

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1992	3. REPORT TYPE AND DATES COVERED Final Report - August 1985 - August 1989	
4. TITLE AND SUBTITLE Chlorine Tank Car Puncture Resistance Evaluation		5. FUNDING NUMBERS RR228/R2027	
6. AUTHOR(S) Michael Coltman, Morrin E. Hazel, Jr.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Research and Special Programs Administration John A. Volpe National Transportation Systems Center Cambridge, MA 02142-1093		8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FRA-91-6	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington, DC 20590		10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-92/11	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the National Technical Information Service, Springfield, VA 22161		12b. DISTRIBUTION CODE	
<p>13. ABSTRACT (Maximum 200 words)</p> <p>Experimental studies have been conducted to evaluate the relative puncture resistance of DOT 105A500W (chlorine) tank cars and DOT 112J340W (propane) tank cars equipped with 1/2-inch steel head shields. These studies included a series of full- and 1/5-scale tests conducted by the Association of American Railroads (AAR) at the Transportation Test Center (TTC) in Pueblo, Colorado. The final phase of testing included the use of actual tank cars. During the tests a number of parameters, such as head and jacket thickness, impact location, and internal pressure were varied to determine their effect on the puncture resistance of the chlorine car.</p> <p>Federal regulations require a demonstrated puncture resistance or head shield protection for high volume tank cars carrying flammable liquids and gases. The test to demonstrate puncture resistance is specified in Title 49, Part 179, section 179.105-5 of the Code of Federal Regulations (CFR). The tests conducted in this study were intended to demonstrate the puncture resistance of both chlorine and liquified propane tank cars relative to this specification requirement.</p> <p>The tests showed that the DOT 105A500W (chlorine) car tested had a puncture resistance near the 18 mph threshold required by 49 CFR 179.105-5 for tank cars in LPG (propane) and other specifically identified flammable gas lading. The DOT 112J340W tank car tested with the 1/2-inch head shield had a puncture threshold well above the 18 mph limit. The tests also showed that the puncture resistance is most strongly influenced by impact location and by jacket thickness.</p>			
14. SUBJECT TERMS Tank Car, Head Shield, Hazardous Material, Puncture Resistance, Train Collision, Accident Survivability		15. NUMBER OF PAGES 92	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

•

•

•

•

PREFACE

This report examines the relative puncture resistance of chlorine tank cars and propane tank cars equipped with 1/2-inch steel head shields. Recommendations are made in the light of this examination. The tests discussed were sponsored by the Federal Railroad Administration (FRA) Office of Research and Development, and directed by the U.S. Department of Transportation Research and Special Programs Administration at the John A. Volpe National Transportation Systems Center. The tests were performed at the U.S. Department of Transportation Test Center by the Association of American Railroads.

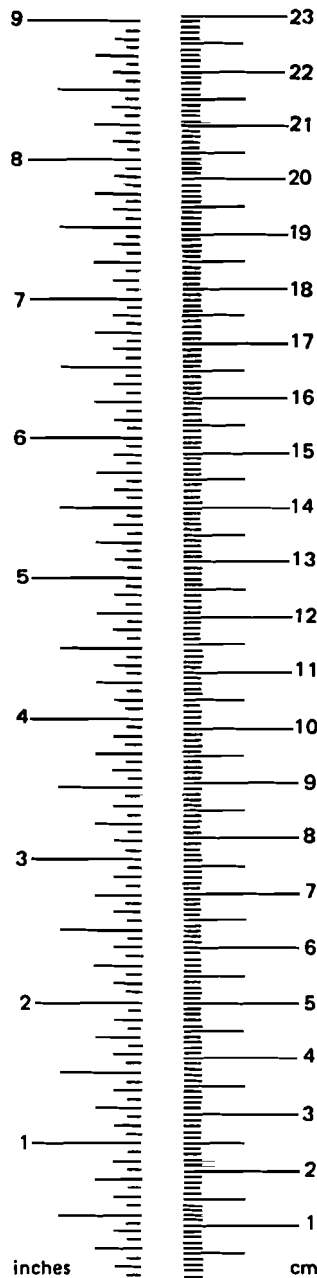
The authors wish to thank Claire Orth and Jose Pena of the FRA for their direction and guidance during the preparation of this report. In addition, special thanks are due to Mark White of the Association of American Railroads at the Transportation Test Center for his consultations throughout the planning, testing, and analysis process.

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

*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

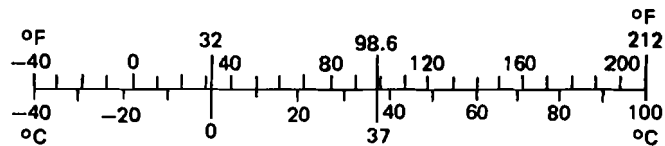


TABLE OF CONTENTS

	<u>Page</u>
1 BACKGROUND	1
2 OBJECTIVES	4
3 DESCRIPTION OF TESTS	5
3.1 1/5-SCALE TESTS	5
3.1.1 Test Apparatus	5
3.1.2 Instrumentation	6
3.1.3 Test Variables	11
3.1.4 Test Matrix	14
3.1.5 Scale Factors	14
3.1.6 Sample Data	17
3.2 FULL-SCALE MODEL TESTS	17
3.2.1 Test Apparatus	17
3.2.2 Instrumentation	26
3.2.3 Test Variables	29
3.2.4 Test Matrix	29
3.2.5 Factors Varied From Actual Vehicle	31
3.3 ACTUAL TANK CAR TESTS	32
3.3.1 Test Specimen	33
3.3.2 Instrumentation	33
3.3.3 Test Variables	33
3.3.4 Test Matrix	34
4 DISCUSSION OF TEST RESULTS	38
4.1 1/5-SCALE TESTS	41
4.1.1 Impact Location	41
4.1.2 Jacket Thickness	42
4.1.3 Head Shield	45
4.1.4 Head Thickness	45
4.1.5 Internal Pressure	46
4.1.6 Insulation Type	47
4.2 FULL-SCALE TESTS RESULTS	47
4.2.1 DOT 105A500W Tank Car Heads	47
4.2.2 DOT 112J340W Tank Car Heads	48
4.3 ACTUAL TANK CAR TESTS RESULTS	48
4.3.1 Chlorine Car Test Results	49
4.3.2 LPG Car Tests Results	49
4.3.3 Chlorine Car Stub Sill Attachment Failure	49
5 CONCLUSIONS	58
6 RECOMMENDATIONS	59
APPENDIX A: 49 CFR 179.105-5 AND 179.106-2	A - 1
APPENDIX B: SUMMARY TABLES OF TEST RESULTS	B - 1
APPENDIX C: SAMPLE TEST LOGS	C - 1
REFERENCES	R - 1

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
3.1 DROP TEST FIXTURE, UPPER SECTION - 1/5-SCALE	7
3.2 DROP TEST FIXTURE, HEAD ASSEMBLY IN TEST PIT	8
3.3 TEST INSTRUMENTATION SCHEMATIC, 1/5-SCALE	9
3.4 IMPACTOR VELOCITY VS TIME, WITHOUT PUNCTURE	20
3.5 IMPACTOR VELOCITY VS TIME, WITH PUNCTURE	21
3.6 IMPACTOR ACCELERATION VS TIME, WITHOUT PUNCTURE	22
3.7 IMPACTOR ACCELERATION VS TIME, WITH PUNCTURE	23
3.8 TYPICAL TEST CONFIGURATION - FULL-SCALE	24
3.9 IMPACTOR CAR AND RAM FIXTURE - FULL-SCALE	25
3.10 TEST INSTRUMENTATION SCHEMATIC - FULL-SCALE	27
4.1 MODEL OF IMPACTING CARS	40
4.2 MODEL IMPACT RESPONSE	40
4.3 DENT SHAPE - DOT 112J340W TANK CAR	43
4.4 DENT SHAPE - DOT 105A500W TANK CAR	43
4.5 DENT DEPTH VS IMPACT VELOCITY	44
4.6 PUNCTURE RESISTANCE - JACKET VS IMPACT VELOCITY	44
4.7 COMPARISON OF DENT DEPTHS, FULL & 1/5-SCALE	46
4.8 FULL-SIZE MEASUREMENT, DOT 105A500W DENT DEPTHS	50
4.9 IMPACT VELOCITY VS DENT DEPTH	51
4.10 SKETCH OF BRACKET AND REINFORCING PAD	53
4.11 HEAD FAILURE AT SILL JUNCTURE REINFORCEMENT	54
4.12 DENT SHAPES, ACTUAL CHLORINE CAR WITH PAD	55
4.13 DENT SHAPES, ACTUAL CHLORINE CAR AND FULL-SCALE CAR.....	56
4.14 DENT SHAPES, ACTUAL LPG CAR AND FULL-SCALE CAR	57

LIST OF TABLES

<u>Table</u>	
1.1 PERCENT INCREASE IN PUNCTURE RESISTANCE	1
1.2 TANK CAR PARAMETERS	3
3.1 TEST INSTRUMENTATION SUMMARY - 1/5-SCALE	10
3.2 SCALING DIMENSION SUMMARY - 1/5-SCALE	13
3.3 HEAD, JACKET AND SHIELD THICKNESS SUMMARY - 1/5-SCALE	15
3.4 TEST MATRIX SUMMARY - 1/5-SCALE	16
3.5 DENT AND PUNCTURE RESULTS SUMMARY - 1/5-SCALE	18
3.6 SCALE FACTOR SUMMARY - 1/5-SCALE	19
3.7 TEST INSTRUMENTATION SUMMARY - FULL-SCALE	28
3.8 SCALING DIMENSION SUMMARY - FULL-SCALE	30
3.9 STANDARD CONFIGURATION SUMMARY - FULL-SCALE	31
3.10 TEST MATRIX SUMMARY - FULL-SCALE	31
3.11 DENT AND PUNCTURE RESULTS SUMMARY - FULL-SCALE	31
3.12 TEST INSTRUMENTATION SUMMARY - ACTUAL TANK CAR	35
3.13 SCALING DIMENSION SUMMARY - ACTUAL TANK CAR	36
3.14 STANDARD CONFIGURATION SUMMARY - ACTUAL TANK CAR	37
3.15 DENT AND PUNCTURE RESULTS SUMMARY - ACTUAL TANK CAR	37

EXECUTIVE SUMMARY

In June, 1984, the Volpe National Transportation Systems Center (VNTSC) began an investigation for the Federal Railroad Administration (FRA) into the relative puncture resistance of DOT 105A500W (chlorine) tank cars and DOT 112J340W (propane) tank cars equipped with 1/2-inch steel head shields. This investigation included a series of full and 1/5-scale tests conducted by the Association of American Railroads (AAR) at the Transportation Test Center (TTC) in Pueblo, Colorado. The final phase of testing included the use of actual tank cars. During the tests a number of parameters, such as head and jacket thickness, impact location, and internal pressure were varied to determine their effect on the puncture resistance of the chlorine car.

