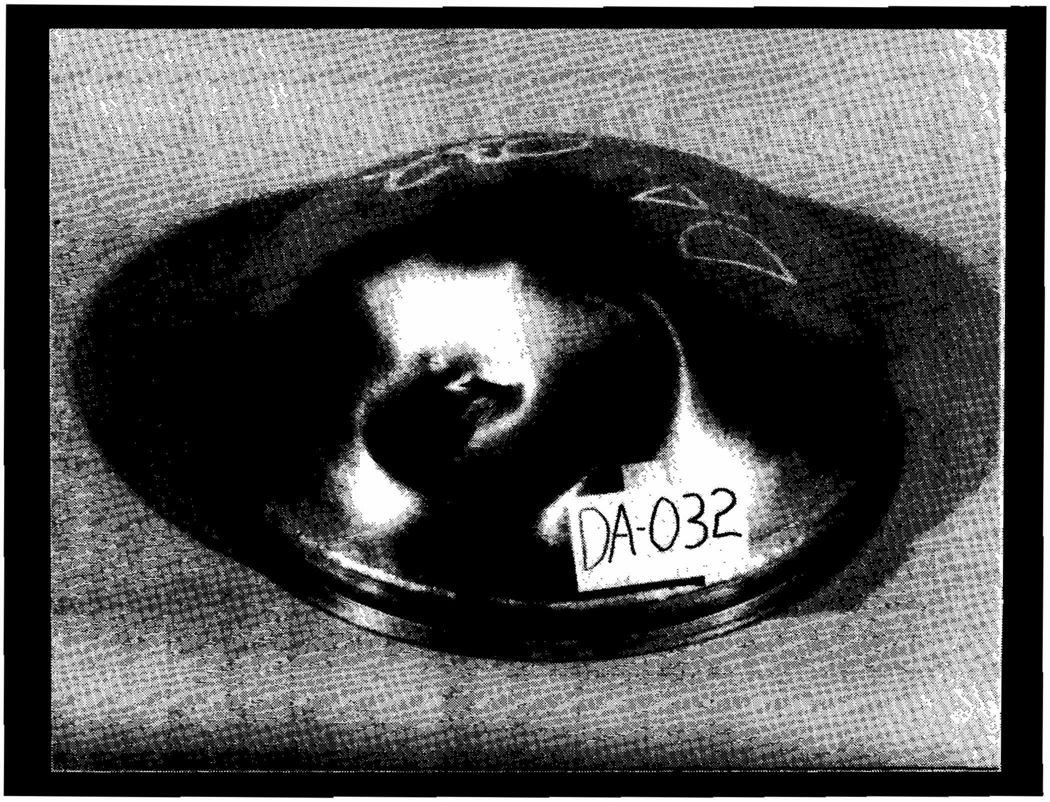


FIGURE 31. TYPICAL PUNCTURE OF 111 BARE ALUMINUM HEAD.

FIGURE 32. PROFILE TEMPLATE USED TO MEASURE DENT DEPTH.

11.6 TANK HEAD/JACKET/SHIELD THICKNESS

Random selections were made of heads, jackets, and shields from each material, thickness, and diameter tested. The heads and jackets were then sawed in half to facilitate material thickness measurements using a micrometer caliper. These thickness measurements were taken along the sawed edge at the same spacing increments as the dent depth measurements. Table 8 contains the material thickness readings.

In all cases, the scale model head fabrication process resulted in tank head thicknesses being less than the calculated one-fifth scale reduction value. The 1/2 inch shield thicknesses were very nearly correct, while the 3/4 inch shield and insulation jacket thicknesses were oversized (Table 1). The decreased thickness of the aluminum heads averaged about 11 percent undersize. The steel heads were closer to ideal, averaging 2 1/2 percent undersize. These percentages were calculated at the location of impact.

11.7 MASS OF DROP TEST IMPACTOR

Scaling of the impact mass was 1/125 of full scale in order to maintain the velocity constant (see Section 2.0). The test impactor was adjusted to 2,104 pounds during fabrication using a vertical hanging load scale. The mass was later checked with a 5 kip load cell, which verified the weight to be within the measurement accuracy of ± 1 percent.

TABLE 8. ONE-FIFTH SCALE MODEL TANK ASSEMBLIES HEAD THICKNESS READINGS (INCHES)

Head Assembly Type	0	1/2	1	2	3	4	5	6	7	8
112 Heads (.138" TC-128):										
DA-011	.116	.124	.132	.135	.134	.135	.137	.137	.137	.138
DA-012	.112	.118	.128	.135	.136	.135	.136	.137	---	---
DA-014	.110	.116	.128	.134	.133	.134	.135	.135	.138	.138
105 Heads (.163" TC-128):										
DA-021	.149	.162	.163	.158	.157	.160	.163	.163	.167	.165
DA-022	.155	.160	.158	.157	.159	.159	.163	.165	.170	.167
DA-023	.151	.158	.156	.157	.162	.158	.164	.165	.169	.167
111 Heads (.100" 5052 Aluminum):										
DA-082	.075	.084	.087	.090	.089	.090	.091	.091	.090	.096
DA-084	.077	.085	.085	.094	.091	.091	.094	.095	.095	.095
111 Heads (.125" 5052 Aluminum):										
DA-033	.099	.116	.117	.114	.116	.116	.119	.121	.121	.121
DA-064	.095	.111	.115	.112	.114	.116	.117	.119	.120	.119
DA-065	.094	.111	.115	.113	.114	.114	.115	.120	.121	.121
111 Heads (.190" 5052 Aluminum):										
DA-53	.133	.162	.164	.145	.160	.162	.172	.176	.179	.179
DA-64	.134	.164	.163	.146	.160	.163	.171	.175	.179	.178
DA-55	.142	.160	.171	.168	.167	.169	.174	.178	.172	.172
Insulation Jackets (.025" A-366):										
DA-61	.035	.036	.043	.041	.042	.042	.042	.040	.046	.045
DA-64	.035	.037	.039	.038	.042	.045	.045	.043	.043	.042
Head Shields (.105" A-606):										
DA-083	.085	.079	.084	.086	.104	.101	.102	.101	.105	.105
DA-084	.081	.081	.089	.101	.103	.101	.100	.102	.101	.102
DA-074	.079	.086	.090	.089	.099	.097	.095	.098	.098	.094

11.8 IMPACTOR HEIGHT

The impactor height was the distance between the point of contact on the head and front face of the coupler knuckle. The point of contact was the point at which the center of the coupler knuckle would make contact with the insulation jacket, shield, or bare head (Figure 30).

A vertical, linear scale was mounted on the drop fixture for visual impactor mass height adjustment. Once the desired drop height was set, the position transducer output readings were adjusted to zero. The impactor mass height with respect to time was collected with the Gould data logger system. Initial and final impactor mass heights were recorded on the test logs.

11.9 **PHOTOGRAPHY**

Color prints were taken with a 6 x 7 large format camera to document head assembly construction, drop fixture configuration, instrumentation, and dent/puncture formations. Print negatives are on file at the TTC Photography Department.

A documentary film, shot in 16mm format, was taken to show test equipment configuration, dent formation during impact, and miscellaneous test setup activities.

11.10 MATERIAL TESTS

Material test reports/certifications were provided by Castle Metals for the aluminum head materials, and by Bethlehem Steel Corporation for the steel head, jacket, and shield material. Tensile test specimens were taken from each plate stock, in both the parallel and perpendicular rolling directions, before forming and fabrication by the subcontractor. Tensile test specimens were also taken from selected heads after impact testing, but only in one random direction, because the rolling direction of the material was indiscernible after the head forming process. All tensile test specimens were the sheet type and were tested in accordance with ASTM A370-88a by Pittsburgh Testing Laboratory. Results of these tests can be found in TTC engineering sketch file 87-77506-112.

The following is a recap of test data for samples taken from plate stock before the head-forming process and random samples taken from tank heads after impact:

1. DOT Type 105A500W/112A340W Steel Heads (TC-128)

Mechanical Properties	ASTM A-612 (TC-128, Gr.B)	Average of Plate Stock Before Head Forming	Post Test Average of Tank Head Sample
Tensile Strength	81-101 Ksi	82.3 Ksi	70.9 Ksi
Yield Strength	> 50 Ksi	57.1 Ksi	51.9 Ksi
Elongation in 2 in.	> 22%	28.1%	27.5%

2. DOT Type 111 Aluminum Alloy Heads (5052)

Mechanical Properties	ASTM B-209 Alloy 5052, 0 Temper)	Average of Plate Stock Before Head Forming	Post Test Average of Tank Head Sample
Tensile Strength	25-31 Ksi	27.6 Ksi	34.2 Ksi
Yield Strength	> 9.5 Ksi	11.9 Ksi	27.5 Ksi
Elongation in 2 in.	> 19%	27.4%	12.8%

Test results between samples taken parallel and perpendicular to the rolled direction, before head fabrication, revealed little difference in values for yield strength in both aluminum and steel. Tensile strength was generally greater for specimens taken parallel, while percent elongation was greater for specimens taken perpendicular to the rolled direction. The variations in yield and tensile strength, between parallel and perpendicular samples, averaged 2.5 percent.

As indicated in the two tables above, the TC-128 steel material had an average loss in tensile strength of 14 percent due to the head forming process; and the 5052 aluminum material had an average increase in tensile strength of 24 percent after the head forming process.

12.0 RESULTS - ONE-FIFTH SCALE

The primary result derived from these puncture resistance tests is the relationship of the dent depth, or puncture, with respect to the impact velocity. Figures 31 through 44 are selected photographs of typical impacted head assemblies. Figures 45 through 62 show the relationships for each test series, and Figures 45 through 52 give the results of the ambient temperature tests, with the remainder showing those of the cold temperature tests.

The velocity value used on the dent depth versus velocity curves is based on theoretical free fall by using the drop height of the impact mass and an acceleration of gravity value of 32.2 feet/second. This value was also used in past scale model tests. (See RPI/AAR Tank Car Safety Project Summary Report RA-05-1-17, FRA Report DOT/FRA/ORD-85/04, and AAR/FRA One-Fifth Scale Model Test Report: Chlorine Tank Car Puncture Resistance Test Program 85-47574-074.)

Dent depths indicated on the charts are the maximum depths, as measured in accordance with Section 10.5 of this report. (See also the test matrices in Tables 4 and 5 for a summation of test parameters for each test series, and the puncture threshold velocity determined in each of those series.)

FIGURE 33. TYPICAL DENT FORMATION OF A SHIELDED 111 HEAD.

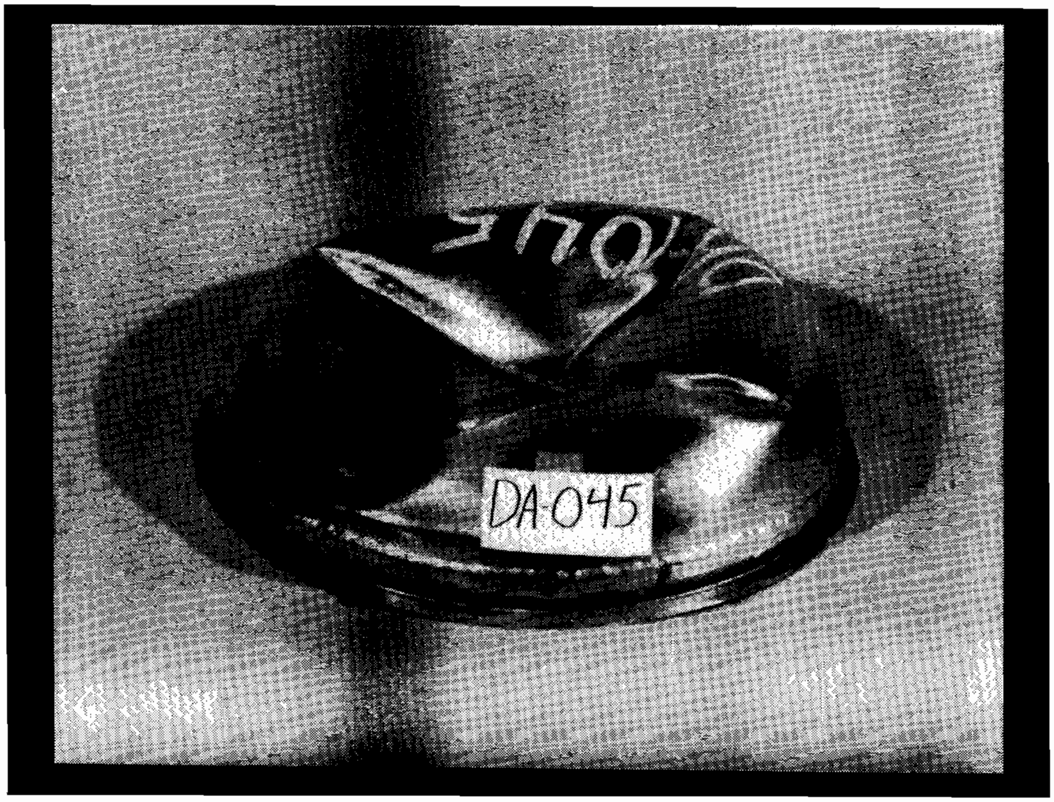


FIGURE 34. VIEW OF IMPACTED 111 HEAD WITH SHIELD REMOVED - NOTE DEFORMATION AT SILL AREA.

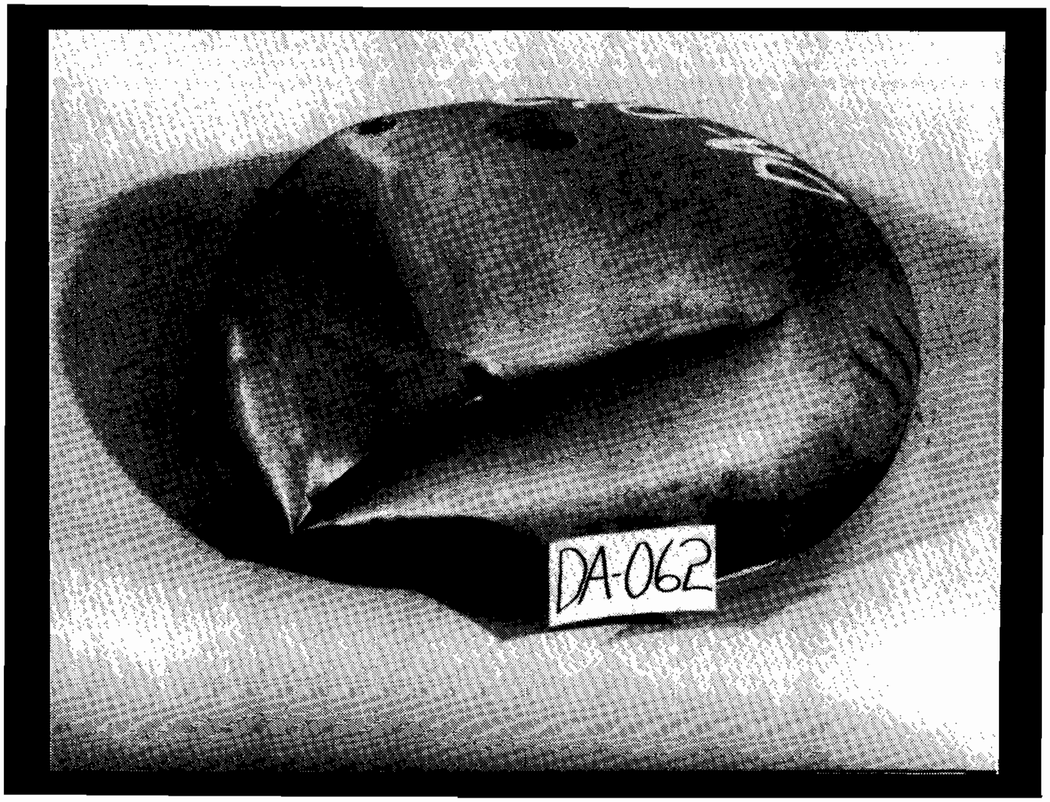


FIGURE 35. TYPICAL DENT FORMATION OF A JACKETED 111 HEAD.