Federal regulations require a demonstrated puncture resistance or head shield protection for high volume tank cars carrying flammable liquids and gases. The test to demonstrate puncture resistance is specified in Title 49, Part 179, section 179.105-5 of the Code of Federal Regulations (CFR)[1]. The AAR also has published recommended practices for tank performance relative to puncture resistance [2]. The tests conducted in this study were intended to demonstrate the puncture resistance of both chlorine and liquified propane tank cars relative to this specification requirement.

The tests showed that the DOT 105A500W (chlorine) car tested had a puncture resistance near the 18 mph threshold required by 49 CFR 179.105-5 for tank cars used for LPG (propane) and other specifically identified flammable gas lading. The DOT 112J340W tank car tested with the 1/2-inch head shield had a puncture threshold well above the 18 mph limit. The tests also showed that the puncture resistance is most strongly influenced by impact location and by jacket thickness.

1 BACKGROUND

Numerous tests have been conducted to determine the puncture resistance of tank cars, ranging from 1/12-scale models up to full-size vehicle tests. The Phase 5 report published by the RPI-AAR Tank Car Safety Project [3] describes most of the tests and analyses conducted prior to 1972 which investigated tank car head puncture resistance. The report included several photographs of tank cars, the heads of which were punctured during accidents. The tests investigated the effect of internal pressure, impact location, material strength, head thickness, and the ratio of the weights of the cars involved. The tests also investigated the effectiveness of 1/2-inch thick steel head shields. It was found that the most influential parameter was the impacting car weight, and the least influential was the ratio of the weight of the struck cars to that of the impacting car. As an example, for a "base" case involving a loaded 33,000 gallon DOT 112A340W tank car without head shield subjected to 100 psig internal pressure, struck by a 100-ton car, and backed up by three 100-ton cars, the puncture speed is 12.2 mph. Table 1.1 specifies the percentage change in puncture resistance for various parametric changes (changed individually and not in combination).

TABLE 1.1 PERCENT INCREASE IN PUNCTURE RESISTANCE FOR SOME PARAMETERS

Parameter	% Change	Puncture Velocity	% Increase
Baseline		12.2 mph	
Tank Head Thickness	20%	13.8 mph	13%
	50%	16 mph	31%
Material Strength	20%	13.7 mph	12.5%
	50%	15.9 mph	30%
Weight Ratio Struck/Ram	(20%)*	12.4 mph	2%
	(50%)*	12.8 mph	5%
Internal Pressure	(20%)*	12.4 mph	2%
	(50%)*	13.1 mph	7.5%
Ram Car Weight	(20%)*	15.3 mph	25%
	(30%)*	17.6 mph	44%
w/Head Shield		>22 mph	100%

()* Indicates reduction

In 1976, full-scale tests were conducted at the Transportation Test Center (TTC) to investigate the mechanism of coupler override. This mechanism was blamed for several accidents occurring during train makeup operations in switch yards [4]. These tests demonstrated that under certain circumstances the coupler on an adjacent car could override a tank car's coupler and impact the tank head with sufficient force to cause puncture. The tests investigated the use of shelf couplers, to reduce the potential for override, and 1/2-inch thick steel head shields to blunt the impacting coupler. The results of these tests and other investigations were used to establish minimum safety standards requiring that cars designed to carry flammable liquids and gases be equipped with shelf couplers and head protection sufficient to withstand an 18 mph impact.

As a result of incidents involving chlorine tank cars and general concern over the commodity, the Federal Railroad Administration (FRA) is considering requiring that these cars demonstrate an ability to withstand impacts as described in the Code of Federal Regulations (CFR). To provide background data for this rule-making, a series of tests were initiated comparing the puncture resistance of 112J340W tank cars, used to carry liquefied propane gas, and DOT 105A500W tank cars which carry chlorine.

Although the DOT 112J340W and the DOT 105A500W tank cars are both 100 ton tank cars, there are differences. Table 1.2 summarizes the characteristics of the two car designs. The DOT 112J340W tank car has a volumetric capacity of 33,000 gallons, a wall thickness of 11/16-inch, an inside diameter of 120 inches, an insulating coating (thermal protection system) to protect the lading from heat if the tank is involved in a fire accident, and a head shield conforming with the performance test specified in 49 CFR 179.105-5. The DOT 105A500W tank car has a rated capacity of 100 tons (19,322 gallons), although its permitted capacity for chlorine lading is limited to 90 tons (17,390 gallons), a wall thickness of 13/16-inch, an inside diameter of 102 inches, and an insulation system consisting of 4 inches of foam or cork covered with an 11 gage thick steel jacket to protect the lading from heat if the tank is involved in a fire accident.

DOT regulations do not require head shields on class DOT 105A tank cars in chlorine service; however, the puncture resistance test conducted showed that a DOT 105A500W car may have a puncture resistance near the 18 mph puncture resistance value prescribed for class 112/114 tank cars in LPG (propane) and other specifically identified flammable gas service. This puncture resistance is probably due to its four inches of insulation and the jacket thickness of an eighth of an inch.

Briefly the test specified in the CFR to demonstrate puncture resistance calls for a 263,000 pounds impact car to strike the reaction car at 21 and 31 inches above the sill along the centerline of the tank head. The reaction car is to be filled to a 6% outage with water and backed up by three cars with a total weight of 483,000 pounds. If the tank car can withstand an impact of 18 mph, without leaking for 1 hour, the car passes the test.

TABLE 1.2 TANK CAR PARAMETERS

Parameter	DOT 112J340W	DOT 105A500W
Tank Head Thickness	11/16 in	13/16 in
Capacity	33,000 gal	17,390 gal
Inside Diameter	120 in	102 in
Insulation Thickness	1/2 in	4 in
Head Shield or Jacket Thickness	1/2 in	1/8 in (11 gage)
Typical Internal Pressure	120 psi	100 psi
Test Pressure	340 psi	500 psi
Burst Pressure	850 psi	1250 psi
Vehicle Weight (Loaded)	263,000 lb	263,000 lb
Lading Density (@ 85 °F)	44 lb/ft. ³	85 lb/ft. ³

2 OBJECTIVES

These tests are part of a continuing research program in the area of hazardous material tank car safety. The objective of the program is to evaluate the puncture resistance of various cars carrying hazardous materials, in absolute terms, and in comparison with the DOT 112J340W tank car which has undergone extensive previous testing.

The specific objectives of this program are:

1. To determine the puncture resistance of tank cars in chlorine service as compared with that prescribed in 49CFR 179.105-5.
2. To evaluate the parameters affecting the puncture resistance of the chlorine tank car such as jacket thickness, insulation material type and thickness, internal pressure, and impact location.
3. To evaluate alternative testing procedures for determining the puncture resistance of any tank car.

3 DESCRIPTION OF TESTS

A series of engineering experiments were conducted to provide the analytical basis for fulfilling these objectives. Three types of tests were used:

1. One-fifth scale drop tower tests of the tank head to investigate parameters affecting the puncture resistance of the chlorine car.
2. Full-scale tests with a tank head mounted on a pressure vessel on a flat car to calibrate the 1/5-scale testing.
3. Full-size actual tank car impact tests demonstrating test results in full-size with full volume and lading.

Three reports describing these tests in detail have been written by Mark White of the Association of American Railroads (AAR) [5,6,7]. In this section some of the important aspects of the tests are reviewed to provide a context for the test results section.

For the actual test, each tank was filled, then pressurized. Then all air, except that representing a 10% outage condition, was purged from the tank. Each 112J340W tank was filled with water. Each 105A500W tank was filled with clay slurry conforming to the density of chlorine.

3.1 1/5-SCALE TESTS

The 1/5-scale drop tower tests were used to investigate the effects of head shield/tank jacket thickness, internal lading pressure, jacket insulation material, and impact location. The results of the 1/5-scale tests cannot be directly extrapolated to full-scale rolling impact tests because the support for the tank in the drop tower setup is essentially rigid.

A 1/5-scale parametric study was performed on factors affecting puncture resistance of tank cars. The study included eleven test conditions: two simulating a DOT 112J340W tank car and nine corresponding to the DOT 105A500W tank car. A series corresponding to a bare head condition was added toward the end of the 1/5-scale tests to provide a complete evaluation of the effect of steel jackets and 4 inches of insulation.

3.1.1 Test Apparatus

A drop test fixture, or drop tower, was installed in the Components Test Laboratory (CTL) at TTC in order to perform the tests in a controlled environment. As modified for use in these tests, the fixture has a

maximum drop height of 18.5 feet with a scale tank head assembly in place, and can develop 23.5 mph theoretical free-fall velocity at impact. See Figures 3.1 and 3.2.

Impact body mass was adjusted to 2,104 pounds during fabrication. This was designed to represent an impacting car weighing 263,000 pounds at 1/125 full-scale. This scale factor provides for a 1:1 scaling of velocity.

The impacting scale coupler was mounted rigidly to the bottom of the impacting mass but the position of the scale tank head assembly could be adjusted to vary the impact location as desired. Position was verified by dropping a plumb line to the target impact zone.

Test tank heads were manufactured with coupling flanges which were then clamped rigidly to a pressure vessel with Marmon clamps. An inverted container was placed inside the pressure vessel to act as a pressure accumulator. When the vessel was filled with water and pressurized, air was purged from it except from inside the inner container, where air representing a 10% outage condition was maintained.

3.1.2 Instrumentation

Instrumentation for the tests is shown schematically in Figure 3.3. Static measurements were recorded in the Test Log. Dynamic measurements were collected by a Gould DASA 9000 System at a rate of 10,000 samples per second using an IBM PC/XT as the operator. Dynamic data were written to floppy disk and later converted to ASCII data on floppy disk for post analysis.

A summary of the test instrumentation parameters is listed in Table 3.1. Accuracy of data was verified by an error analysis based upon manufacturer's specifications and TTC calibrations. In most dynamic measurements, the largest source of error is the resolution of the Gould Transient Recorder (1 part in 127). All accuracies were calculated by the combined error (RMS) method.

For temperature measurements, a thermocouple was attached to the exterior side of the pressure vessel near the top. Static temperature readings were taken prior to each impact and were recorded in the Test Log. Temperature was primarily a function of the TTC water supply and varied between 62 °F and 76 °F.

Impact location was set manually by adjusting the impacting coupler position on the impact mass using a plumb line to the tank head from the center of the coupler. The location on the tank head was determined using a head template and calculating the required scale distance from the outside edge of the tank.

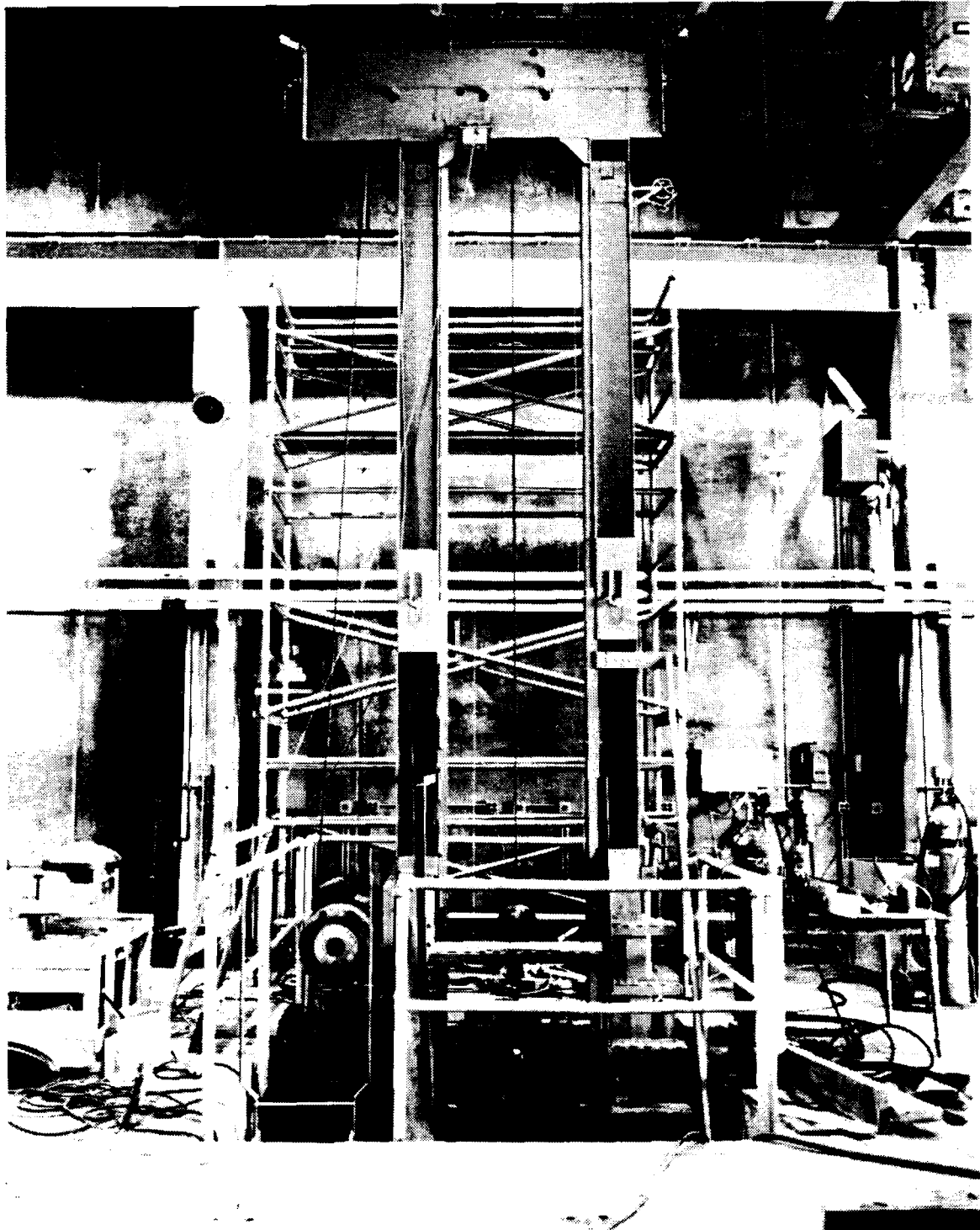


FIGURE 3.1 DROP TEST FIXTURE, UPPER SECTION - 1/5-SCALE MODEL IMPACT TESTS

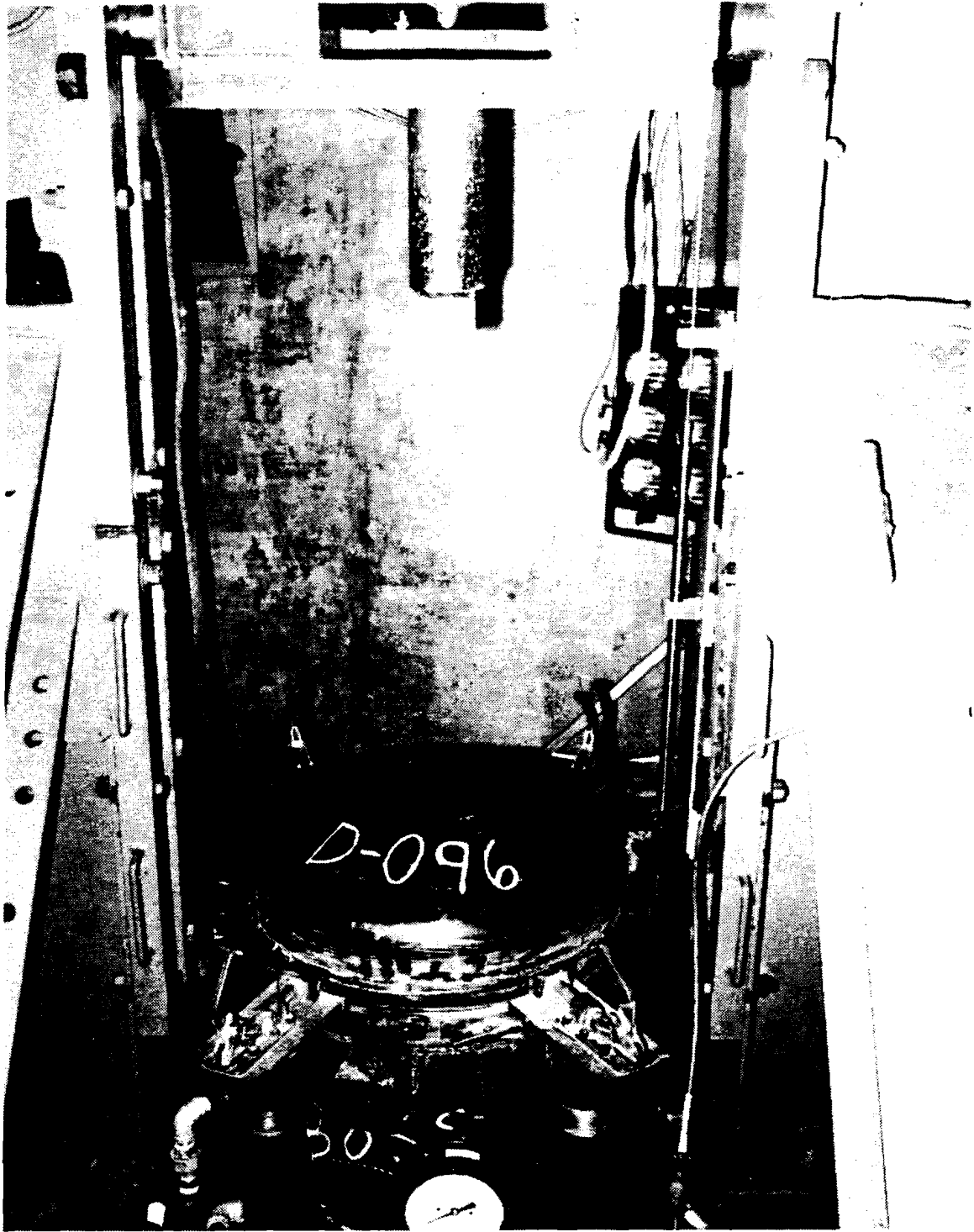


FIGURE 3.2 DROP TEST FIXTURE, HEAD ASSEMBLY IN TEST PIT - 1/5-SCALE MODEL
IMPACT TESTS

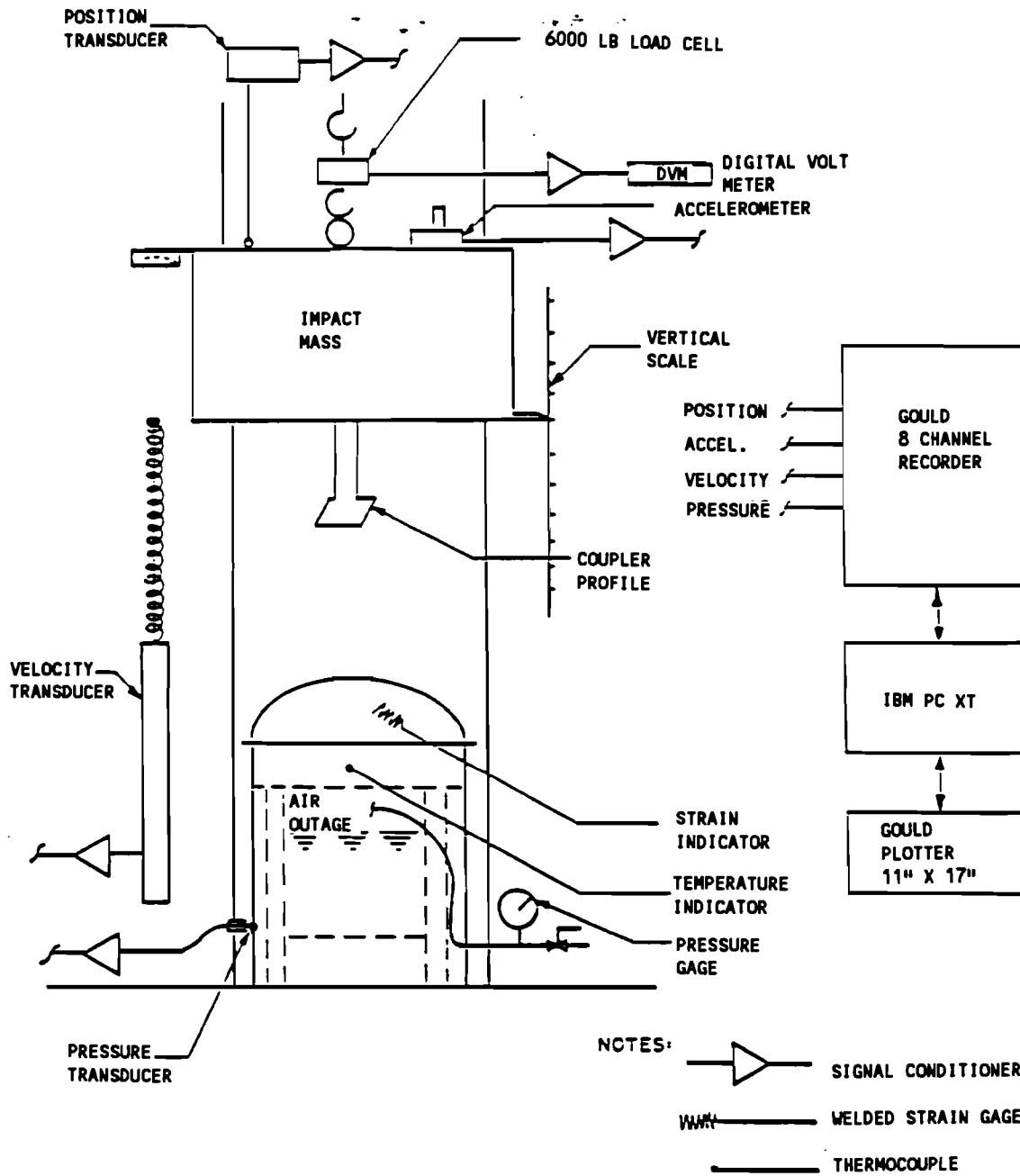


FIGURE 3.3 TEST INSTRUMENTATION SCHEMATIC - 1/5-SCALE MODEL IMPACT TESTS

TABLE 3.1 TEST INSTRUMENTATION SUMMARY - 1/5-SCALE MODEL IMPACT TESTS

Measurement Parameter	Frequency Response	Transducer Type/MFG	Total System Accuracy (+/-)	Comment
Mass, Impactor	Static	Scale/Dillion	10 lb	
Temperature, Tank	Static	Surface Thermocouple/Omega	5 °F	
Pressure, Tank	Static	Test Gage/Omega	0.5 psig	
Pressure, Tank	0-1 KHz	Strain Gage Transducer/Bell & Howell CEC 1000	1.8 psi	Assume 100 psi starting pressure
Position, Impactor	Static	Steel Tape	1/16 in	
Position, Impactor	2 Hz	Potentiometer/Celesco	1 in	Assume 100 inch drop
Velocity, Impactor (Final)	0-5 KHz	Velocity/Schaevitz	1.74%	
Acceleration, Impactor	0-1 KHz	Piezoelectric Accelerometer/B&K	4.2 G	
Strain, Surface (Delta)	Static	Bonded Strain Gage/Micro Measurement	10% of reading	

Impact acceleration and deceleration were calculated from three different devices, a piezoelectric accelerometer, a position transducer, and a velocity transducer. Signal outputs were collected by a Gould DASA 9000 system at 10,000 samples per second, triggered to start just prior to impact by movement of the velocity transducer.

Shape and depth of impact dents were measured using a linear profile template marked with reference lines. Measurements were taken at 1.5-inch increments from the tank bottom rim to the tank head center. Measurements were recorded in the Test Log.

Adjustment of the initial impact mass height was made with the aid of a vertical scale mounted on the drop fixture. The drop height was measured from the point at which the center of the coupler knuckle would make contact with the head, jacket, or shield to the front face of the coupler knuckle. Once the initial height was set to the desired value, the position transducer output readings were zeroed. Dynamic impact mass height was recorded by the Gould system and included in the data written to floppy disk. Initial and final impact mass heights were recorded in the Test Log.

Tank head strain was measured in the first few tests using three weldable strain gages on each tank head. The intent was to determine the extent of the permanent deformation produced by an initial impact in order that a second impact could be applied to an unaffected region of the head. Second impacts were not used due to gross geometry changes resulting from first impacts. Gages were calibrated to zero reading after pressurizing the vessel prior to the first impact. Readings on the first few tests were well below the safety limit and gages were not used in subsequent tests for economic reasons. Strain readings were recorded in the Test Logs before and after impacts when gages were used.

Still photographs were taken to document head assembly construction, drop fixture configuration, instrumentation, and dent and puncture formations. A documentary movie film was also made.

3.1.3 Test Variables

The puncture resistance of a chlorine tank car head is presumed to be dependent upon the following parameters. These can be controlled in the tests:

- Head thickness
- Insulation jacket thickness
- Insulation material
- Head shield thickness
- Internal pressure
- Outage condition
- Impact location

A set of 12 combinations of these parameters was chosen and the speed of impact was varied over a range sufficient to determine the puncture velocity for the combination. A new head was used for each impact. Expected speed of impact was set for each drop by manually adjusting the drop height. Actual impact speed was calculated from the instrumentation outputs.

The parameters for these tests were held as close to the design scale as possible, considering that the reaction vessel was not actually a tank car on wheels. For a summary of the scaled dimensions used and actual scale factors, see Table 3.2. For values of theoretical scale factors, see Table 3.6.

Heads were manufactured from ASTM A612 (AAR TC 128, Grade B) steel purchased in standard sheets 3/16 and 1/4-inch thick and ground to the desired thickness. Heads were then cold spin-formed and, after welding the coupling flanges, were post weld heat treated in accordance with 49 CFR 179.100-10. The spin-forming process caused the thickness to vary across a radius. Thickness was generally slightly greater than the 1/5-scale reduction near the center and smaller at the tank circumference. The thickness of a sampling of heads was measured at ten locations along a radius and the measurements are summarized in Table 3.3. In addition, two additional thicknesses of DOT 105A500W tank car heads were impacted in order to examine the effect of head thickness on puncture velocity. The dimensions of the two additional thicknesses were based on the standard thickness, with one increased by 1/8-inch and the other by an additional 1/8-inch.