FIGURE 36. VIEW OF PUNCTURED 111 HEAD WITH JACKET REMOVED - NOTE FOLDING AND PINCHING AT SILL AREA.

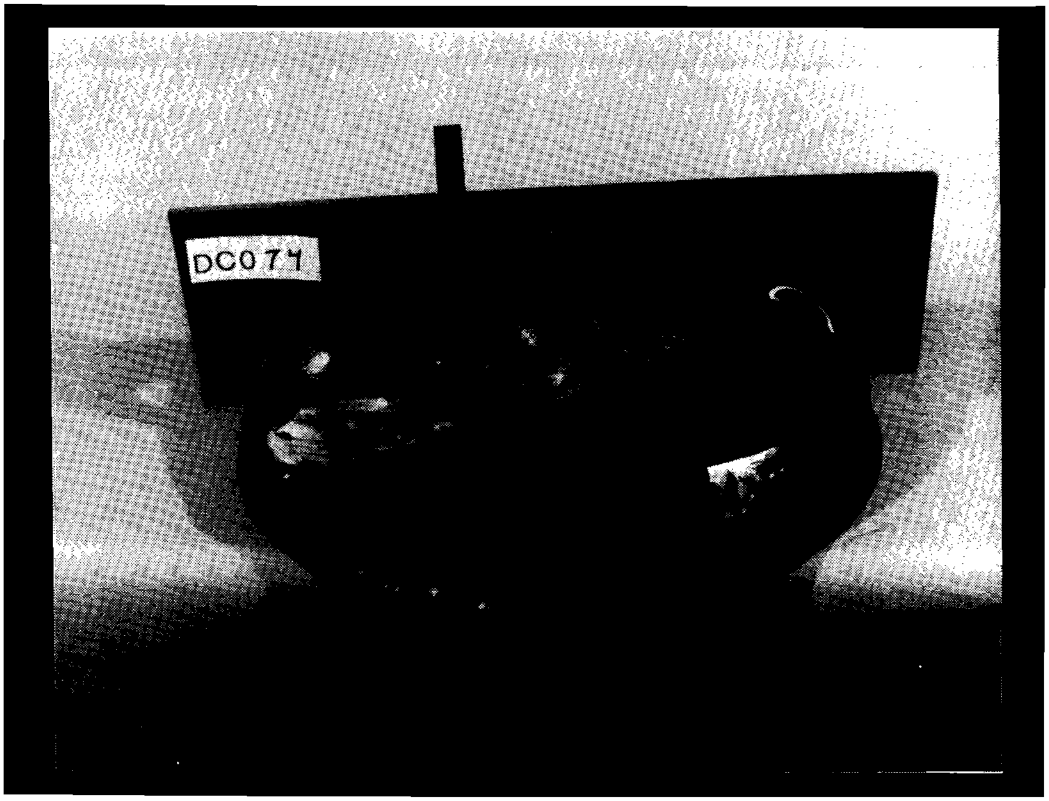


FIGURE 37. TYPICAL DENT FORMATION OF A 112 STEEL HEAD - NOTE THERMOCOUPLE, USED FOR COLD TEMPERATURE TESTS.

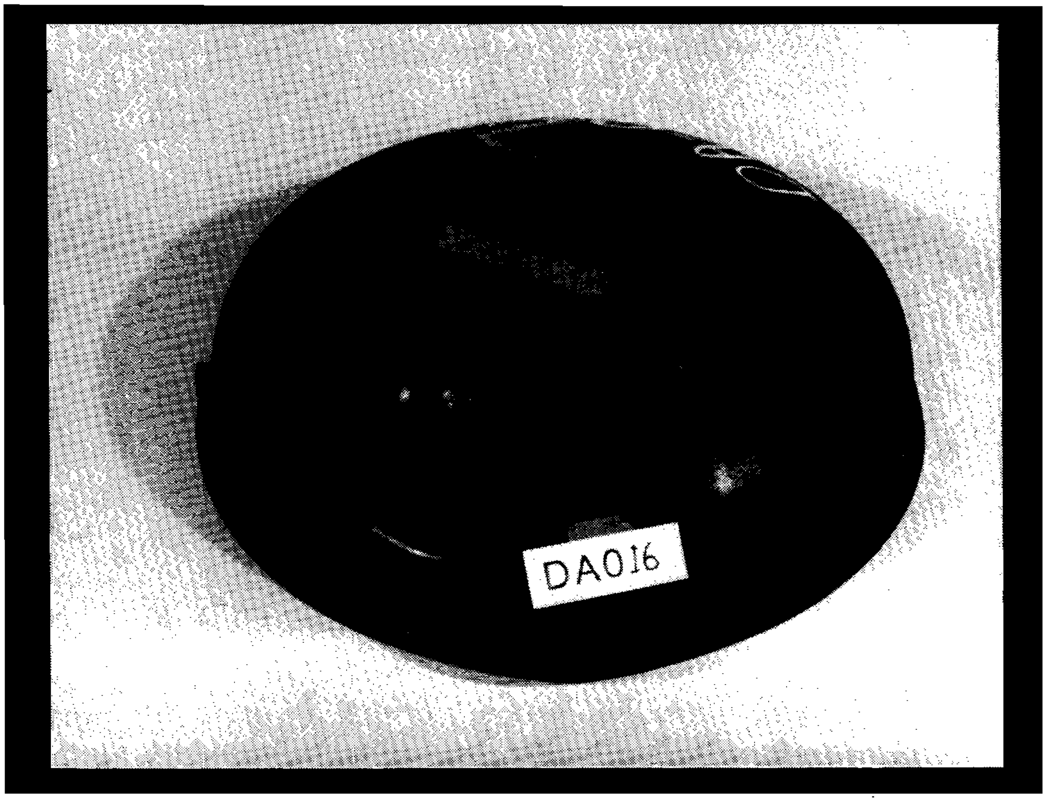


FIGURE 38. TYPICAL PUNCTURE OF A 105 STEEL HEAD - NOTE PERIMETER WELDS FOR BOLT ATTACHMENTS, USED FOR 100 PSI TESTS.

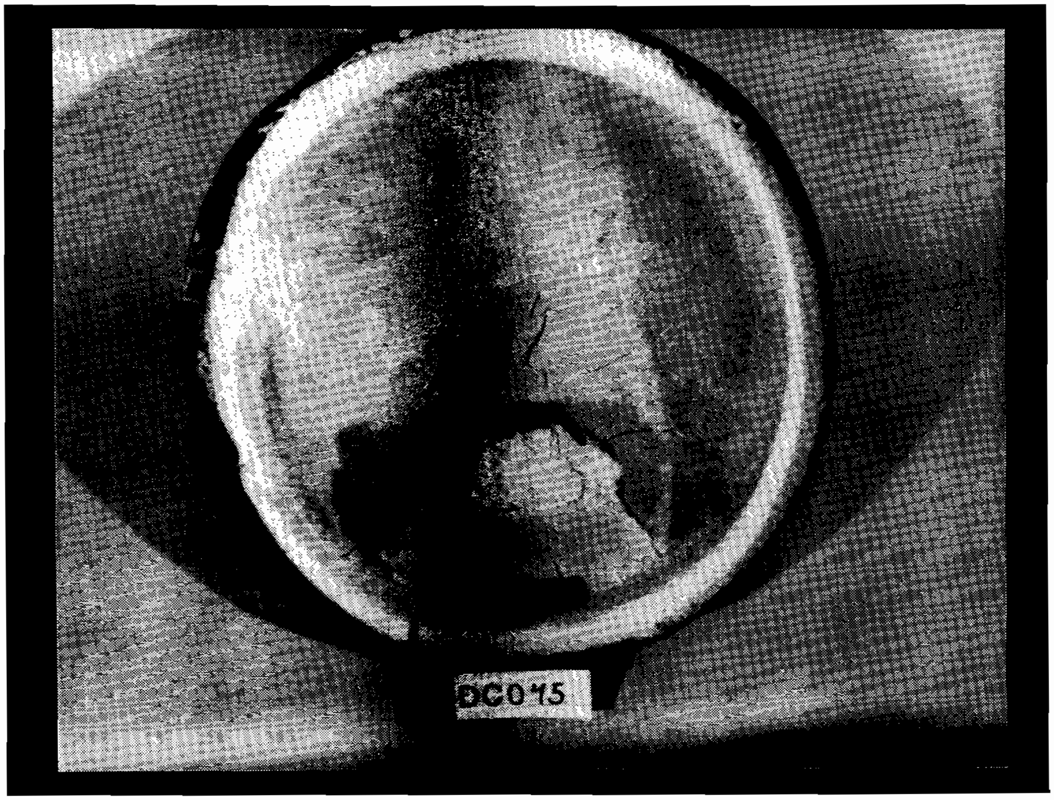


FIGURE 39. TYPICAL VIEW OF JACKET WITH .8" THICK URETHANE FOAL INSULATION, AFTER IMPACT.

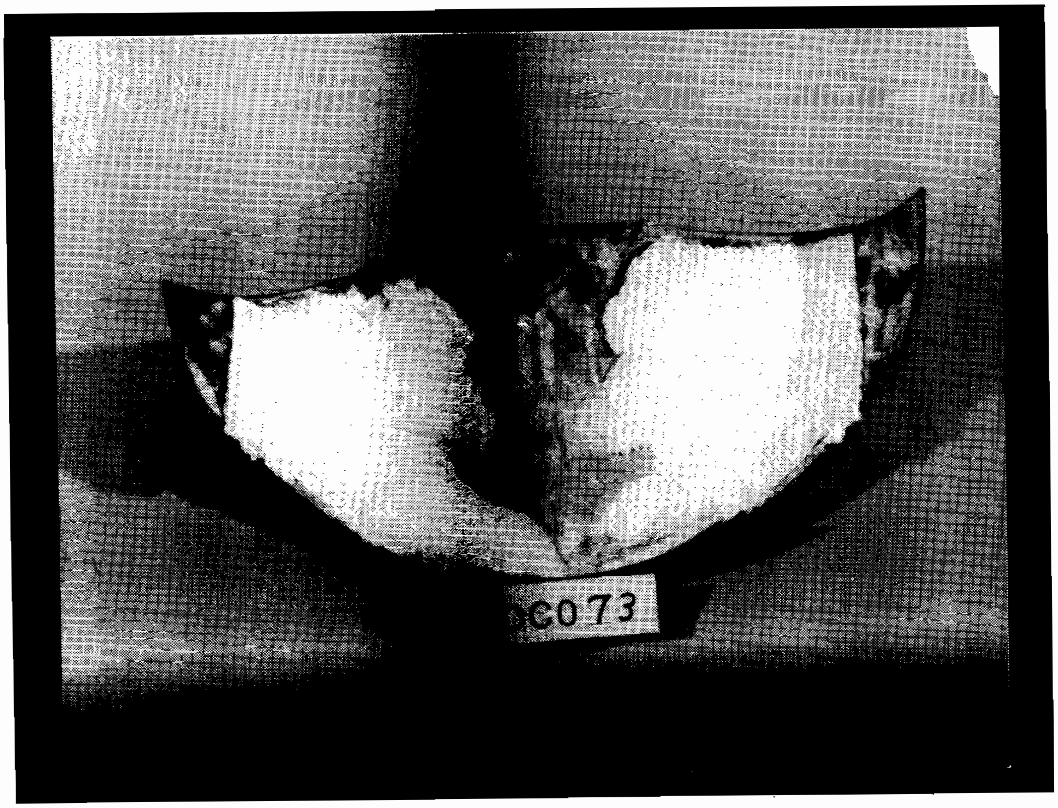


FIGURE 40. TYPICAL VIEW OF SHIELD WITH .1" THICK CERAMIC FIBER INSULATION, AFTER IMPACT.

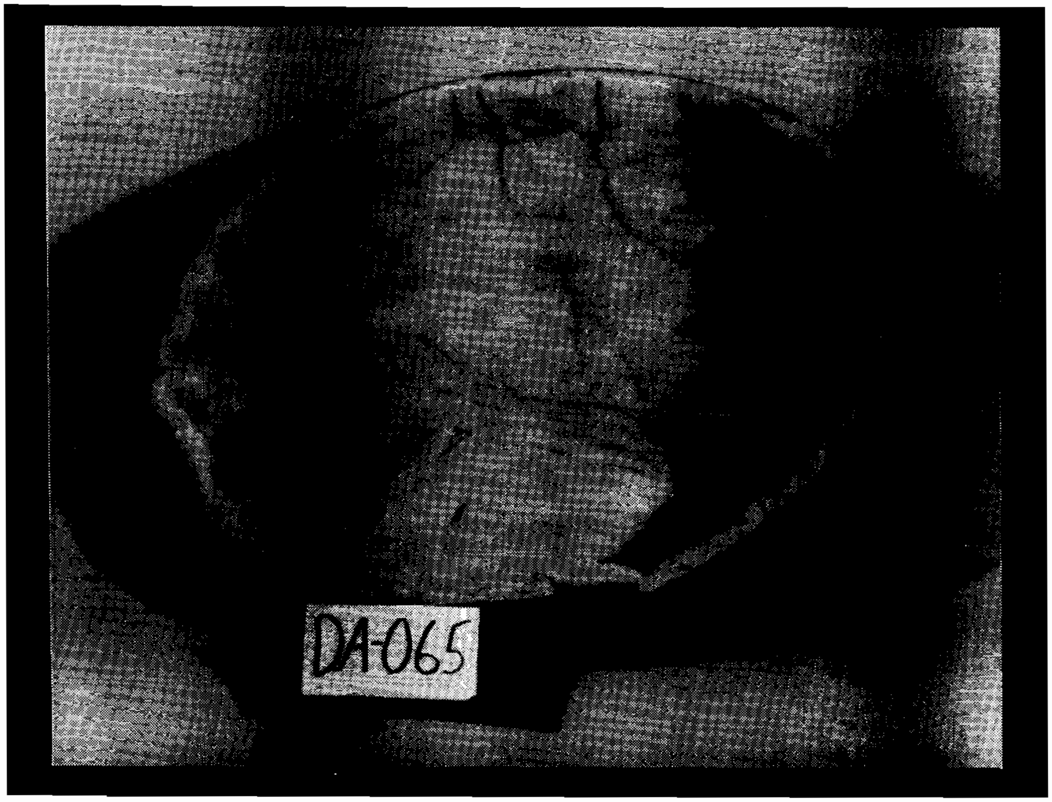


FIGURE 41. TYPICAL VIEW OF JACKET WITH .8" THICK GLASS FIBER INSULATION, AFTER IMPACT.