Insulation jacket material was ASTM A366 sheet steel in 24, 18, or 14 gage thicknesses to model the standard 1/8-inch thick jacket with increasing thickness in steps of 1/8-inch (full-size). The jackets were cold spin-formed using the DOT 112J340W tank car head mold. As a result, the thickness varied as it did in the heads. A sampling of thickness measurements is summarized in Table 3.3.

Insulation material on chlorine cars is normally a polyurethane foam with a design density of 2 pounds per cubic foot. The molding process of the thin wall for the scale model resulted in a greater than normal density, in the range 3.7 to 4.4 pounds per cubic foot. Some impact tests were also performed with ceramic fiber blanket in addition to the foam. The blanket was 1/2-inch thick instead of the scaled 0.8 inch, at a density of 4 pounds per cubic foot, and with glass fiber blanket hand separated to the correct scale thickness at a density of 1 pound per cubic foot.

Head shields were formed from the same mold as the DOT 112J340W tank car heads but cut in half along a diameter. Material was ASTM A607, 12 gage steel. Sample measurements are summarized in Table 3.3. All shields were designed to be the same thickness as the current DOT 112J340W tank car type shields as scaled.

Internal pressure for the standard condition was set to 100 psi with water purged of any air trapped directly under the head. To test for pressure effects, impacts were also made with pressures of 50 psi and 200 psi.

Outage of 10% was provided by an open inverted container inside the tank vessel. As the tank was filled with water, air was trapped in the container and not purged.

Impact location was set at a scale of 21 inches from the outside surface of the tank to the impacting coupler centerline. For one series of tests with each car type, a scale of 31 inches was used.

TABLE 3.2 SCALING DIMENSION SUMMARY - 1/5-SCALE MODEL IMPACT TESTS

Measurement Parameter	Full-size Car Actual Value	1/5-Scale Value	Tested Value	Actual Scale Factor
Head Thickness, 105A500W Tank Car	0.813 in	0.163 in	0.198 in*	1/4.11*
Head Thickness, 112J340W Tank Car	0.688 in	0.138 in	0.172 in*	1/4*
Tank Diameter, 105A500W Tank Car	102 in (i.d.)	20.4 in	20.4 in	1/5
Tank Diameter, 112J340W Tank Car	119 in (i.d.)	23.8 in	24.0 in	1/4.96
Insulation Thickness, 105A500W Tank Car	4.0 in [Foam]	0.80 in	0.80 in	1/5
Insulation Thickness, 112J340W Tank Car	0.5-1.0 in [Glass fiber]	0.1-0.2 in	0.2-0.1 in	1/5
Jacket Thickness 105A500W Tank Car	0.125 in [11 ga.]	0.025 in	0.024 in*	1/5.21*
Head Shield Thickness 112J340W Tank Car	0.5 in	0.1 in	0.103 in*	1/4.85*
Impactor Mass (Ram Car)	263,000 lb (+/- 5%)	2,104 lb	2,119 lb	1/124
Reaction Car Weight	263,000 lb (+/- 5%)	2,104 lb	N/A	NA
Backup Car Weight	> 480,000 lb	3,840 lb	N/A	NA
Tank Volume, 105A500W Tank Car	17,360 gal (nom)	139 gal		NA
Tank Volume, 112J340W Tank Car	34,000 gal (nom)	272 gal		NA

* Thickness varied across profile due to manufacturing process.

3.1.4 Test Matrix

The test matrix was designed to provide a range of values for each of the parameters discussed above and is summarized in Table 3.4. There were 12 test series, each involving a number of impacts. Series 01 was the baseline for DOT 112J340W tank cars and series 03 was the baseline for DOT 105A500W chlorine cars. The parameter variations and their respective test series are as follows:

- Series 10, 11 : Head thickness
- Series 04, 05, 12 : Insulation jacket thickness
- Series 09 : Insulation material
- Series 07, 08 : Internal pressure
- Series 02, 06 : Impact location

The maximum dent depth without puncture and the velocity needed for puncture for each of the test series are shown in Table 3.5.

3.1.5 Scale Factors

Any testing performed with scale models requires a study of the scaling effects upon all of the physical properties of interest. Scaling laws apply which relate scale factors for each physical property depending upon the relationships between the properties. Scale factors K_x are defined for each x property based upon the property of primary interest. The scale factors for these tests are summarized in Table 3.6.

Given a 1/5-scale model, the scale factor for length, K_L , is determined by:

$$K_L = \frac{L'}{L} = \frac{1}{5} \quad (1)$$

where L is length, the primed variable applying to the model and the unprimed to the prototype.

Fixing the length scale factor also fixes the scale factors for area and volume, K_A and K_V :

$$K_A = \frac{A'}{A} = \frac{L' \cdot L'}{L \cdot L} = K_L^2 \quad (2)$$

$$K_V = \frac{V'}{V} = \frac{L' \cdot L' \cdot L'}{L \cdot L \cdot L} = K_L^3 \quad (3)$$

To model dent and puncture formation from impact where the materials (and therefore the material densities) in the model are identical to those in the prototype, the scale factor for stress, K_σ , should be unity.

$$K_\sigma = \frac{\sigma'}{\sigma} = 1 \quad (4)$$

**TABLE 3.3 HEAD, JACKET AND SHIELD THICKNESS SUMMARY - 1/5-SCALE MODEL
IMPACT TESTS**

Measured Item	1/5 Scale inch	10 Readings Across Radius					
		Highest		Lowest		Mean**	
		inch	%	inch	%	inch	%
112 Head # 011	0.138	0.174	27	0.135	-2	0.159	16
112 Head # 012	0.138	0.173	26	0.125	-9	0.159	16
112 Shield # 012	0.100	0.110	10	0.080	-20	0.100	0
112 Shield # 013*	0.100	0.109	9	0.082	-18	0.101	1
112 Shield # 013*	0.100	0.110	10	0.082	-18	0.101	1
112 Shield # 014	0.100	0.111	11	0.083	-17	0.101	1
112 Shield # 015	0.100	0.110	10	0.080	-20	0.099	-1
105 Head # 032	0.163	0.204	25	0.165	2	0.189	16
105 Head # 039	0.163	0.205	26	0.167	3	0.191	17
105 Head # 039A	0.163	0.203	25	0.174	7	0.192	18
Thick Head # 102	0.187	0.227	21	0.183	-2	0.208	11
Thick Head # 103	0.187	0.220	17	0.178	-5	0.208	11
Thick Head # 104	0.187	0.222	18	0.180	-4	0.205	10
Thick Head # 111	0.213	0.259	22	0.217	2	0.241	13
Thick Head # 113	0.213	0.255	20	0.219	3	0.240	13
105 Jacket # 032	0.025	0.029	16	0.015	-40	0.022	-12
105 Jacket # 039	0.025	0.027	8	0.016	-36	0.025	0
105 Jacket # 039A	0.025	0.024	-4	0.014	-44	0.021	-15
Thick Jacket # 042	0.050	0.048	-4	0.035	-30	0.043	-14
Thick Jacket # 043	0.050	0.047	-6	0.034	-32	0.043	-14
Thick Jacket # 051	0.075	0.076	1	0.058	-22	0.069	-8
Thick Jacket # 053	0.075	0.076	1	0.056	-25	0.069	-8

* Two different radii on same head.

** Mean of 10 readings, not necessarily mean over whole surface.

TABLE 3.4 TEST MATRIX SUMMARY - 1/5-SCALE MODEL IMPACT TESTS
(All Dimensions Are Full-scale)

Test Series	Head Thickness	Jacket Thickness	Impact Location	Internal Pressure	Insulation Type*
DOT 112J340W					
01	11/16 in	1/2 in	21 in	100 psi	1/2 in
02	11/16 in	1/2 in	31 in	100 psi	1/2 in
DOT 105A500W					
03	13/16 in	1/8 in	21 in	100 psi	4 in F
04	13/16 in	1/4 in	21 in	100 psi	4 in F
05	13/16 in	3/8 in	21 in	100 psi	4 in F
06	13/16 in	1/8 in	31 in	100 psi	4 in F
07	13/16 in	1/8 in	21 in	200 psi	4 in F
08	13/16 in	1/8 in	21 in	50 psi	4 in F
09	13/16 in	1/8 in	21 in	100 psi	4 in C/G
10	15/16 in	1/8 in	21 in	100 psi	4 in F
11	1-1/16 in	1/8 in	21 in	100 psi	4 in F
12	13/16 in	none	21 in	100 psi	none

* Insulation materials are coded as follows:
C-Ceramic Fiber, F-Foam (polyurethane), G-Glass fiber

The defining equation for stress, $\sigma = F/A$, determines the scale factor for force as:

$$K_F = K_\sigma \cdot K_A = K_L^2 \quad (5)$$

However, since the material densities are identical ($\delta' = \delta$), the scale factor for density, K_δ , is unity, and the scale factor for mass is determined by the relationship $\delta = M/V$:

$$K_M = K_V \cdot K_\delta = K_L^3 \quad (6)$$

Newton's equation, $F = M \cdot a$, gives the scale factor for acceleration:

$$K_a = \frac{K_F}{K_M} = \frac{K_L^2}{K_L^3} = \frac{1}{K_L} \quad (7)$$

and the 1/5-scale model experiences five times the acceleration or deceleration of the prototype.

By definition, $a = d^2x/dt^2$, the scale factors for acceleration, distance, and time are related by $K_a = K_L/K_T^2$ and the scale factor for time is

$$K_T = \sqrt{(K_L/K_s)} = K_L \quad (8)$$

This means that events occur five times as fast (or in 1/5 the time) on the model as on the prototype.

Speed is defined as dx/dt which gives the scale factor for speed

$$K_s = \frac{K_L}{K_T} = 1 \quad (9)$$

Consequently, the model should travel at the same speed as the prototype.

Pressure is defined as force per unit area, so the scaling factor for pressure is

$$K_p = \frac{K_F}{K_A} = \frac{K_L^2}{K_L^2} = 1 \quad (10)$$

and the tank pressure of the model should be equal to that of the prototype.

3.1.6 Sample Data

A few samples of typical processed data are presented here; however, no attempt is made to provide a complete set of data for the tests.

Figure 3.4 plots impactor velocity with time from the point of contact. This head did not puncture, so the impact body bounced on the tank head a few times before coming to rest. When the impact produces a head puncture the impacting body bounces very little and the plot becomes more like Figure 3.5.

Similarly, acceleration plotted versus time for two cases, one a puncture and the other a dent, is shown in Figures 3.6 and 3.7.

3.2 FULL-SCALE MODEL TESTS

The full-scale tests were intended to determine the approximate puncture resistance of the cars in a realistic rolling impact test. For these tests a pressure vessel was mounted on a flat car which was connected to three backup cars. The effective mass distributions of the test cars are not the same as actual tank cars; however, the tests produce realistic dent shapes and impact velocities.

3.2.1 Test Apparatus

Full-scale model impact tests were conducted on full-size tank head assemblies, exactly as produced for commercial tank cars, attached to a pressurized vessel mounted on a railroad car. This reaction car was backed up by three loaded freight cars. The tests were designed to resemble the 49 CFR 179.105-5 Tank Head Puncture Resistance requirement, except for the pressurized tank volume behind the head.

TABLE 3.5 DENT AND PUNCTURE RESULTS SUMMARY - 1/5-SCALE MODEL IMPACT TESTS

Test Series	# of Heads	# of Impacts	Parameter Varied	Dent Depth	Puncture Velocity
DOT 112J340W					
01	9	10	Baseline for 112	2.8 in	10.6 mph
02	5	5	Impact Location	4.7 in	18.5 mph
DOT 105A500W					
03	12*	21	Baseline for 105	2.7 in	10.2 mph
04	4	6	Jacket Thickness	3.5 in	13.1 mph
05	5	5	Jacket Thickness	4.6 in	16.6 mph
06	6	6	Impact Location	4.3 in	15.1 mph
07	6	6	Higher Pressure	3.3 in	12.6 mph
08	4	4	Lower Pressure	2.8 in	10.5 mph
09	8	9	Insulating Material	2.7 in	9.7 mph
10	6	6	Head Thickness	2.7 in	10.8 mph
11	6	6	Head Thickness	3.4 in	14.1 mph
12	2	4	Bare Head	1.7 in	6.8 mph

* Six heads were used in system shakedown.

Testing was performed on a track with constant downward gradient of about 1 percent, allowing the impactor car to accelerate by gravity from selected stationary starting locations to the desired speeds at impact. See Figure 3.8 for a typical test configuration.

The impactor car was a donated scrap locomotive. A support structure for a ram fixture was installed on the mainframe. Total car weight was adjusted to 263,000 pounds +/- 2%. The traction motors were disconnected from the axles to reduce rolling friction. See Figure 3.9 for a view of the impactor car and ram fixture.

The ram fixture consisted of two parts. The ram itself was a simulated rail car center sill with a coupler and draft gear assembly mounted on one end. The ram was mounted to a structural reaction frame on the front of the impactor car with height adjustment in increments of 2 inches. The coupler was a standard AAR Type E 60 CE with rotary operation mechanism removed and knuckle welded in the engaged position. Couplers were replaced as they became distorted from repeated impacts. The draft gear was a Westinghouse Mark 50.