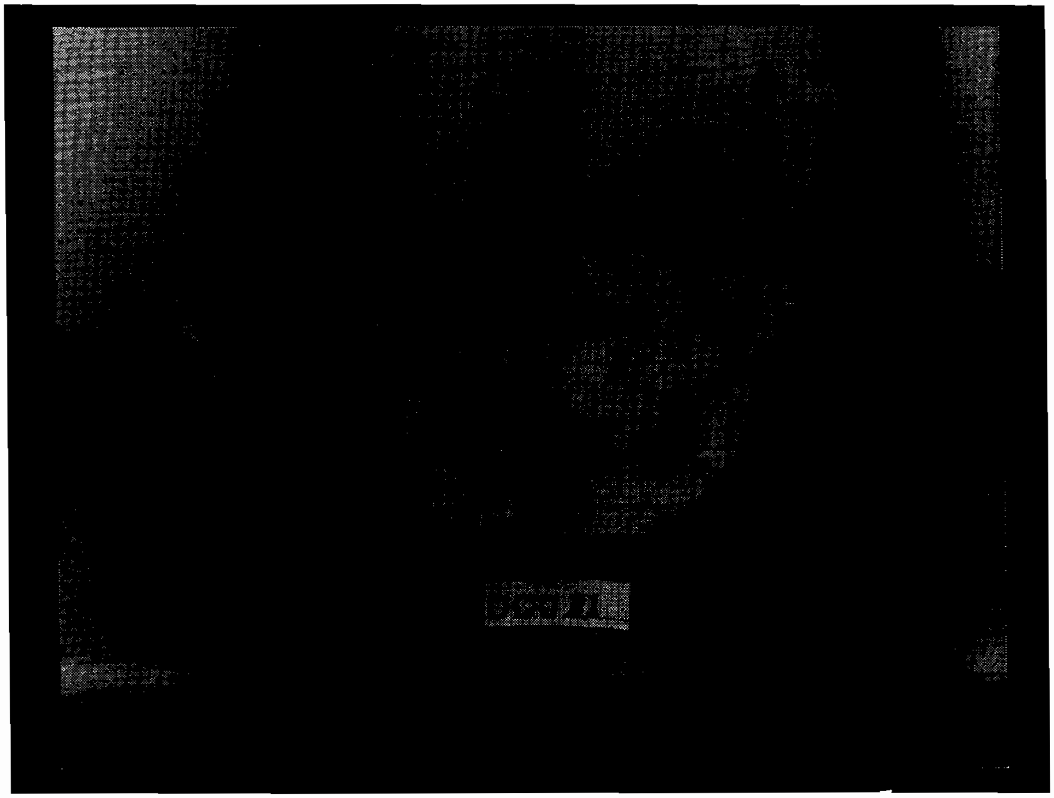


FIGURE 42. TYPICAL VIEW OF SHIELD WITH .8" THICK GLASS FIBER INSULATION, AFTER IMPACT.

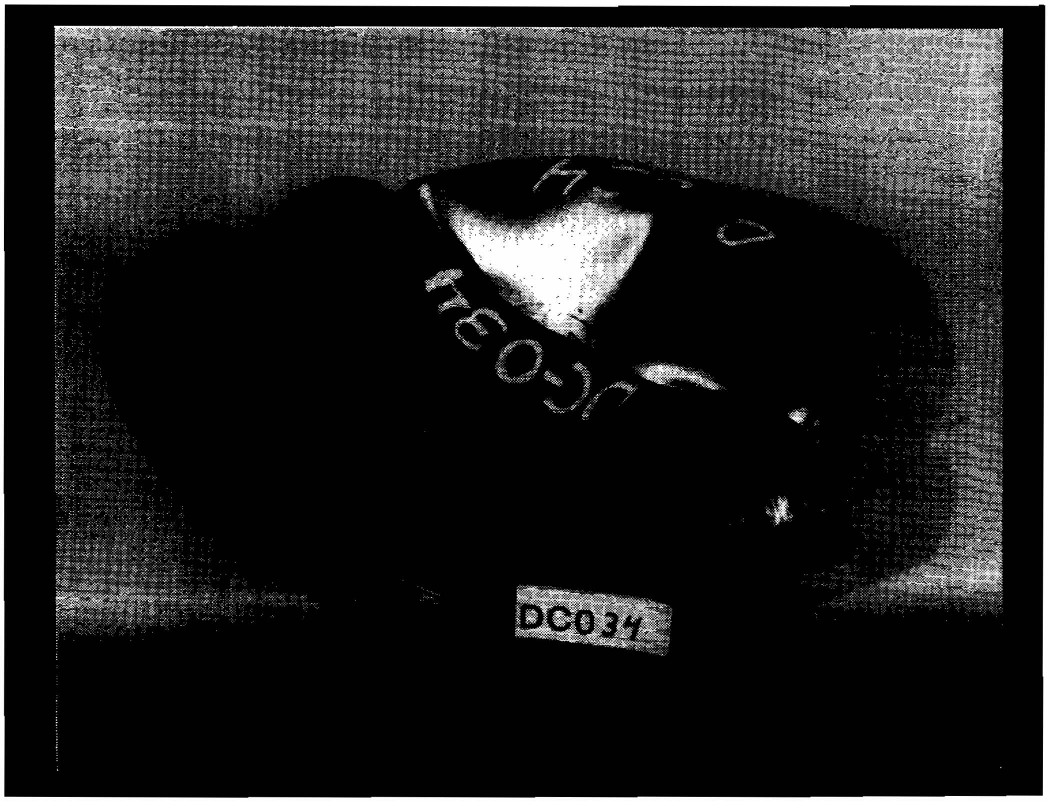
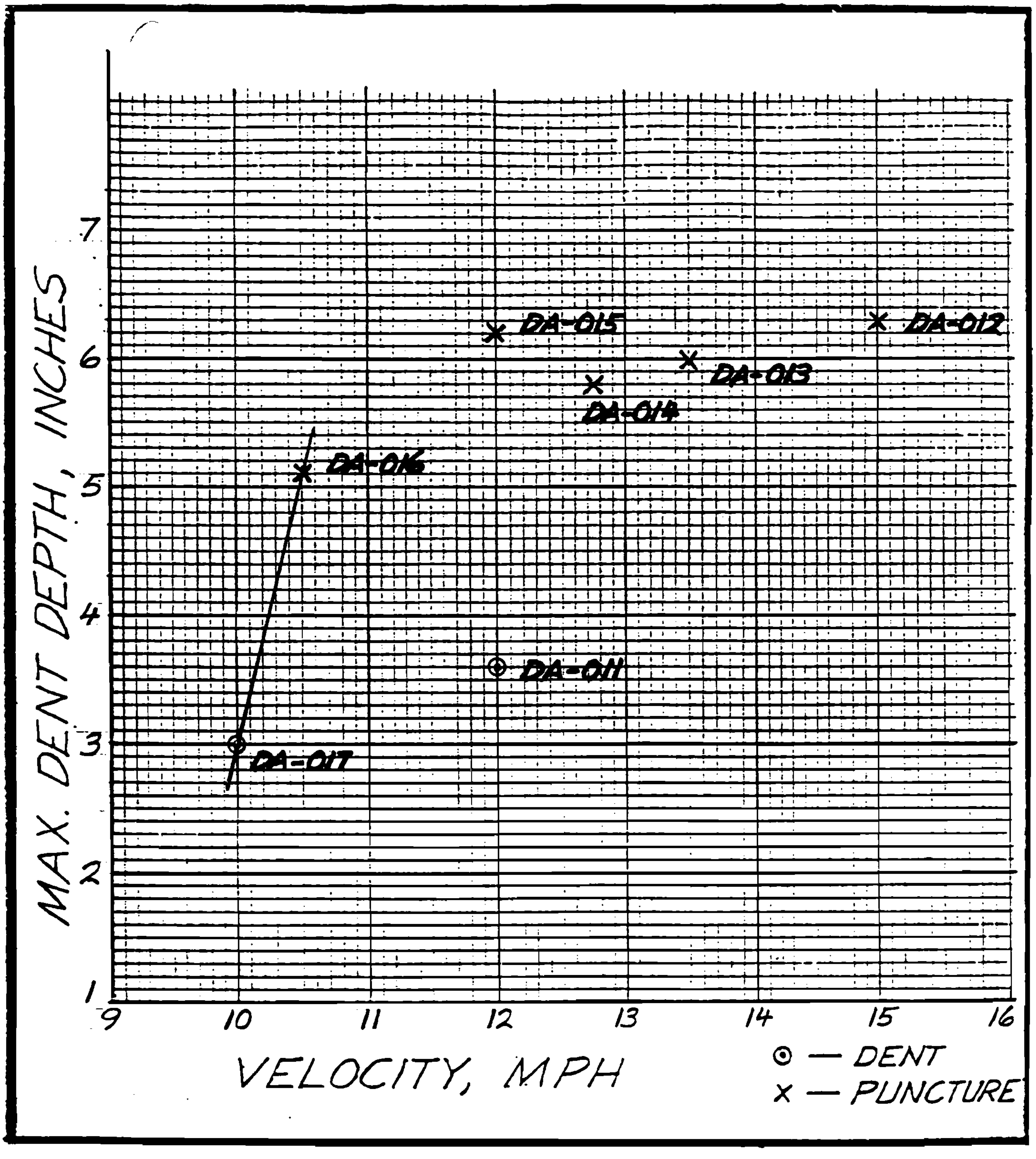


FIGURE 43. TYPICAL DENT FORMATION OF A SHIELDED 111 HEAD - NOTE THERMOCOUPLE ATTACHED FOR COLD TEMPERATURE TESTS.

FIGURE 44. VIEW OF IMPACTED 111 HEAD, SHIELD REMOVED, AT SILL AREA - NOTE SEVERE FOLDING AND PINCHING AT FLANGE WELD AREA.



*MOVEMENT OF TANK FIXTURE DURING IMPACT, SUSPICIOUS RESULTS

FIGURE 45. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-01. AMBIENT TEMPERATURE.

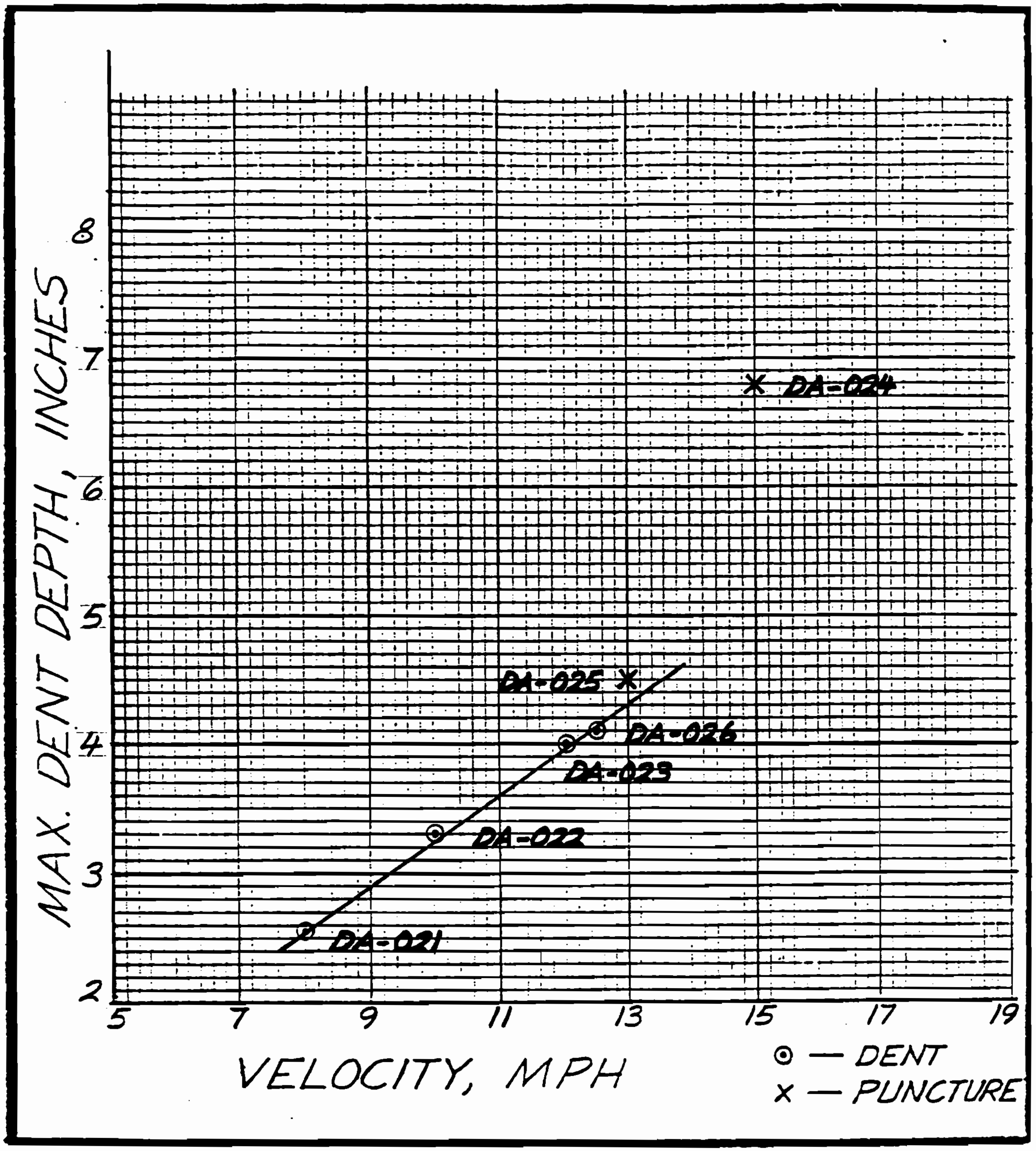


FIGURE 46. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-02. AMBIENT TEMPERATURE.