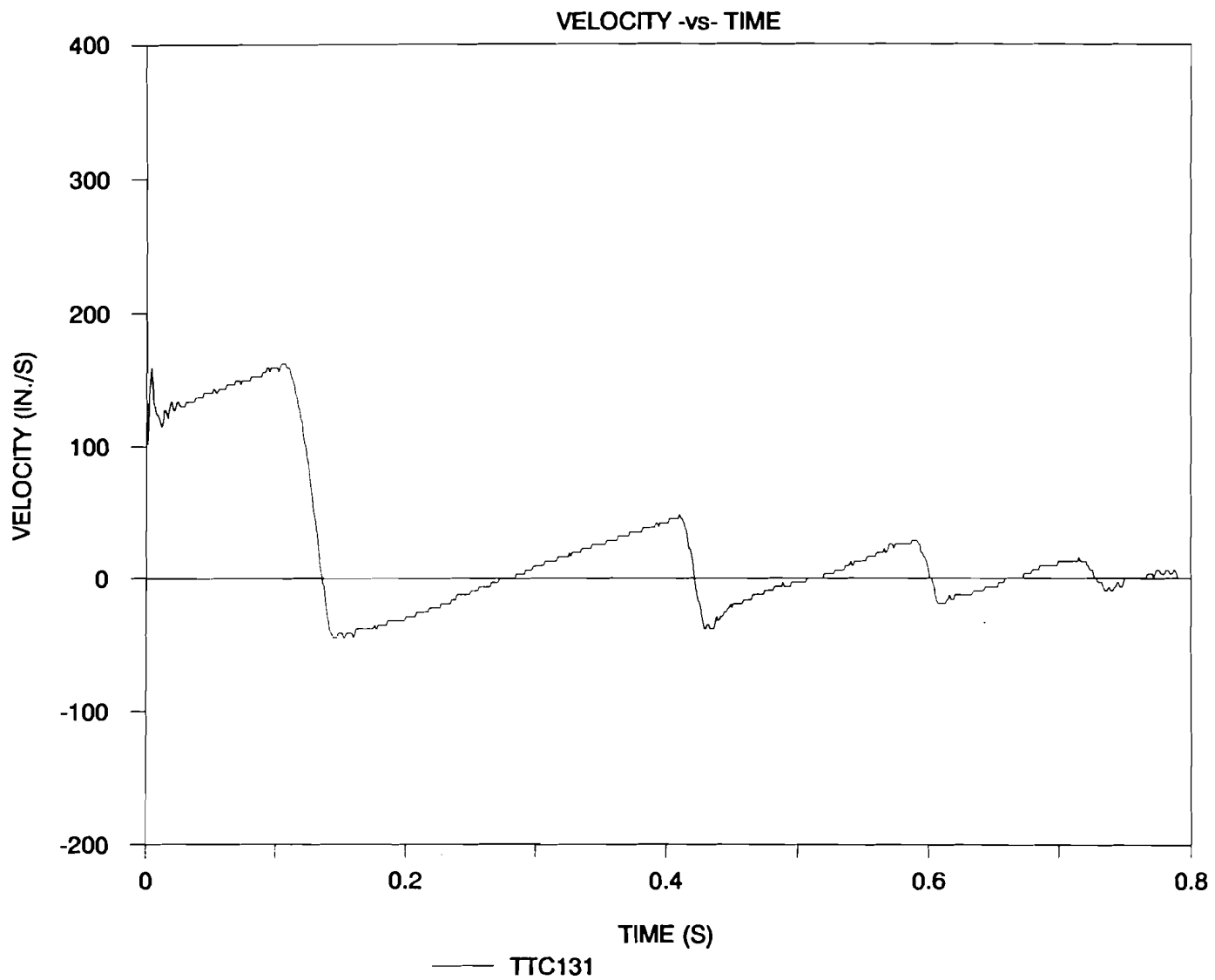
TABLE 3.6 SCALE FACTOR SUMMARY - 1/5-SCALE MODEL IMPACT TESTS

Physical Parameter	Symbol	Scale Factor Symbol/Function	Scale Factor Value
Length	L	K_L	1/5
Area	A	$K_A = K_L^2$	1/25
Volume	V	$K_V = K_L^3$	1/125
Speed	S	$K_S = 1$	1
Acceleration	a	$K_a = 1/K_L$	5
Time	T	$K_A = K_L$	1/5
Mass	M	$K_M = K_L^3$	1/125
Density	δ	$K_\delta = 1$	1
Force	F	$K_F = K_L^2$	1/25
Pressure	P	$K_P = 1$	1
Stress	σ	$K_\sigma = 1$	1

The reaction car was a 100-ton flat car with added structural modifications and supports for the pressure vessel. An adapter ring was mounted between the pressure vessel and DOT 112J340W tank car heads to accommodate the larger diameter of those heads. Concrete blocks were mounted on the flat bed of the car to bring the total car weight, as set up for a test, to 263,000 pounds. One of the blocks was removed for the DOT 112J340W tank car series tests to make up for the weight of the additional water in the adapter ring.

Tank heads were made of ASTM A612 (AAR TC 128, Grade B) steel, hot press-formed and normalized in accordance with 49 CFR 179.100-8. Flanges were welded to the tank heads to provide a means of attachment and a pressure seal to the reaction vessel. The flanges were standard AWWA Class D pipe flanges rated for 150 psi maximum working pressure.

The backup cars were 100-ton hopper cars partially loaded with track ballast material to a total weight for the three cars of 483,000 pounds.