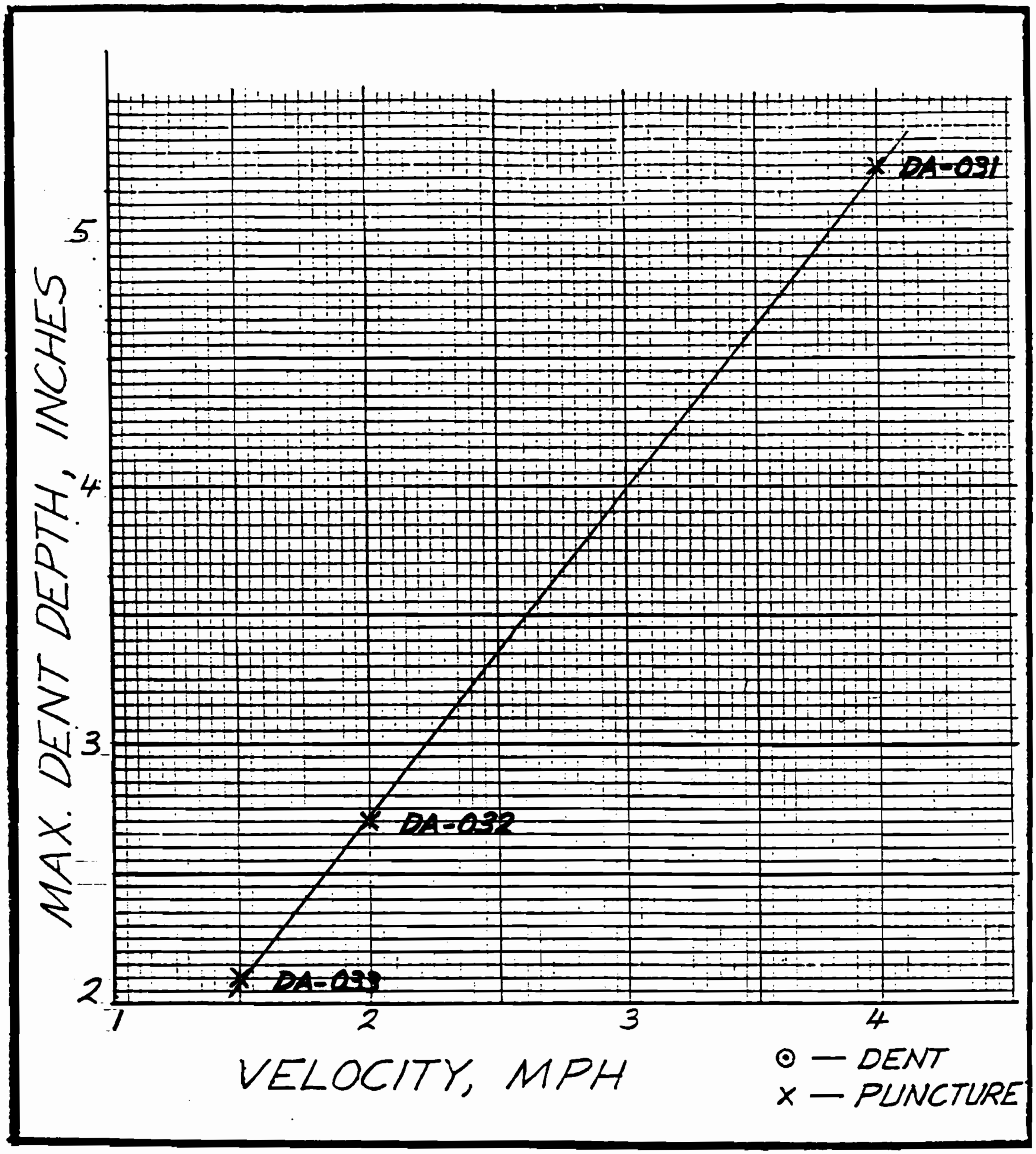


FIGURE 47. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-03. AMBIENT TEMPERATURE.

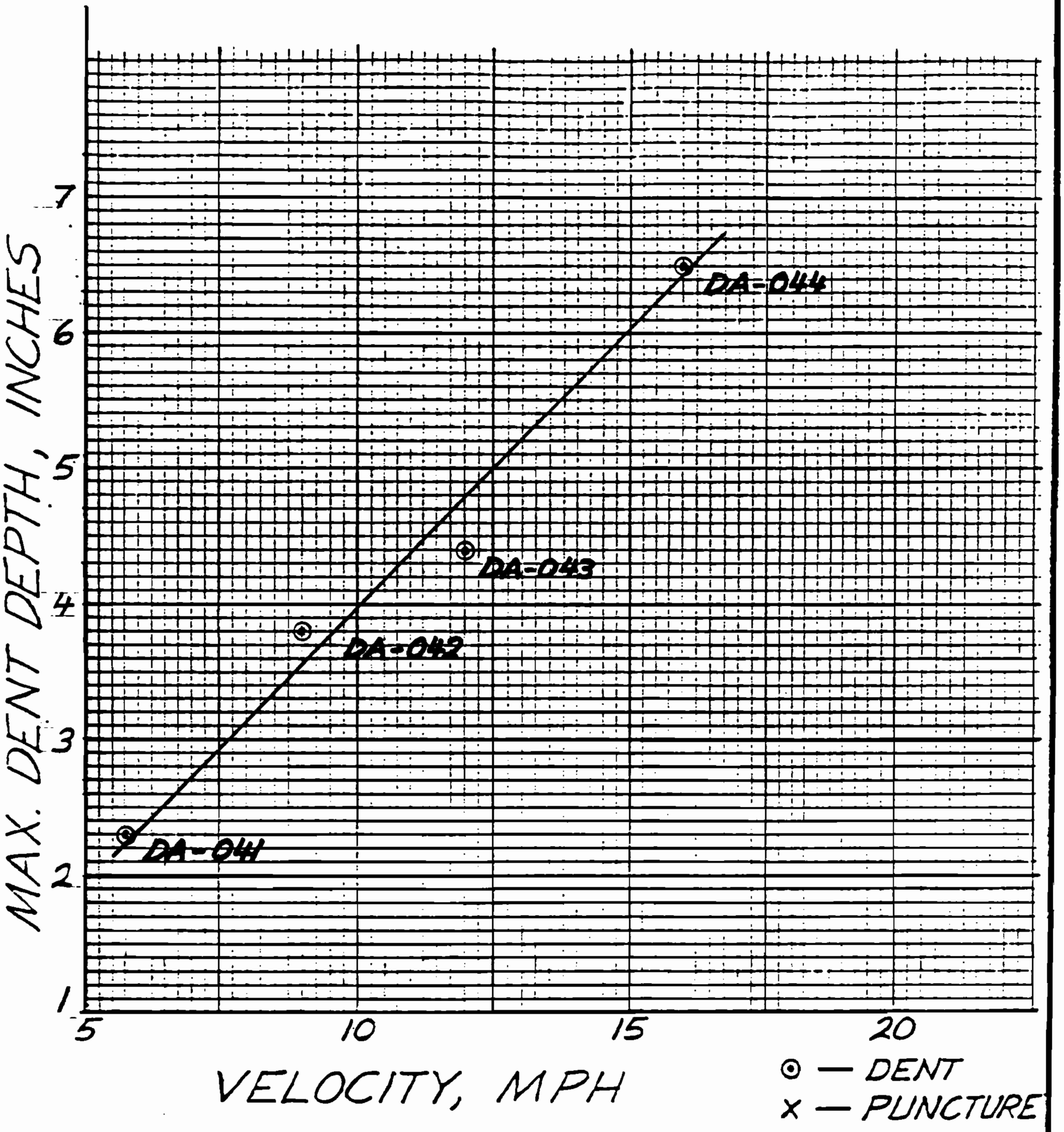


FIGURE 48. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-04. AMBIENT TEMPERATURE.

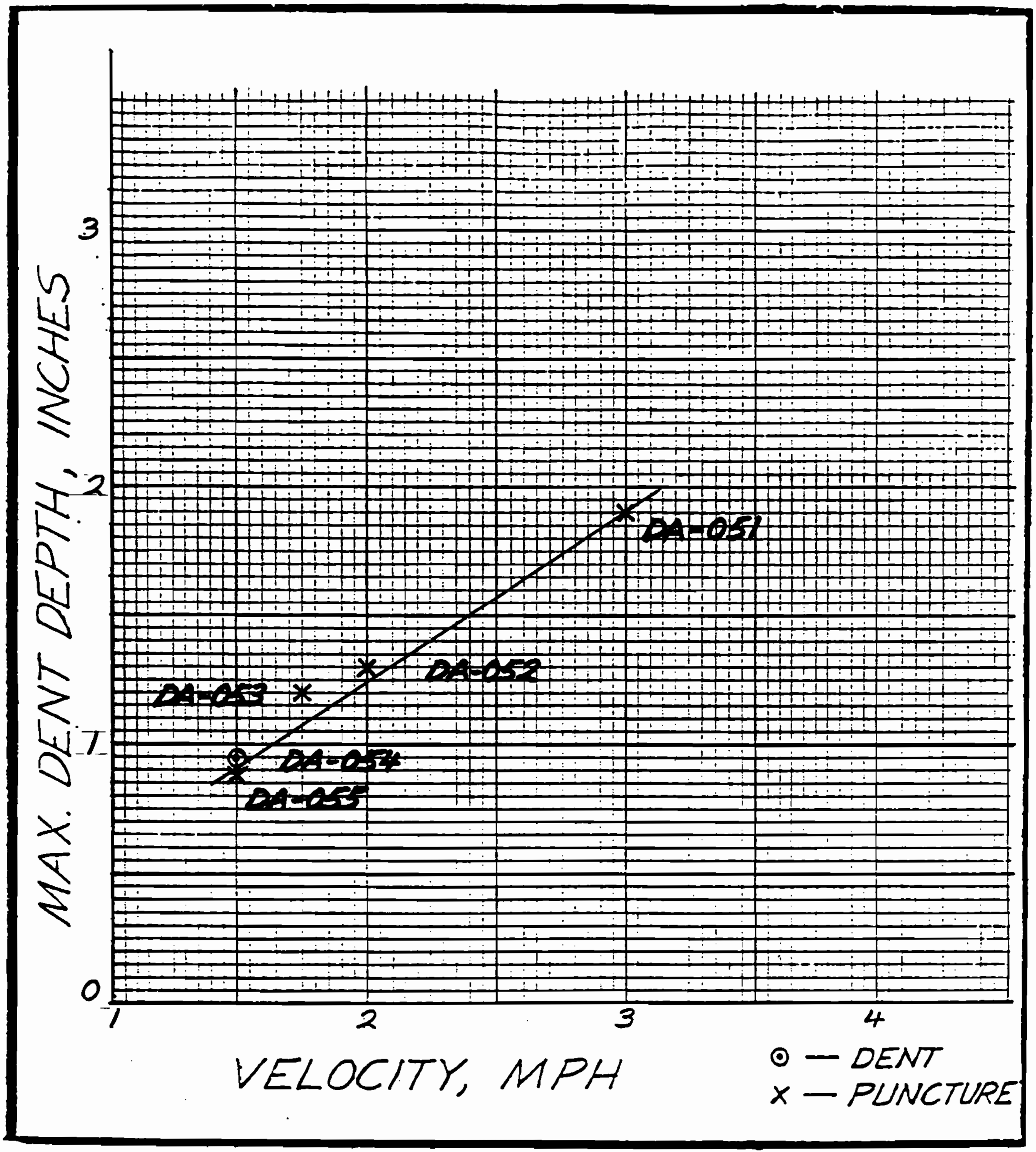


FIGURE 49. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-05. AMBIENT TEMPERATURE.

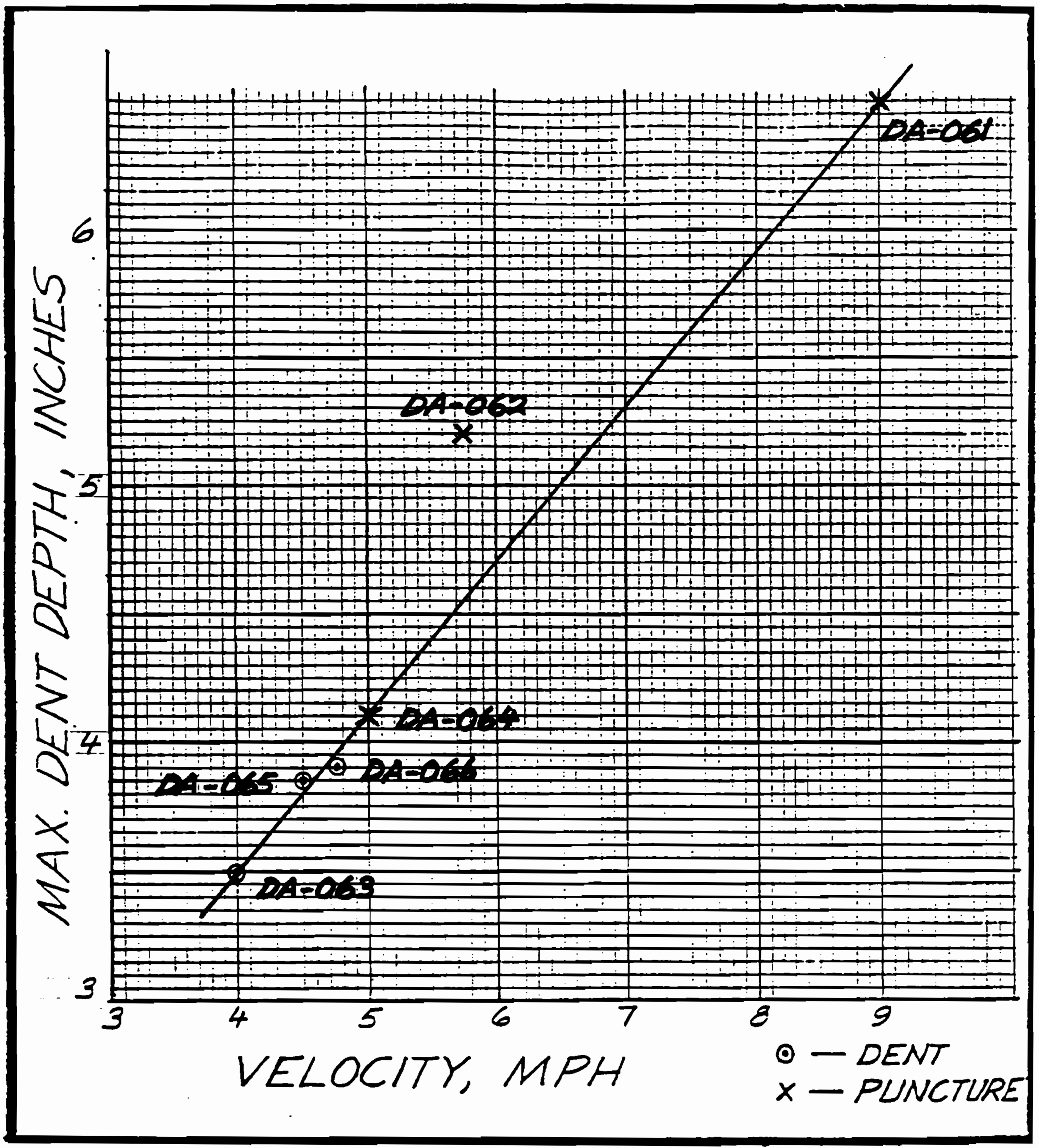


FIGURE 50. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-06. AMBIENT TEMPERATURE.