**FIGURE 3.4 IMPACTOR VELOCITY VS TIME, WITHOUT PUNCTURE - 1/5-SCALE MODEL
IMPACT TESTS**

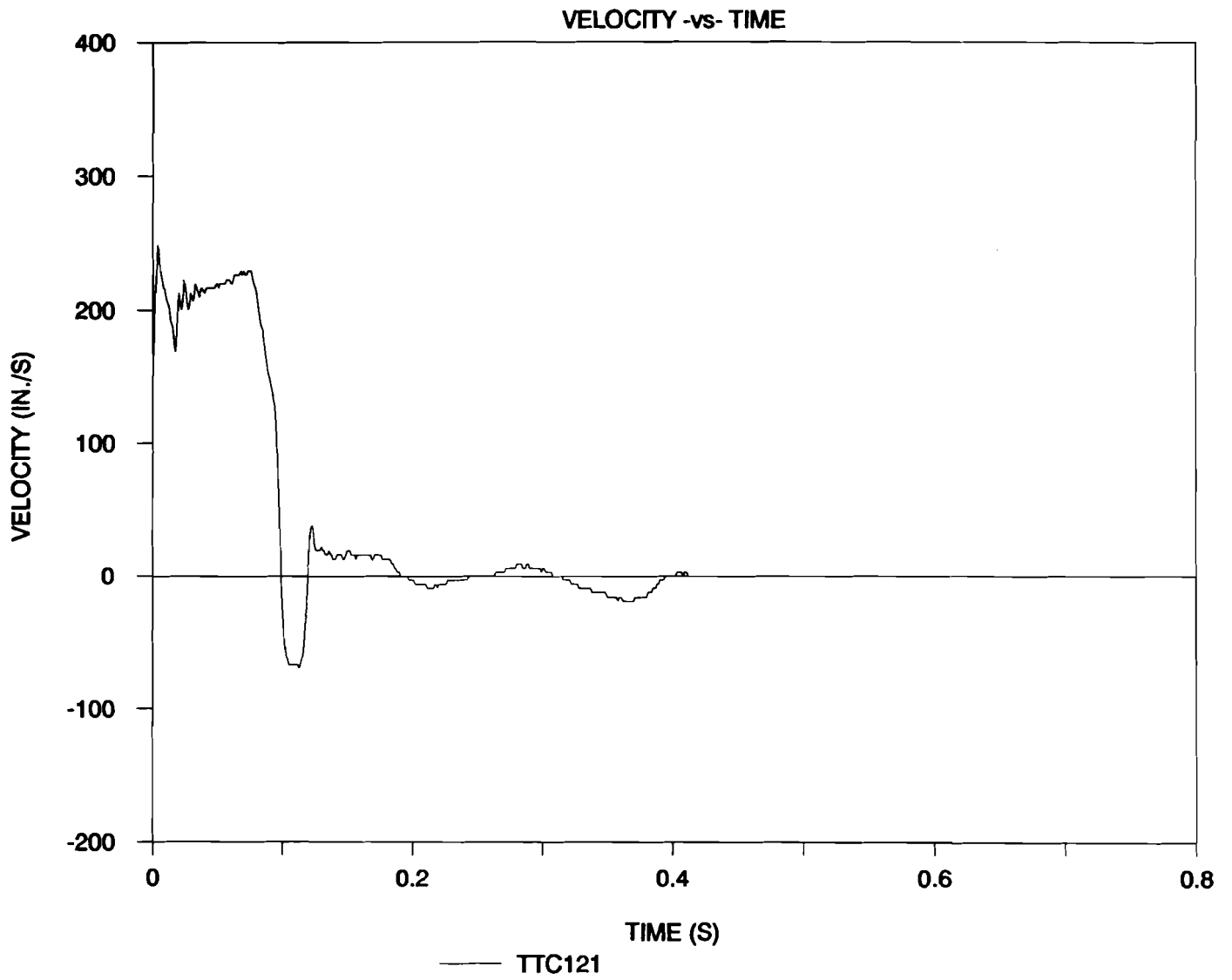


FIGURE 3.5 IMPACTOR VELOCITY VS TIME, WITH PUNCTURE - 1/5-SCALE MODEL IMPACT TESTS

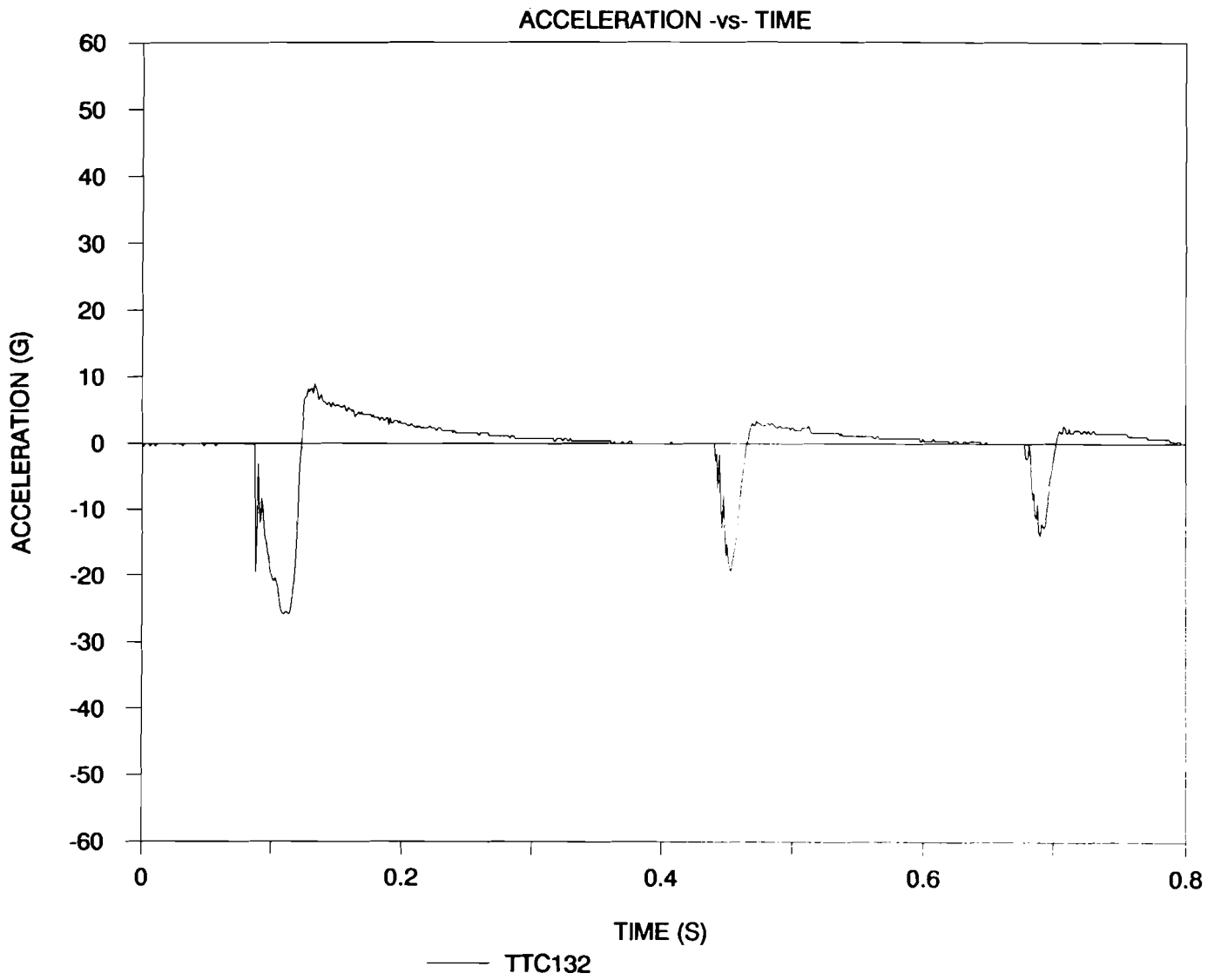
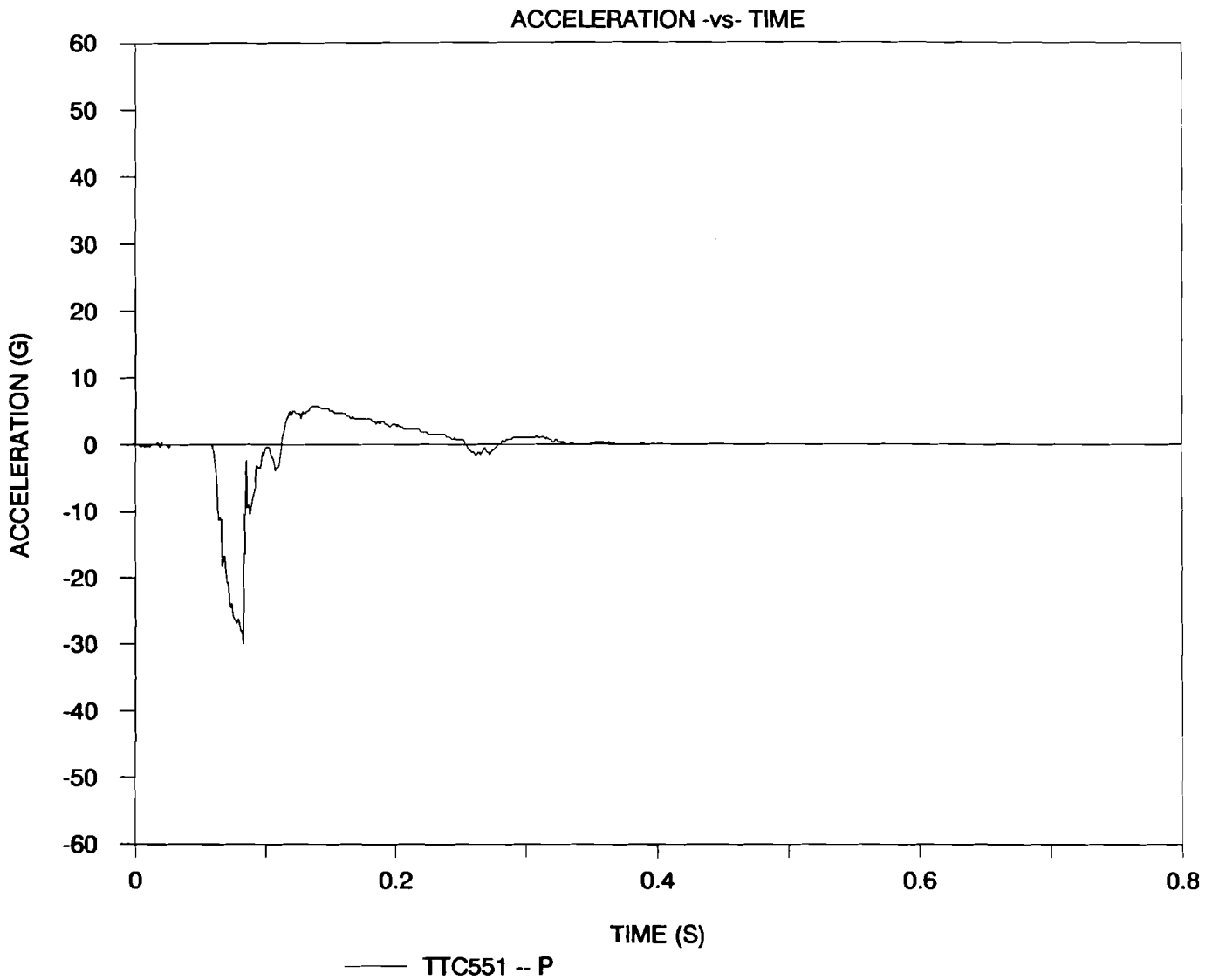


FIGURE 3.6 IMPACTOR ACCELERATION VS TIME, WITHOUT PUNCTURE - 1/5-SCALE MODEL IMPACT TESTS



**FIGURE 3.7 IMPACTOR ACCELERATION VS TIME, WITH PUNCTURE - 1/5-SCALE MODEL
IMPACT TESTS**

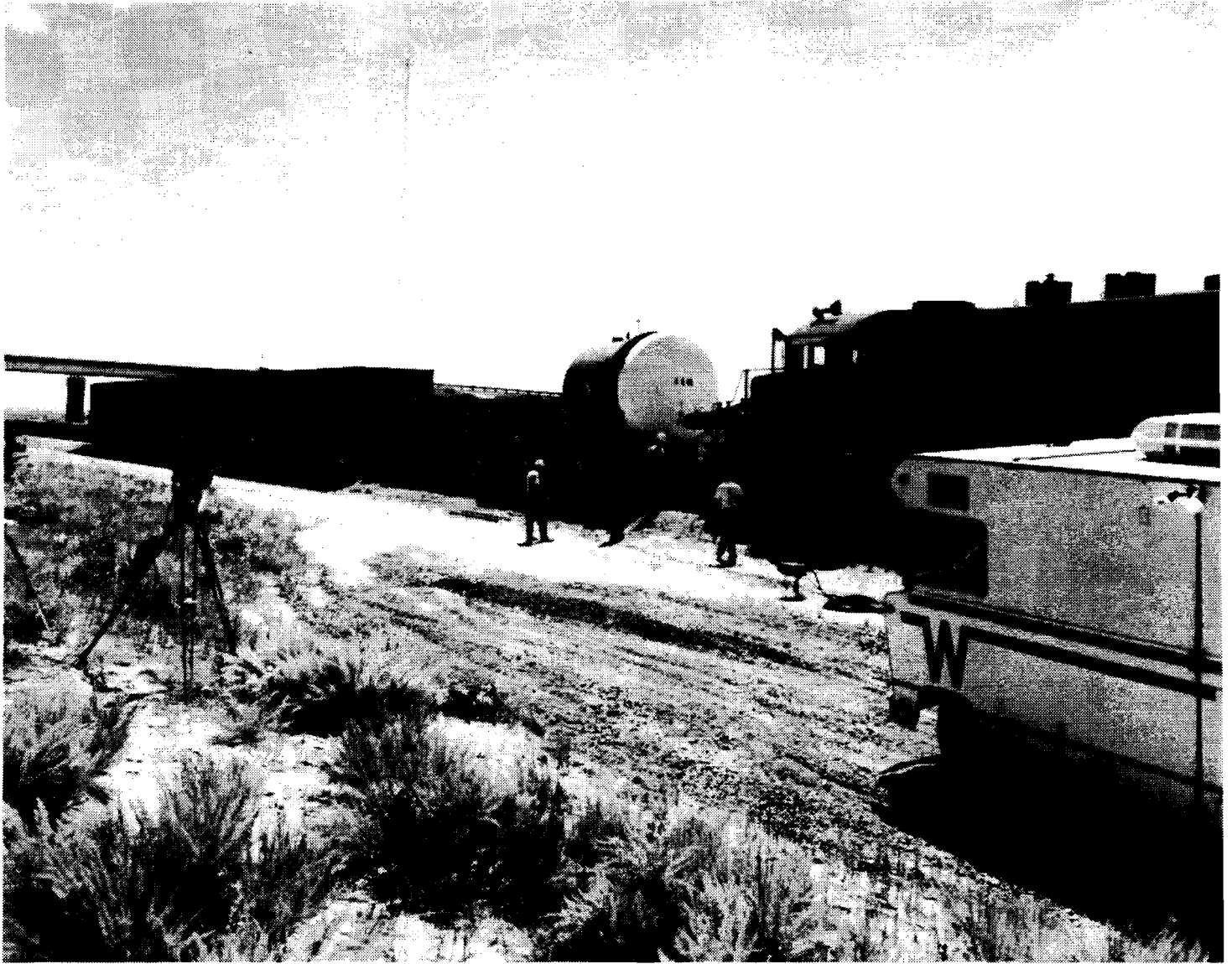


FIGURE 3.8 TYPICAL TEST CONFIGURATION - FULL-SCALE MODEL IMPACT TESTS



FIGURE 3.9 IMPACTOR CAR AND RAM FIXTURE - FULL-SCALE MODEL IMPACT TESTS

3.2.2 Instrumentation

Instrumentation for the full-scale model tests is shown schematically in Figure 3.10. Static measurements were recorded in the Test Log. Two dynamic measurement systems were used. On the impactor car, transducer outputs were conditioned, digitized, and transmitted via a pulse code modulated (PCM) telemetry system to a signal processing system running on a Digital Equipment Corp. PDP-11/34 minicomputer in the Rail Dynamics Laboratory. Processed impactor car data were stored on magnetic tape for post processing. The reaction and backup car sensors were hard-wired through drop cables to a wayside data processing system consisting of the Gould DASA 9000 system also used in the 1/5-scale model tests and controlled by an IBM PC/XT microcomputer. Processed wayside data were stored on floppy disks for post analysis. Both measurement systems collect data at 10,000 samples per second on each data channel. Time synchronization for all dynamic data collection was provided by an Inter-Range Instrumentation Group (IRIG) time signal telemetry system. A summary of the test instrumentation parameters is listed in Table 3.7.

For temperature measurements, a thermocouple was attached to the exterior underside of the pressure vessel. Static temperature readings were taken prior to each impact and recorded in the Test Log. Temperature was primarily a function of season and weather because the pressure vessel was normally filled 24 or more hours in advance for logistic reasons. Temperature varied between 38.1 and 49.4 °F for the DOT 112J340W tank car tests and between 49.4 and 76.5 °F for the DOT 105A500W tank car tests.

Tank pressure was monitored visually with a pressure gage mounted on the top of the pressure vessel. Three pressure transducers were installed at the top, center of back end, and center side of the pressure vessel. The vessel was filled with water to 90% capacity. Transducers were then adjusted to zero. The top air was then pressurized to 100 psig on the top gage. Dynamic pressures were recorded on the wayside system. In most cases, impact acceleration and deceleration of the impactor car were measured by an accelerometer in a deep web section on the car mainframe; however, for the first four impacts (tests 21 - 24) on DOT 105A500W tank car heads, the accelerometer was mounted on the ram support structure. These four impacts showed large spikes due to the flexure of the structure.