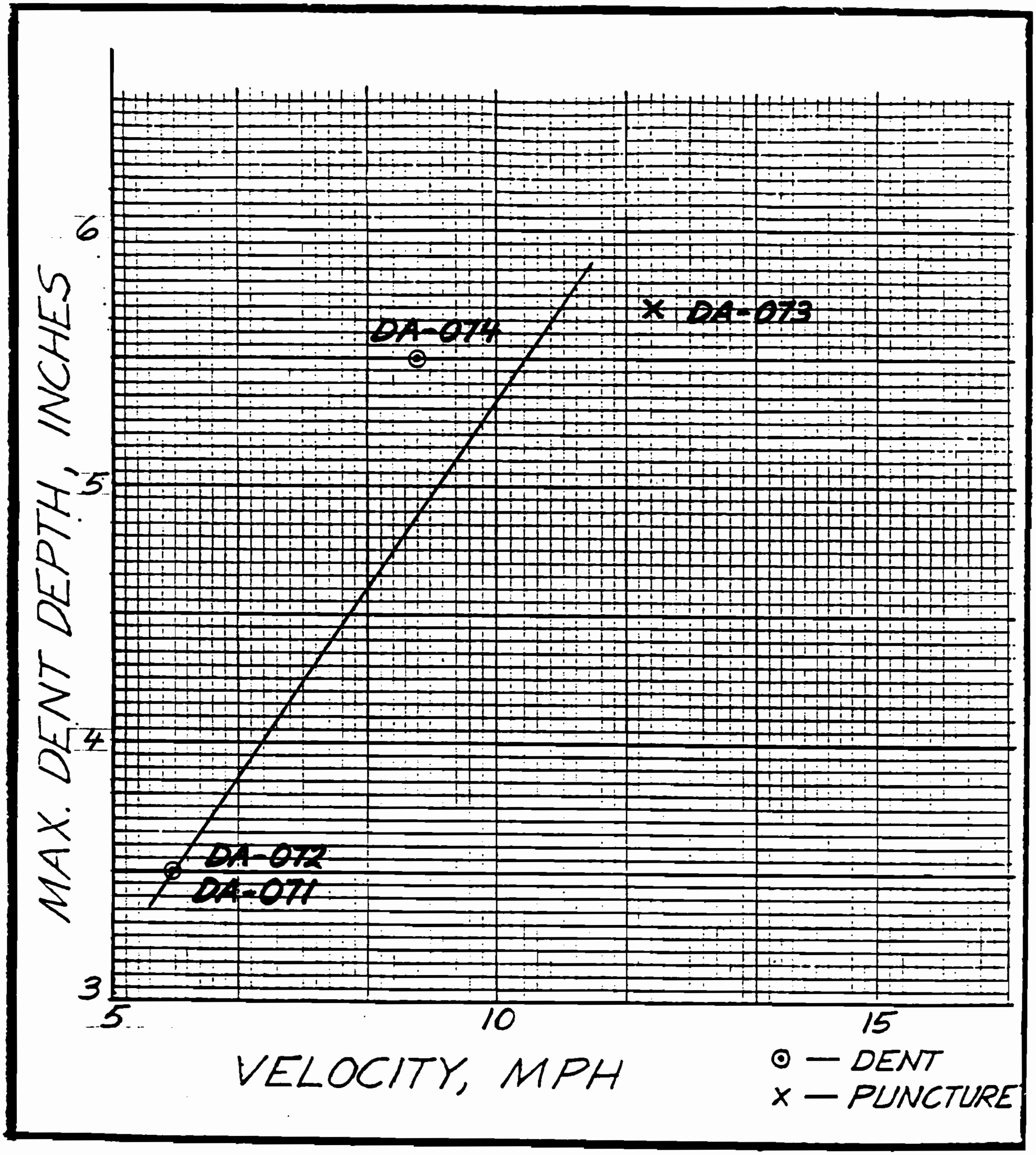


FIGURE 51. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-07. AMBIENT TEMPERATURE.

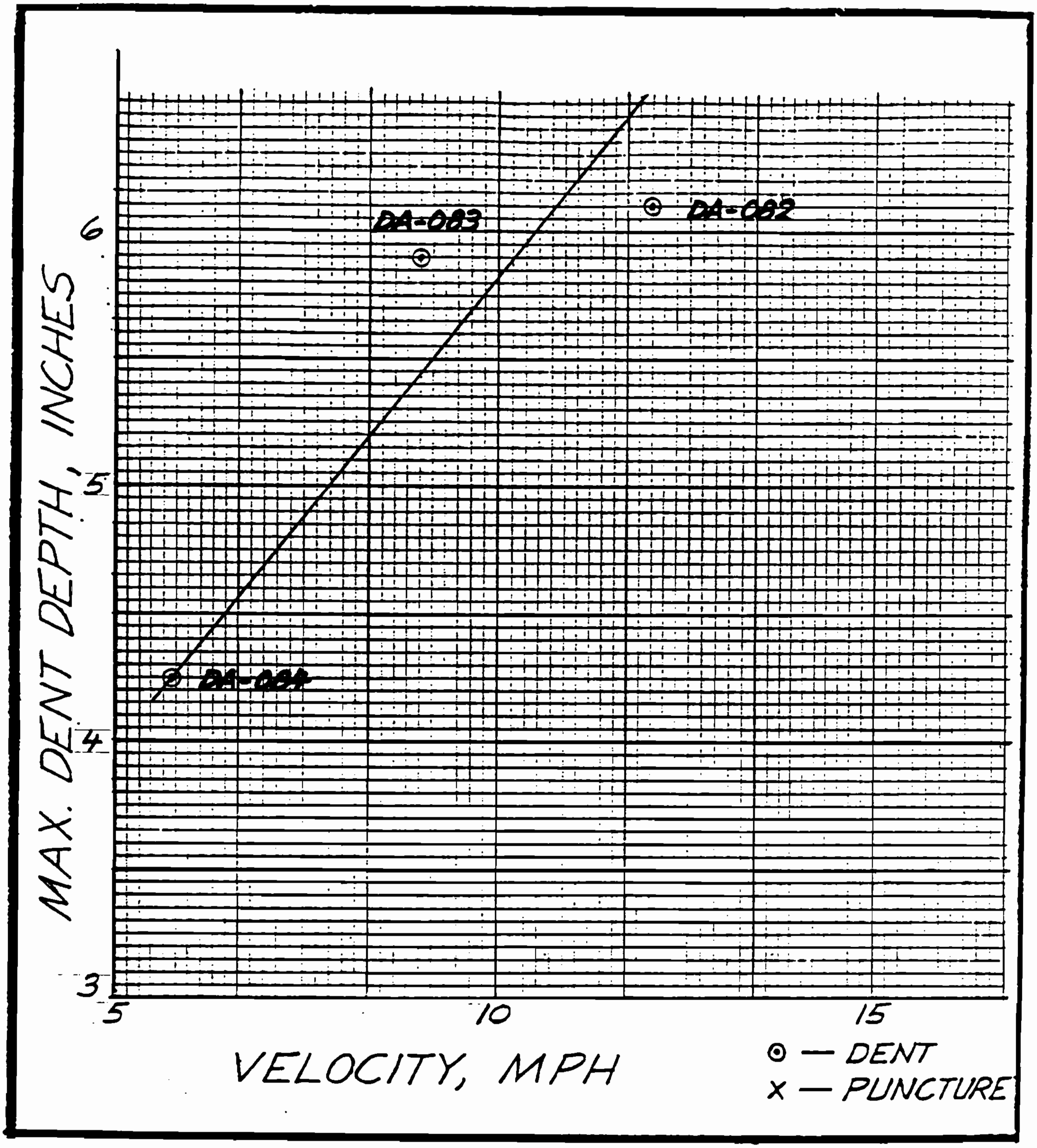


FIGURE 52. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DA-08. AMBIENT TEMPERATURE.

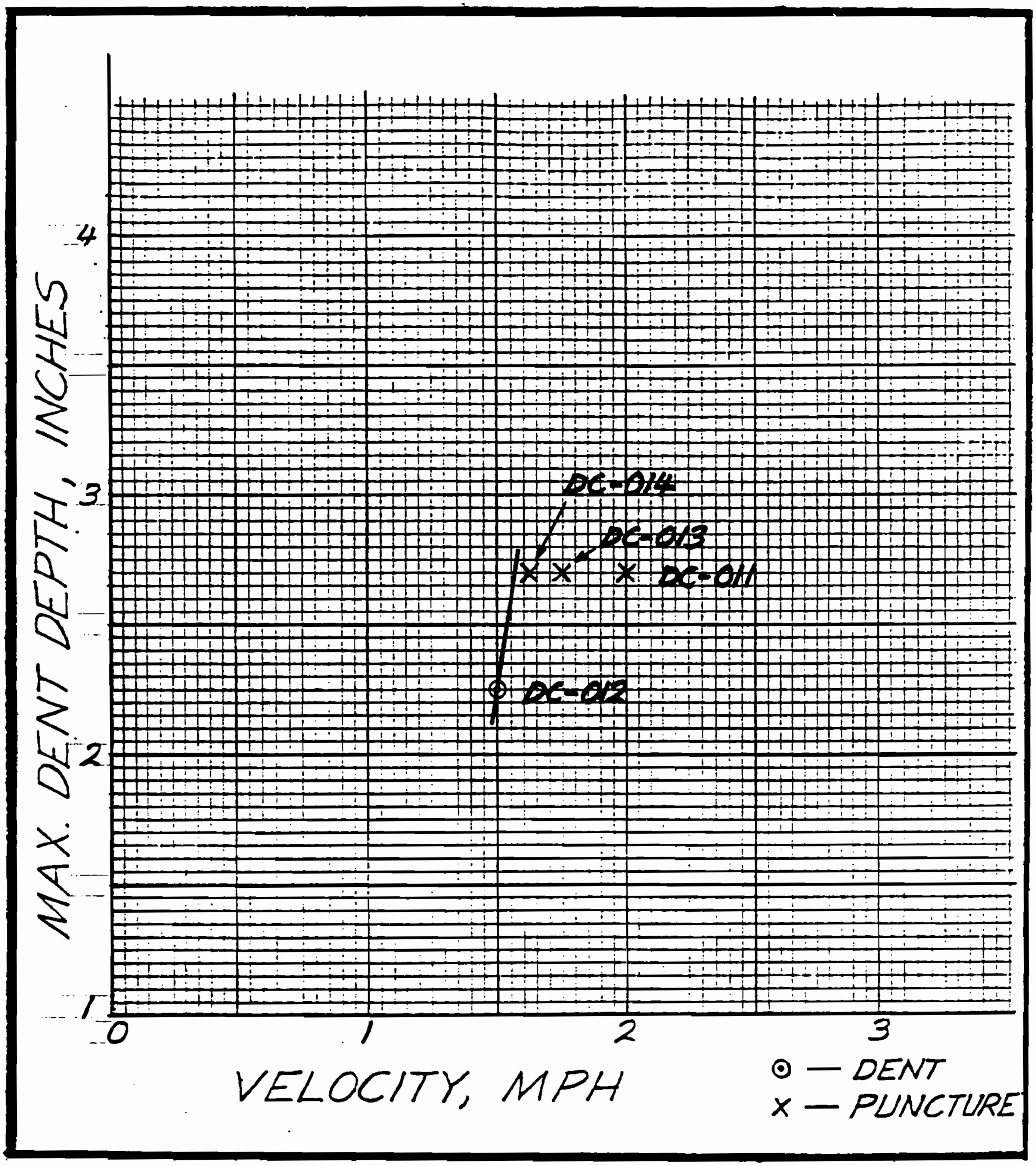


FIGURE 53. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-01. COLD TEMPERATURE (+32°F).

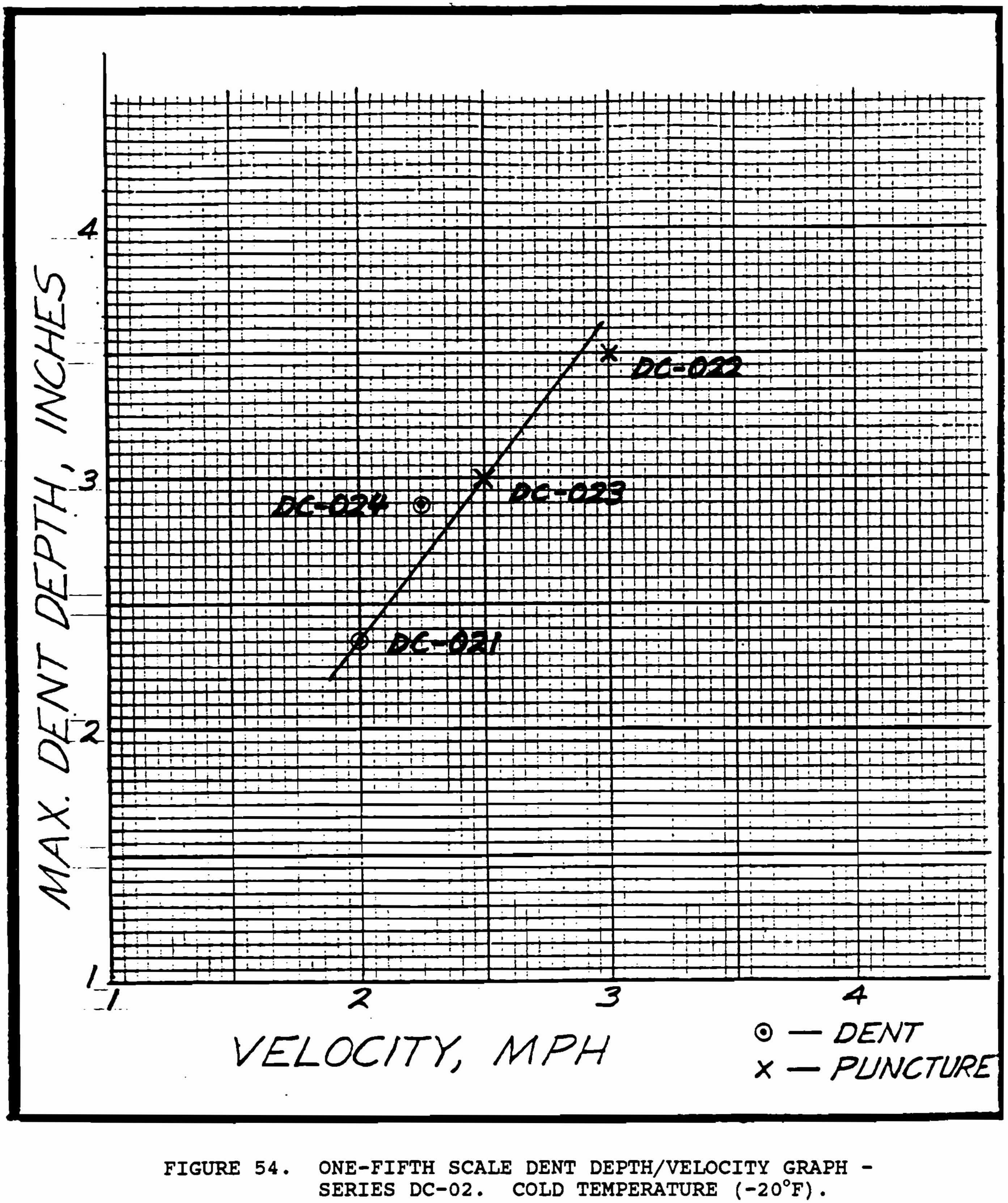


FIGURE 54. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-02. COLD TEMPERATURE (-20°F).

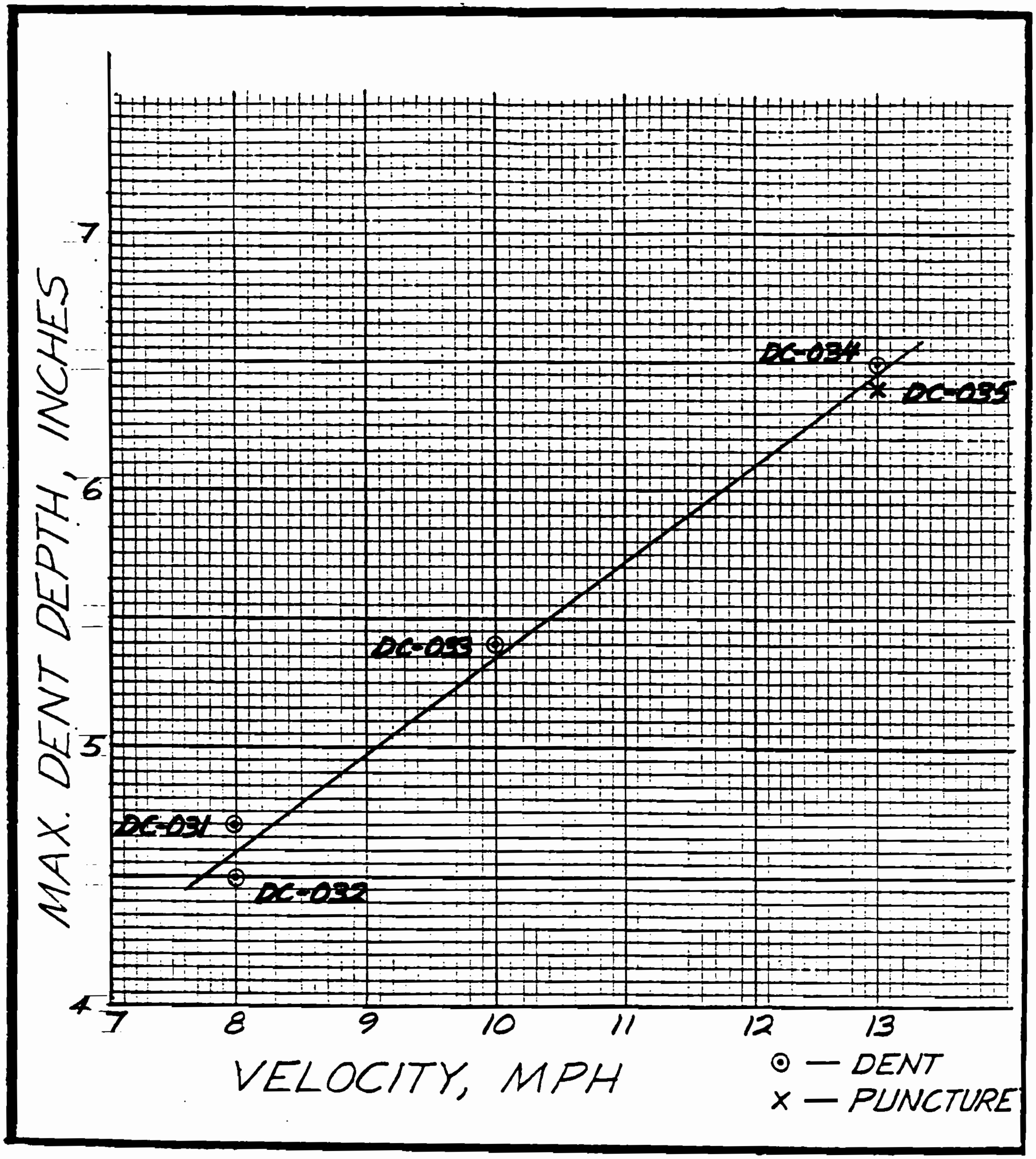


FIGURE 55. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-03. COLD TEMPERATURE (-20°F).

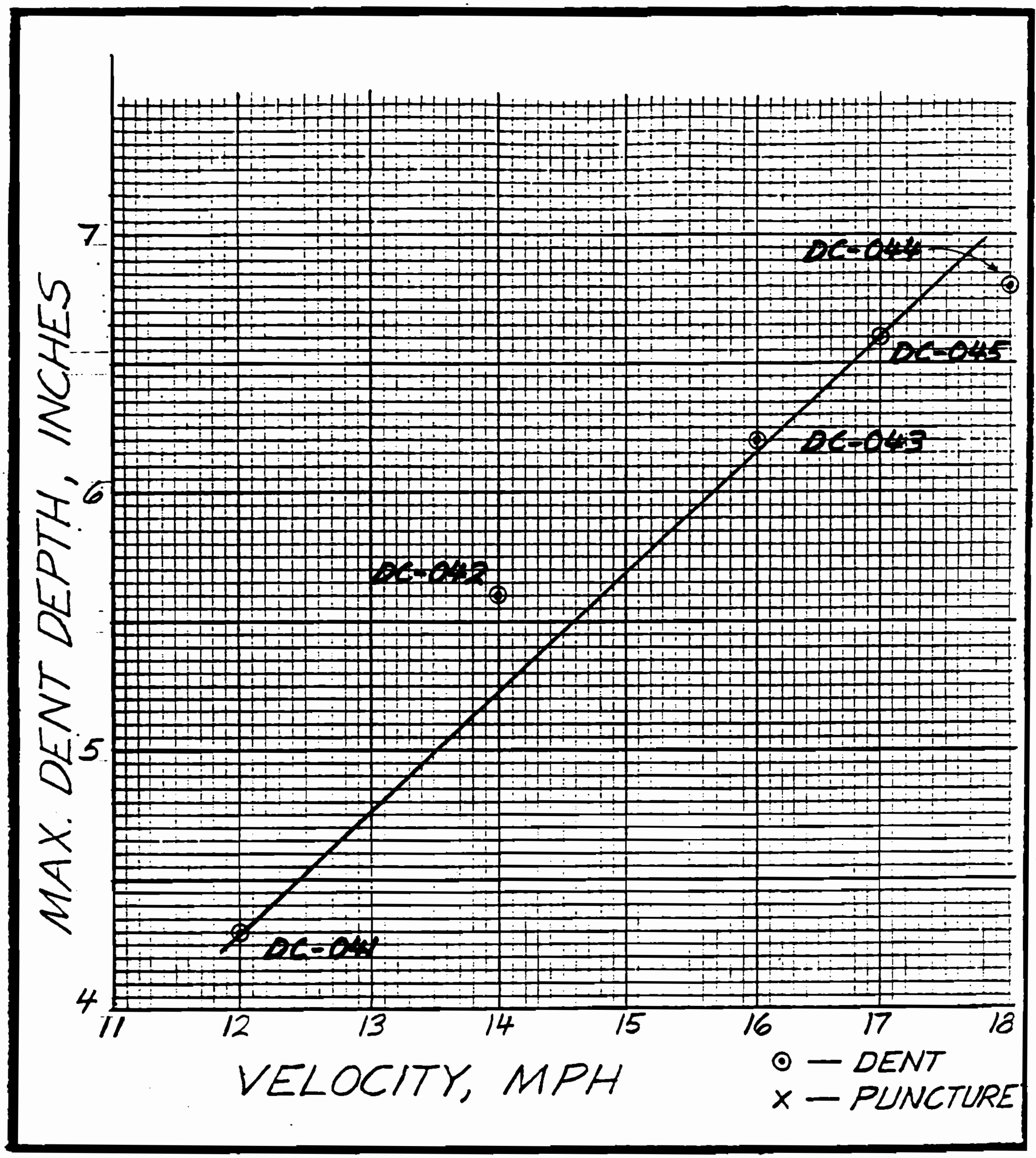


FIGURE 56. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-04. COLD TEMPERATURE (+32°F).

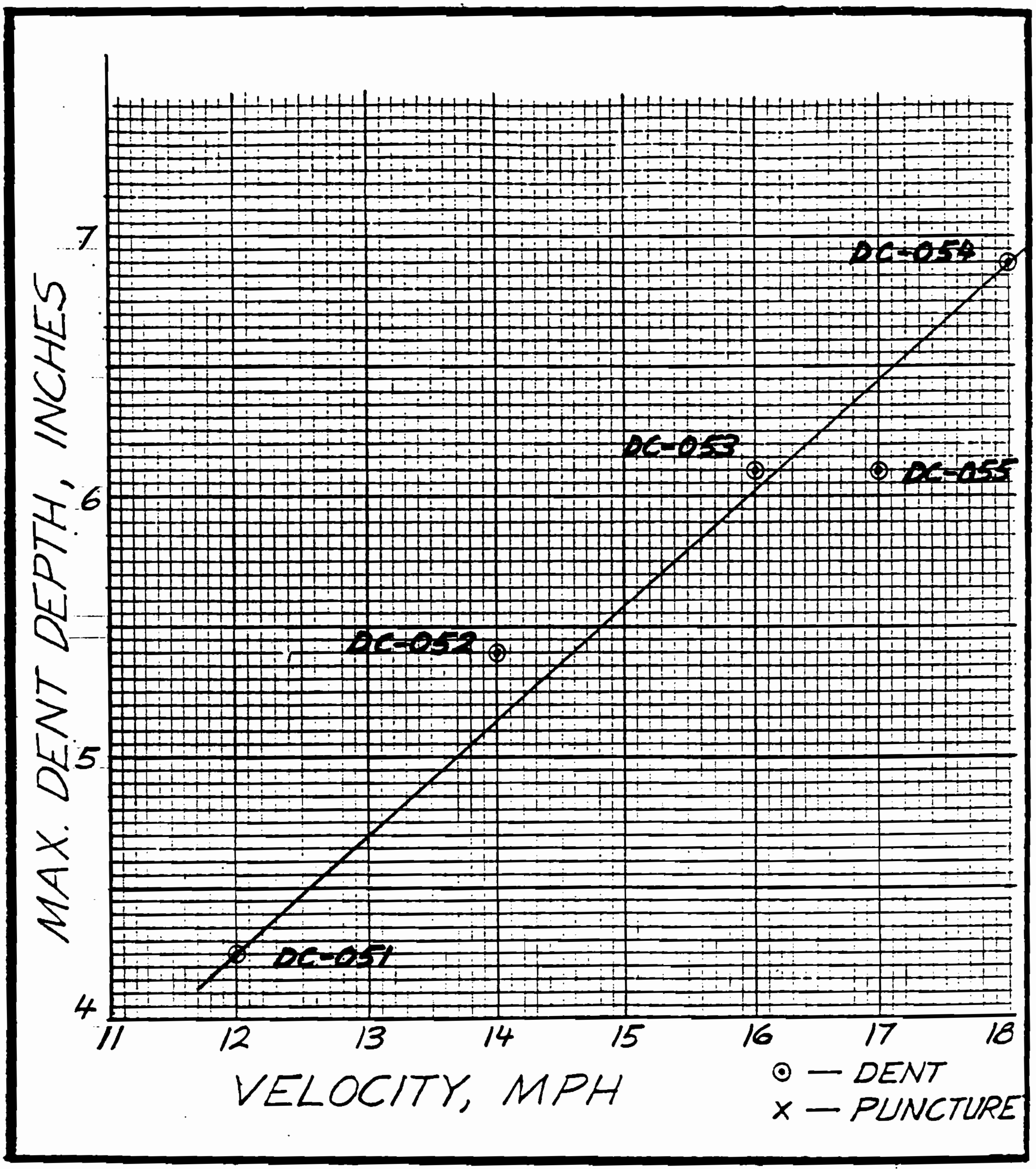


FIGURE 57. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-05. COLD TEMPERATURE (-20°F).

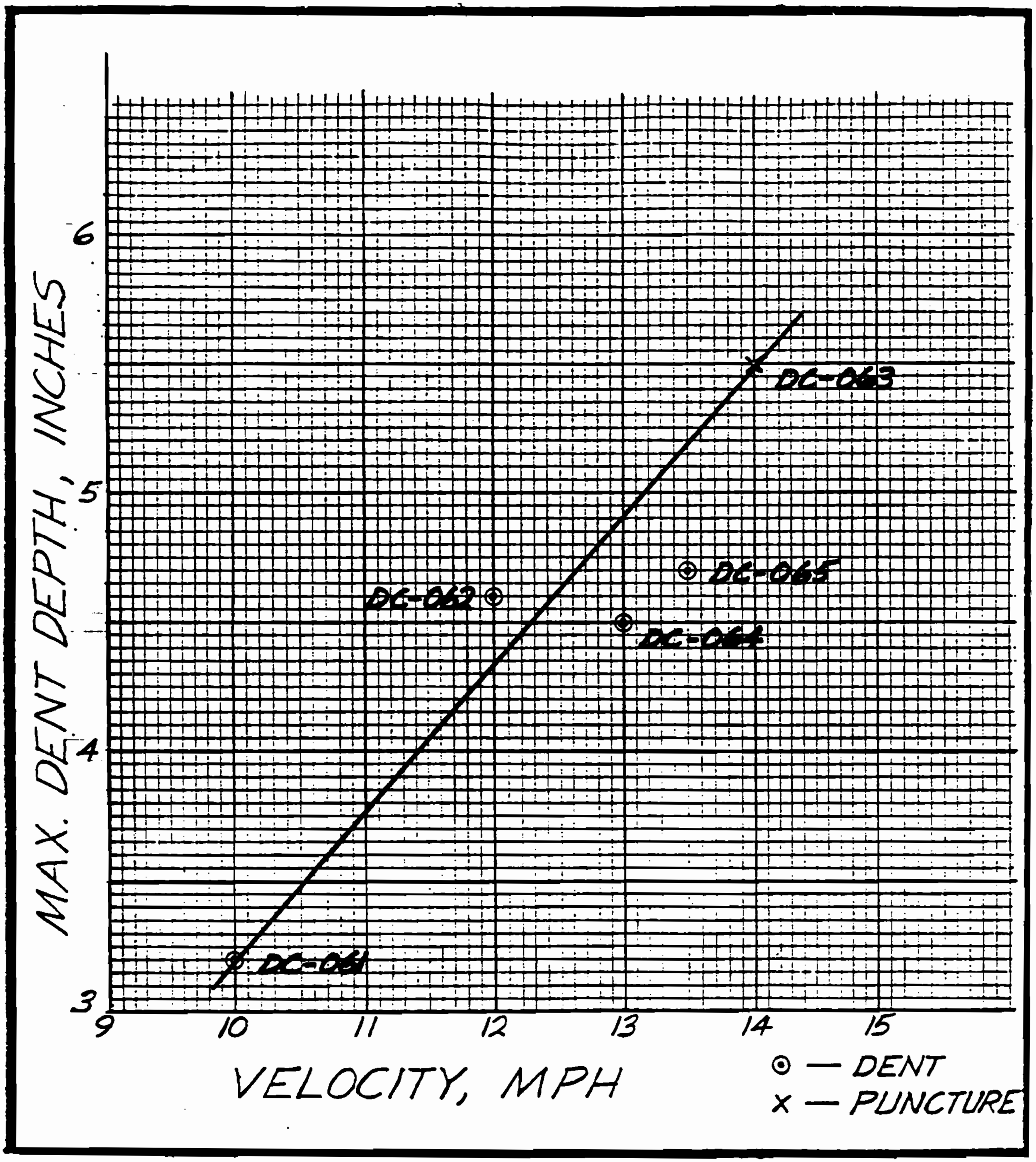


FIGURE 58. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-06. COLD TEMPERATURE (+32°F).

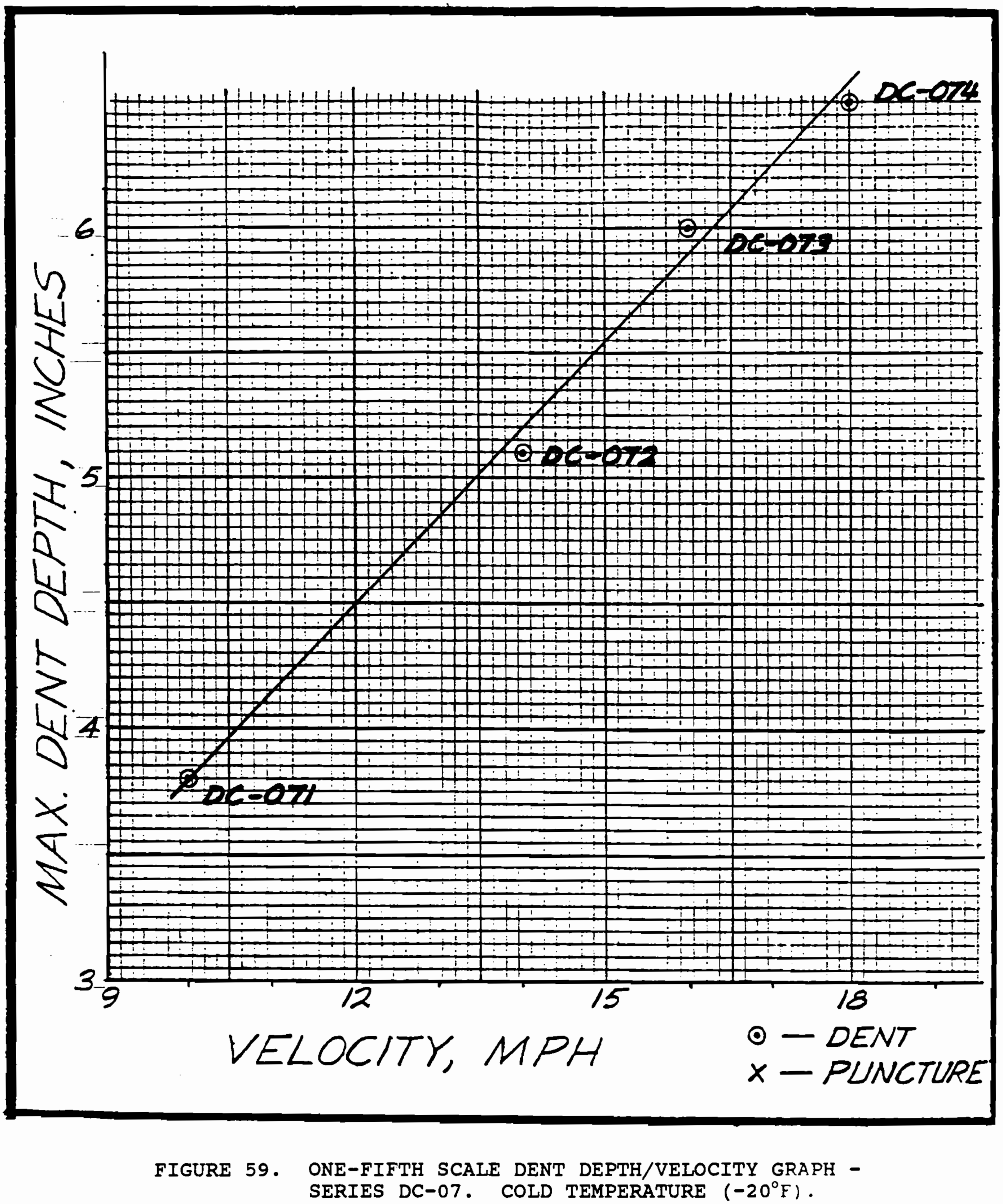


FIGURE 59. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-07. COLD TEMPERATURE (-20°F).

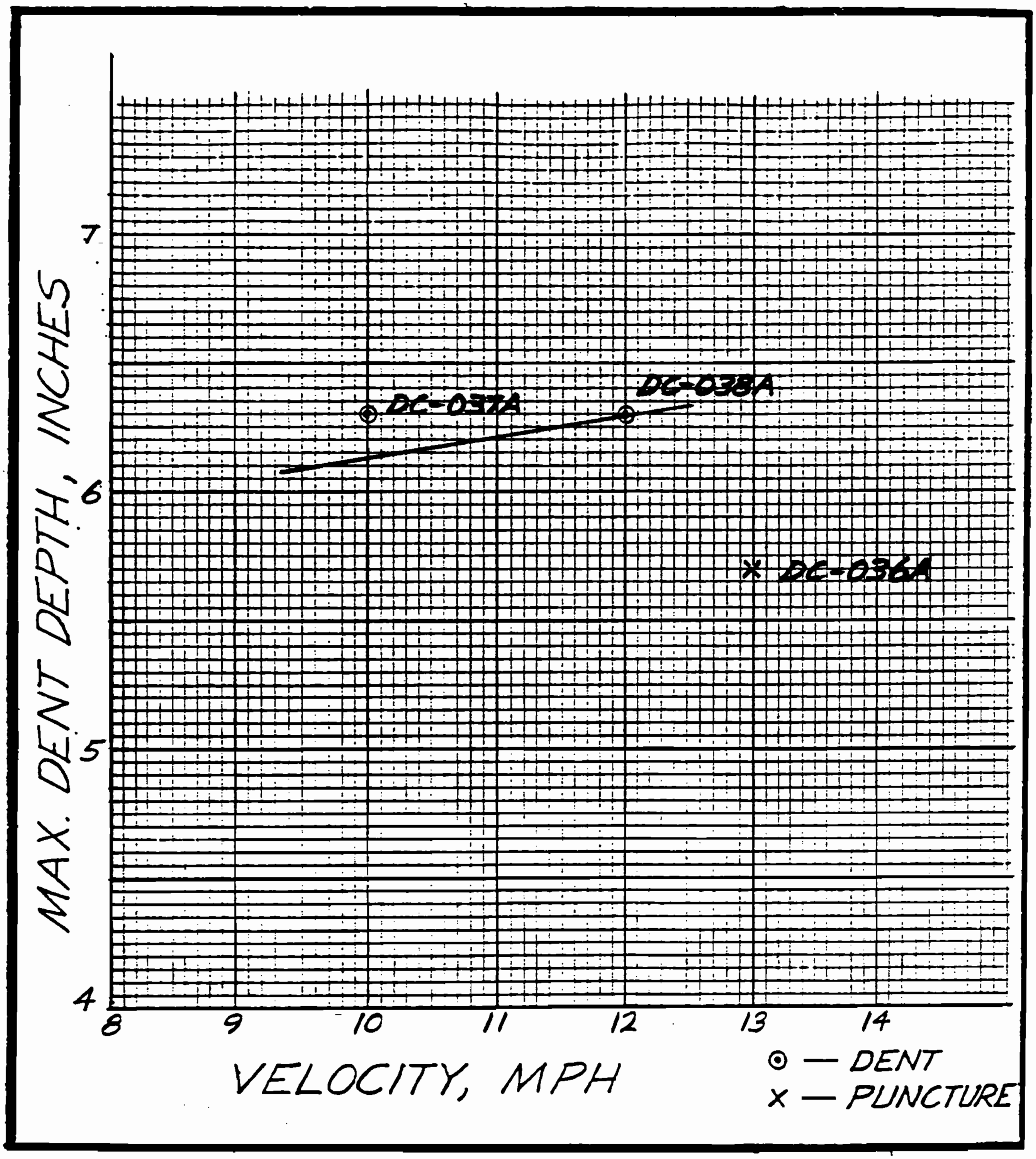


FIGURE 60. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-03A. COLD TEMPERATURE (-20°F).

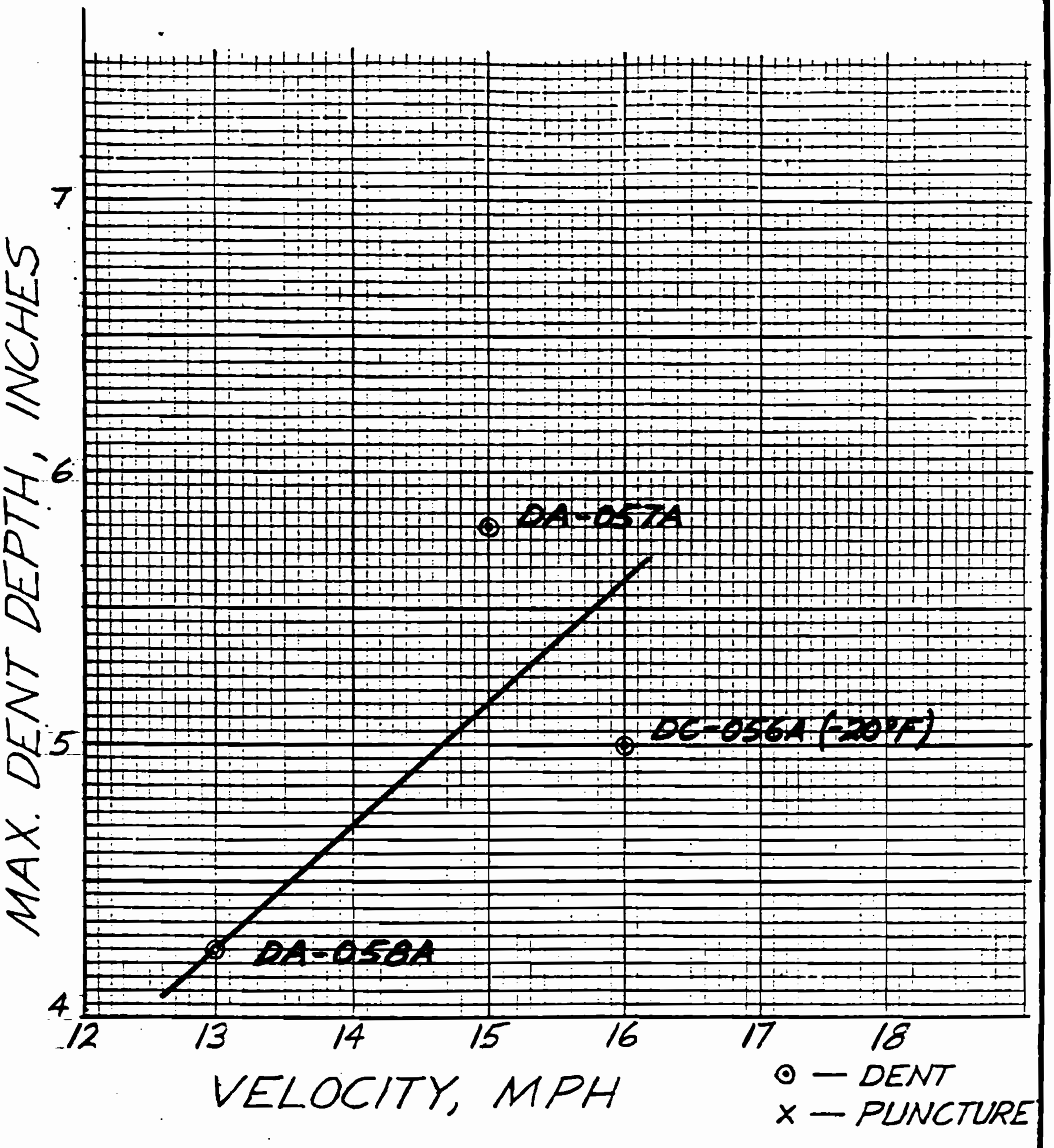


FIGURE 61. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-05A. COLD/AMBIENT TEMPERATURE.

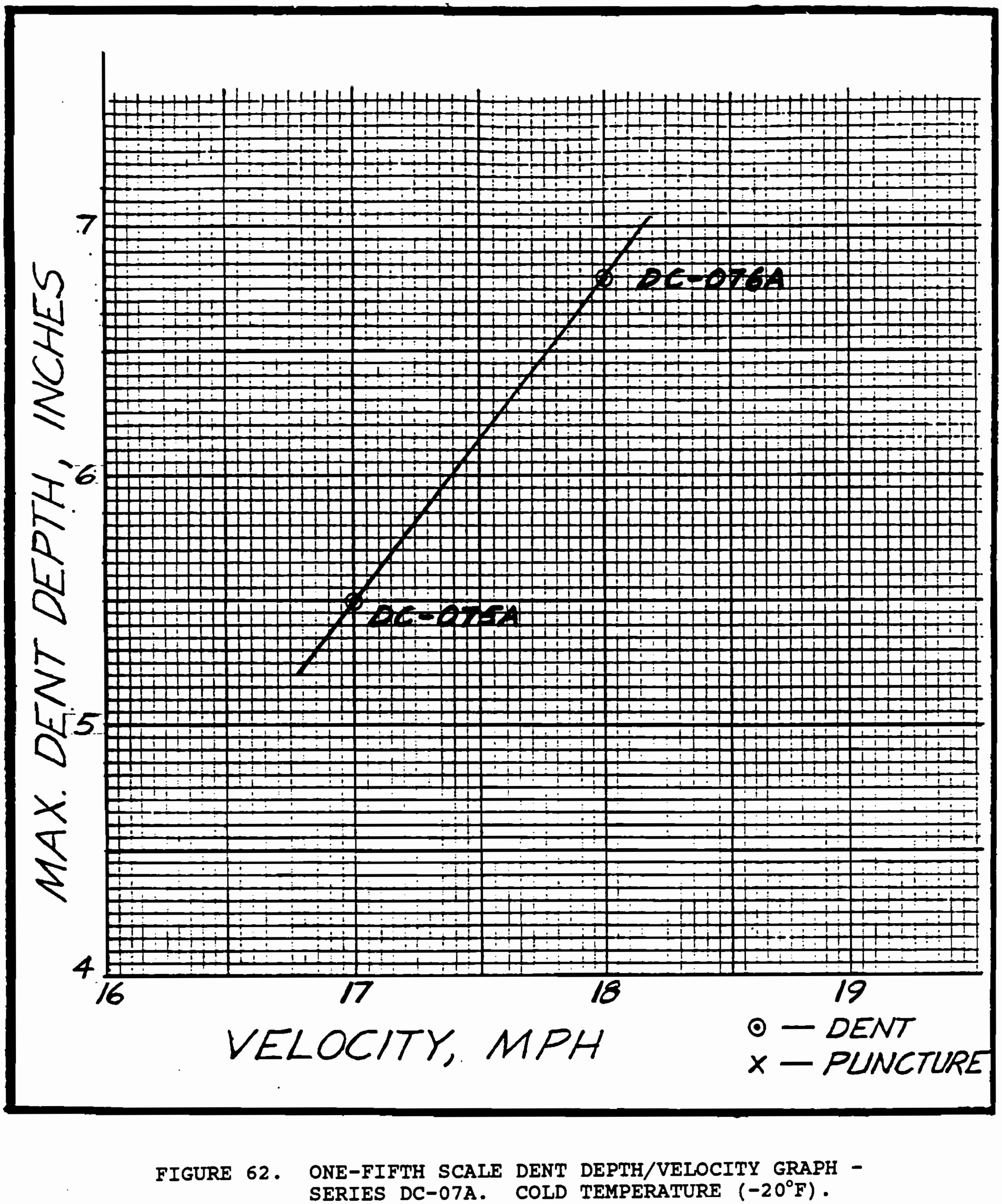


FIGURE 62. ONE-FIFTH SCALE DENT DEPTH/VELOCITY GRAPH - SERIES DC-07A. COLD TEMPERATURE (-20°F).

In Table 4, test series DA-01, DA-02, and DA-03 represented the base test parameters for head assembly construction of DOT Type 112, 105, and 111 tank cars, respectively. All other test series, including those tested at cold temperature conditions (Table 5), have at least one test variable changed from the baseline condition (i.e., temperature, pressure, and thickness).

The following sections attempt to identify any influences on puncture resistance which each test variable appears to have contributed.

12.1 DOT TYPE 105, 112, AND 111 HEAD ASSEMBLY CONSTRUCTION - BASELINE CONFIGURATION

As stated above, test series DA-01, DA-02, and DA-03 represented the base test configurations of the three types of tank cars under ambient temperature conditions. Their corresponding puncture resistance curves are presented in Figures 45 through 47.

The Type 112 LPG configuration of test series DA-01 represented a full scale 120-inch-diameter, 11/16-inch-thick TC-128 steel head. It incorporated a scaled down carbon steel head shield with ceramic fiber insulation blanket (both from 1/2 inch down to .100 inch thick). Internal pressure was 100 psig.

The Type 105 chlorine configuration of test series DA-02 represented a full scale 102-inch diameter, 13/16-inch-thick

TC-128 steel head. This assembly incorporated a scaled down steel jacket with urethane foam insulation (from 1/2-inch and 4-inches-thick down to .025 inch and .8 inch, respectively). Internal pressure was 100 psig.

The last of the three baseline head configurations was the Type 111 aluminum tank car of test series DA-03. This series represented a full scale 102 inch diameter, 5/8-inch-thick aluminum alloy head. This assembly was a bare head configuration with no shield or jacket protection. The head thickness was scaled down to an actual .125 inch. Internal pressure was 4 psig.

12.1.1 Type 112 vs. 105 Puncture Resistance (Figures 45 and 46, Respectively)

The test results between the two steel head configurations (Type 105 and Type 112) show a 24 percent greater puncture resistance velocity of the 105 head construction versus the 112. This is despite the fact that the composite steel thickness of the head/shield system of the 112 head assembly is 27 percent greater than the thickness of the 105 head/jacket system. Furthermore, the tensile and yield strengths of the Type 112 shield material are approximately 100 percent greater than those of the jacket material used in the Type 105 assembly. The corresponding dent depth/velocity graphs (Figures 45-46) show dent depths, near puncture thresholds, being very nearly the same; close to 4 inches.

In consideration of the above results, one possible explanation for the increased puncture resistance of the Type 105 configuration is the insulation type and thickness used. The nearly 1-inch-thick urethane foam may have greatly contributed to energy absorption and puncture protection. Figure 39 is a typical impacted, foamed jacket. Conversely, the thin .100-inch ceramic fiber blanket of the Type 112 configuration (Figure 40) appears to provide very little in puncture protection qualities.

12.1.2 Type 111 Puncture Resistance (Figure 47)

Test results of the Type 111 bare aluminum heads show very low puncture resistance, as expected. The 1.5 mph puncture velocity threshold was a full 9 mph less than that of the Type 112 configuration. The tensile and yield strengths of the 5052 aluminum alloy are only 48 percent and 53 percent, respectively, of the TC-128 steel alloy.

12.2 TYPE 111 ALUMINUM - HEAD THICKNESS VARIABLES

Two test series were designed to deviate from the Type 111 baseline conditions by varying head thickness only. Test series DA-04 incorporated a thinner, 1/2-inch-thick aluminum head (scaled down to an actual .100 inch thickness). Test series DA-05 had a thicker, 15/16-inch head (scaled down to .190 inch).

Test series DA-04 was modified further by adding a head shield. The reason for this change from the original plan was because of the extremely low puncture velocities experienced in test series DA-03. Section 12.3 discusses results from this series.

The test results from series DA-05, shown in Figure 49, indicate very low puncture threshold velocities, between 1.5 and 1.75 mph. This is practically the same as found in series DA-03. It would indicate that a 29 percent thicker aluminum head offers very little in increased puncture resistance.

12.3 DOT TYPE 111 ALUMINUM - JACKET OR SHIELD VARIABLES

Four test series deviated from the Type 111 baseline condition by varying the type of insulation jackets or head shields installed over the heads and also the head thickness.

As mentioned in the previous section, test series DA-04 was modified by installing a 3/4-inch-thick steel shield. The shield was TC-128 steel alloy (.150 inch actual thickness), cut from existing one-fifth scale heads left over from a previous test program. Insulation was 4-inch-thick glass fiber, scaled down to .8 inch. Figure 42 shows a typical impacted shield with glass fiber insulation.

Test series DA-06 was a 5/8-inch-thick aluminum head with 1/8-inch steel jacket, scaled to .125 inch and .025 inch, respectively. Insulation was 4-inch-thick glass fiber. Figure 41 shows a typical impacted jacket with glass fiber insulation.

Test series DA-07 was a 5/8-inch-thick aluminum head with 1/2-inch-thick shield. Insulation was 4-inch-thick glass fiber.

Test series DA-08 was a 1/2-inch-thick aluminum head with 1/2-inch-thick shield. Insulation was 4-inch-thick glass fiber.

The test results from series DA-04 and DA-06 through DA-08 show that head shield protection increases puncture resistance dramatically, while the light gage jacket material provides only a modest increase (Figure 48 and 50, 51 and 52). The shield protected aluminum heads, regardless of head thickness, deformed easily with no punctures occurring at the impact area. Further deformation by the impactor coupler was prevented by contact with the inner air tank of the pressure vessel. In one test series (DA-07), a leak did appear at the weld joint between the head and the cylindrical section during a 12 mph impact. This was a result of extreme folding and pinching at the sill area; Figure 44 is an example of this.

12.4 COLD TEMPERATURE CONDITIONS

Test series DC-01 through DC-07 were conducted at temperatures below ambient, specifically +32°F and -20°F. Four of these series were conducted on Type 105 and Type 112 steel heads, with the remainder being Type 111 aluminum. Their corresponding puncture resistance curves are presented in Figures 53 through 62.

12.4.1 Type 111 Aluminum - Bare Head (Figures 53-54)

Two test series were designed to deviate from the Type 111 baseline condition by varying temperature only. All other variables were the same, including a bare head configuration. Test series DC-01 was conducted at a head temperature of +32°F, and test series DC-02 was conducted at -20°F. Figures 53-54 show the related puncture resistance curves.

The test results from series DC-01 and DC-02 indicate that a low temperature condition appears to increase puncture resistance to a slight degree; the lower the temperature, the higher the puncture threshold. At +32°F, puncture occurred at 1.625 mph versus less than 1.5 mph for ambient temperature (DA-03). However, at -20°F, the puncture threshold rose to 2.5 mph. The low temperature appears to toughen the aluminum alloy, rather than giving it a brittle quality.

12.4.2 Type 111 Aluminum with Shield (Figure 55)

One test series, DC-03, was conducted with the addition of a scaled down 1/2-inch-thick shield and 4-inch-thick glass fiber insulation. Head temperatures were at -20°F. This configuration compares directly with test series DA-07, with all variables other than temperature being the same.

The test results (Figure 55) compare very closely with the ambient temperature tests. Cold temperature series DC-03 survived five impact tests without a puncture in the impact area. However, at an impact velocity of 13 mph, a crack developed at a weld in the sill area due to severe folding and pinching in the sill area (Figure 44). In the related ambient temperature test, a crack developed at an impact velocity of 12 mph. These results are too nearly the same to draw any conclusions about increased puncture protection due to cold temperature conditions.

12.4.3 Type 105 Steel with Jacket (Figures 56-57)

Two test series, DC-04 and DC-05, were conducted on the Type 105 steel head and jacket configuration, using a scaled down 4-inch-thick urethane foam insulation. All variables were the same as in the baseline test configuration of series DA-02, with the two exceptions of temperature and pressure. Pressures were reduced to

20 psi from 100 psi baseline, and temperatures were +32°F for series DC-04 and -20°F in series DC-05. Figures 56-57 show the corresponding puncture resistance curves.

The test results indicate an increase in puncture resistance for both cold temperature test series compared to the baseline configuration. Both DC-04 and DC-05 test series survived impact velocities of 18 mph, compared to a puncture threshold of 13 mph for the baseline series DA-02. This increase in puncture resistance can be attributed to a decrease in temperature or pressure, or a combination of both. Section 12.5 discusses additional related tests and conclusions.

12.4.4 Type 112 Steel with Shield (Figures 58-59)

Two test series, DC-06 and DC-07, were conducted on the Type 112 steel head and shield configuration, using a scaled down 1/2-inch-thick ceramic fiber insulation. Variables were the same as in the baseline configuration of series DA-01, again with the two exceptions of temperature and pressure. Pressures were reduced from 100 psi to 40 psi in series DC-06, and to 20 psi in series DC-07. Temperatures were at +32°F and at -20°F in the series DC-06 and DC-07, respectively. Figures 58-59 show the corresponding puncture resistance curves.

The test results, again, indicate an increase in puncture resistance for both cold temperature tests series when compared to the baseline configuration. DC-06 had a puncture threshold of 14 mph, compared to 10.5 mph for the baseline series DA-01. Series DC-07 survived an impact velocity of 18 mph. These results indicate that pressure and/or temperature have a marked effect on puncture resistance, the same conclusion drawn from Section 12.4.3. Section 12.5 discusses additional related tests and conclusions.

12.5 ADDITIONAL 1/5 SCALE IMPACT TESTS

As discussed in previous Sections 12.4.3 and 12.4.4, a dramatic increase in puncture resistance appears to be the results of decreased temperature or pressure, or both. To determine which variable has the greatest effect on puncture resistance, three additional series of impact tests were requested by TSC and FRA.

The three additional series included various configurations from each type of head tested in this program; i.e., Types 105, 112, and 111. Some were tested at ambient temperature, but most were tested in the cold condition. An additional variable was identified as the scaled impact coupler itself. It was reprofiled before each of these three series to determine if rounding of the impact face, from repeated impacts, could have affected puncture threshold velocities of previous tests.

12.5.1 Type 105 Steel with Jacket (Figure 60)

One of the additional test series investigated the puncture resistance of Type 105 heads at different temperatures and pressures. It was dealt with as an addition to series DC-05, with the corresponding puncture resistance curve shown as Figure 60.

Variables were the same as those in the baseline test configuration of series DA-02, with the two exceptions of temperature and pressure. Three impacts were conducted: the first was at -20°F and 20 psi pressure; the second was at ambient temperature and 20 psi pressure; the third at ambient temperature and 100 psi pressure.

The test results show no puncture at low pressure, regardless of temperature. And, a 13 mph puncture at high pressure, the same as the baseline test. This would confirm the suspicion that internal pressure, and not head temperature, has the greatest effect on the puncture resistance of the steel heads tested in this program. That is, the higher the container pressure, the lower is the puncture threshold resistance of the container.

12.5.2 Type 111 Aluminum with Shield (Figure 62)

The second additional test series investigated puncture resistance of three Type 111 heads at -20°F cold temperature conditions. The configuration was the same as series DC-03 and was therefore considered an extension of it. Figure 61 shows the corresponding puncture resistance curve. The test results show that a puncture occurred at 13 mph, which is the same velocity that a leak developed in series DC-03. However, the difference is that a puncture did not occur in the area of impact for series DC-03. Rather, a crack developed in the sill area due to folding and pinching at the perimeter weld. This difference may indicate that a puncture in the impact area occurred due to reprofiling the edge of the coupler face.

12.5.3 Type 112 Steel with Shield (Figure 62)

This third series of additional impacts investigated puncture resistance of two Type 112 heads at -20°F and -1°F cold temperature conditions, and 10 psi low pressure conditions.

The configuration was the same as in series DC-07 and was therefore considered an extension of it. Figure 62 shows the related puncture resistance curve.

The test results show that no puncture occurred up to the maximum velocity of 18 mph. This is the same result as in series DC-07. These tests seem to merely support the former results, which conclude that a low internal pressure condition in itself contributes to a higher threshold velocity than a high pressure condition. Also, reprofiling the coupler had no effect on the puncture threshold at a velocity up to 18 mph.

13.0 SUMMARY

This part of the aluminum tank car puncture test program was composed of impact tests on 78, one-fifth scale tank heads. Forty of the heads were Type 111 aluminum, some of those having different head thicknesses, and some in the bare head configuration or with jackets or head shields installed. All 20 of the Type 105 steel heads were configured with insulation jackets. The remaining 18 Type 112 steel heads were configured with head shields. Fifty percent of the heads were tested at ambient temperature conditions, and 50 percent were tested at cold temperature conditions. Two other test variables were the internal head pressure and the insulation material.

The bare aluminum heads, tested in nominal material thicknesses of .100 inch, .125 inch, and .190 inch, had an extremely low puncture resistance threshold at 2.5 mph or less. Those tested at -20°F had the highest threshold velocity of 2.5 mph. The very cold temperature conditions did appear to improve puncture resistance.

In comparison with the bare head full scale aluminum puncture tests, the same configured one-fifth scale heads had a lower puncture threshold velocity (less than 1.5 mph versus approximately 4 mph). This comparison was at ambient temperature conditions.

The .125-inch-thick aluminum heads with .8-inch-thick glass fiber insulation and .025-inch-thick steel jacket did much better than the bare configuration at the 5 mph puncture threshold. Tests were conducted at ambient temperature.

The shield protected, 5/8-inch aluminum heads survived much higher impact velocities than any other configuration. The 1/2-inch-thick shields with 4-inch fiberglass insulation (scaled down) survived impacts up to 13 mph in -20°F conditions. The 1/2-inch aluminum heads with 3/4-inch-thick shields survived impact speeds up to 16 mph before contacting with the inner tank vessel. Those tests were conducted at ambient conditions.

In comparison with the 1/2-inch shield protected full scale aluminum tests, the one-fifth scale configuration had a puncture threshold of 2 mph to 3 mph less (12 mph to 13 mph versus 16 mph).

The one-fifth scale and full scale aluminum heads tested with the heavier shields (3/4 inch and 5/8 inch, respectively) had higher puncture thresholds than those with 1/2-inch shields. However, test results were inconclusive because the one-fifth scale tests contacted (bottomed-out on) the inner tank vessel at 16 mph; and, the single full scale test had a coupler interference problem that may have prevented full ram penetration of the tank head during that 17.5 mph impact. In these tests, no punctures occurred. A retest would be recommended to confirm the puncture threshold.

The jacket and insulation covered Type 105 steel heads pressurized to 100 psi had a puncture threshold that compared closely with shield protected aluminum heads at 4 psi. At 13 mph, they had the same puncture threshold. However, when the internal pressure was reduced from 100 psi to 20 psi, puncture resistance increased dramatically to above 18 mph. This was true for both ambient and cold temperature tests. At an internal pressure of 20 psi or below, it appears that a Type 105 tank head with jacket and foam insulation will meet the minimum 18 mph requirement of the CFR. However, the reader should understand that the Type 105 tank car was designed for pressure service and may only meet the minimum 18 mph requirement when used for non-pressure service.

The shield protected Type 112 steel heads, pressurized to 100 psi, had a puncture threshold of 10.5 mph. This was 2.5 mph less than the 105 and 111 configurations described above. However, when internal pressure was decreased to 40 psi and 10 psi, puncture thresholds increased to 14 mph and above 18 mph, respectively. Although the lower pressure configurations were also tested at low temperature conditions, it is reasonably certain that the increased puncture thresholds were the result of reduced pressure and not temperature. It appears, therefore, that a Type 112 configuration at 10 psi internal pressure will exceed the minimum 18 mph requirement of the CFR. However, as in the case of the Type 105 tank car above, the Type 112 car was designed for pressure service and may only meet the 18 mph minimum requirement when used for non-pressure service as these test results would indicate.