Reaction car acceleration and deceleration were measured by an accelerometer mounted on top of the pressure vessel near the back end. For one test of DOT 112J340W tank car head an additional accelerometer was mounted on top of the center sill near the back end of the pressure vessel.

Shape and depth of impact dents were measured using a linear profile template marked with reference lines parallel to the tank centerline. Measurements were taken at 7.5-inch increments from the tank bottom rim to the head center. Measurements were recorded in the Test Log.

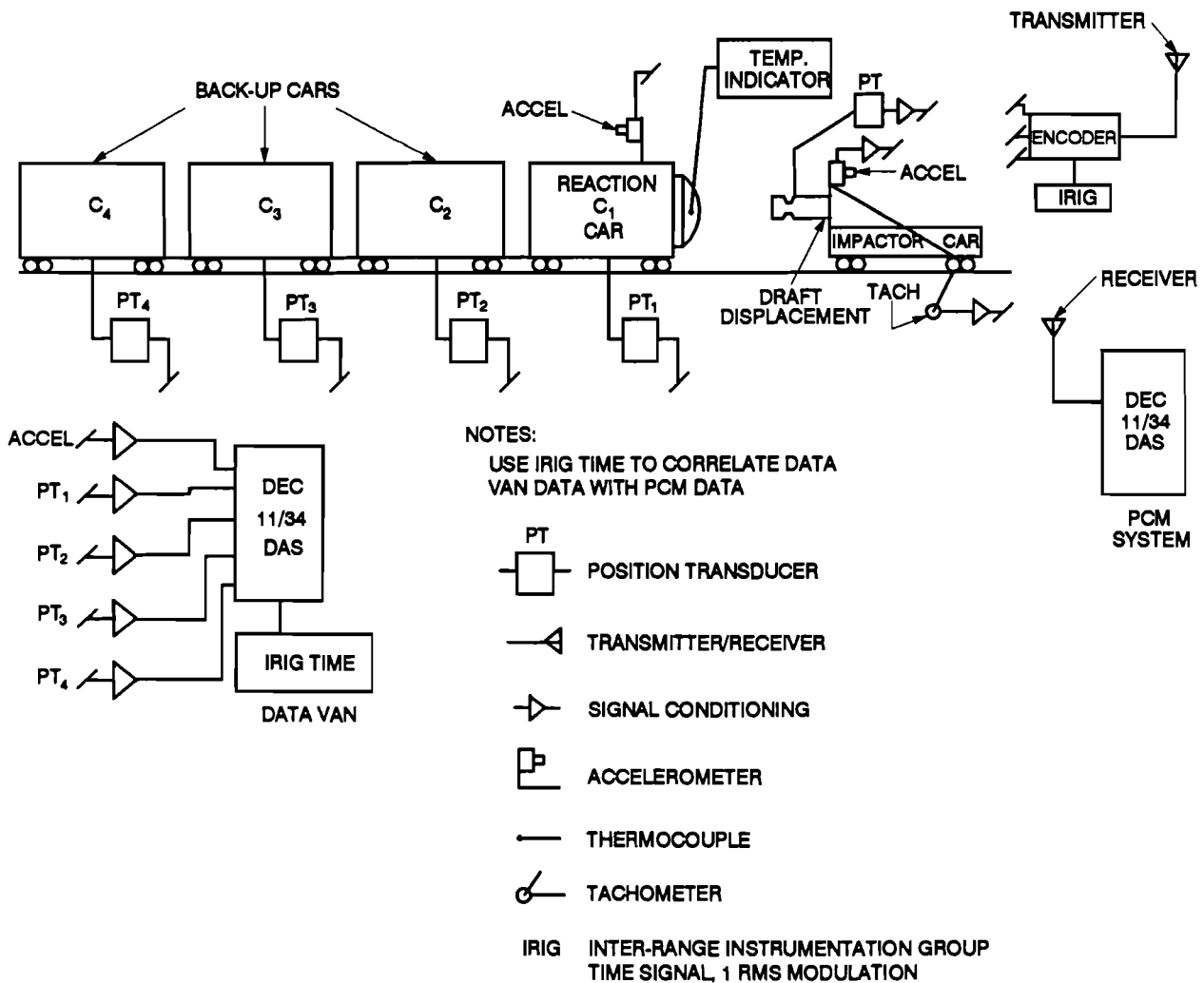


FIGURE 3.10 TEST INSTRUMENTATION SCHEMATIC - FULL-SCALE MODEL IMPACT TESTS

TABLE 3.7 TEST INSTRUMENTATION SUMMARY - FULL-SCALE MODEL IMPACT TESTS

Measurement Parameter	Frequency Response	Transducer Type/MFG	Total System Accuracy (+/-)	Comment
Mass, Test Cars	Static	Track Scale	0.14%, 35 lb	
Temperature, Tank	Static	Surface Thermocouple/Omega	5 °F	
Pressure, Tank	Static	Test Gage/Omega	0.5 psig	
Pressure, Tank	0-1 KHz	Strain Gage Transducer/Bell & Howell CEC 1000	1.8 psi	Assume 100 psi starting pressure
Displacement, Ram Coupler	12 Hz	Potentiometer/Celesco	0.13 in	+/- 5 inch full-scale
Position, Reactor/Backup Cars	> 2 Hz	Potentiometer/Celesco	2.1 in	Assume 250 inch full-scale range
Velocity, Impactor Car	200 Hz	Tachometer/Air Pax	0.04 mph	20 mph full-scale (32 kmh)
Acceleration, Impactor Car, Reaction Car	500 Hz	Strain Gage Accelerometer/ENDEVCO	1.55 G	Assume 25 G range
Event Marker, PCM/Wayside Systems	100 Hz	Photocell/Warner	0 to 4 in	

Impact velocity was measured with a tachometer mounted on the second wheel/axle set at the front of the impactor car. Average speed reading at impact was used as the impact speed. Accuracy of the tachometer system was checked on one test by setting up two automatic location detectors (ALD) and a timing clock. The two methods agreed within 0.5%.

Displacement of the reaction car and each backup car was measured dynamically with a Celesco model PT-101-250-A position transducer. Static manual measurements were taken after each test to verify the dynamic readings and to record the data when range of the transducers was exceeded.

Still photographs were taken to document head assembly construction, test configuration, instrumentation, and dent and puncture formations. Sequenced still slide photos for each impact in 35 mm format were also taken with an automatic fast-wind camera. A documentary movie camera and four high-speed movie cameras were used to document the impacts.

3.2.3 Test Variables

Three of the DOT 105A500W tank car heads were made from 7/8-inch plate and three from the same 13/16-inch plate from which DOT 105A500W tank car heads are normally made. All other parameters except tank volume and contents were held as close to the actual tank car configuration as possible. See Table 3.8 for a summary of scaling dimensions used in these tests.

Impact location was set manually by adjusting the position of the ram structural support frame. Bolt spacing allowed only for 2-inch increments of adjustment. Average actual heights above the sill were 20 inches for DOT 105A500W tank car head tests and 21 inches for DOT 112J340W tank car head tests.

Impact speed was varied by changing the location on the track where the stationary impactor car was set free to roll under the influence of gravity towards the reaction car. The release location was adjusted depending upon average wind speed and direction at the time of each test.

For a summary of the standard configuration parameters used see Table 3.9.

3.2.4 Test Matrix

The test matrix consists of only two elements, summarized in Table 3.10. Each element consists of one impact of different speed on each head.

The maximum dent depth without puncture and the velocity needed for puncture for each of the test series are shown in Table 3.11.

TABLE 3.8 SCALING DIMENSION SUMMARY - FULL-SCALE MODEL IMPACT TESTS

Measurement Parameter	Full-size Car Actual Value	Tested Value
Head Thickness, 105A500W Tank Car	0.813 in	0.875 in plate, First 3 impacts 0.813 in, Second 3 impacts
Head Thickness, 112J340W Tank Car	0.688 in	0.688 in, plate
Insulation Thickness, 105A500W Tank Car	4.0 in [Foam]	4.0 in, nominal
Insulation Thickness, 112J340W Tank Car	0.5-1.0 in [Glass fiber]	0.5 in, ceramic fiber
Head Shield Thickness, 112J340W Tank Car	0.5 in	0.5 in
Insulation Jacket, 105A500W Tank Car	0.125 in	0.125 in
Impactor Mass (Ram Car)	263,000 lb (+/-5%)	268,250 lb* 261,250 lb**
Reaction Car Weight	263,000 lb (+/-5%)	268,450 lb* 263,550 lb**
Backup Car Weight	> 480,000 lb	483,300 lb, 3 cars total
Tank Volume, 105A500W Tank Car	17,360 gal (nom)	139 gal
Tank Volume, 112J340W Tank Car	34,000 gal (nom)	272 gal

* Chlorine Tank Car Service
 ** DOT 112J340W Tank Car Service

TABLE 3.9 STANDARD CONFIGURATION SUMMARY - FULL-SCALE MODEL IMPACT TESTS

Parameter	DOT 112J340W	DOT 105A500W
Head Thickness	0.688 in	0.813 in
Head Diameter	120 in	102 in
Insulation Material	Ceramic Fiber	Foam
Insulation Thickness	0.5 in	4 in
Insulation Jacket	none - head shield	0.125 in steel
Head Shield	0.5 in steel	none
Impact Height (Nominal)	21 in	20 in
Internal Pressure	100 psi 129 psig @ 80°F (propane)	100 psi 101 psig @ 80°F (chlorine)
Outage	10%	10%

TABLES 3.10 TEST MATRIX SUMMARY - FULL-SCALE MODEL IMPACT TESTS

Test Series	Car/Head Type	Number of Heads/Impacts	Head Thickness
FS-1	DOT 112J340W	3	0.688 in
FS-2	DOT 105A500W	3	0.875 in
		3	0.813 in

TABLE 3.11 DENT AND PUNCTURE RESULTS SUMMARY - FULL-SCALE MODEL IMPACT TESTS

Test Series	Car/Head Type	Maximum Dent Depth	Puncture Velocity
FS-1	DOT 112J340W	24 in	Above 23.4 mph
FS-2	DOT 105A500W	16.6 in	15.1 mph

3.2.5 Factors Varied From Actual Vehicle

A full-scale test fixture such as the one used in these tests provides an economic alternative to using actual tank cars for testing puncture resistance. Only the head is damaged in each test, and it can be

replaced with another relatively easily by means of the bolted mating flanges. Different diameters can be accommodated with flanged reducing sections as used with the DOT 112J340W tank car heads.

However, some of the properties of the fixture are different from the properties of an actual tank car.

3.2.5.1 Tank Volume - The pressure vessel used in these tests was considerably smaller than the tank on an actual tank car. It had only 30% of the DOT 105A500W tank car volume and 23.5% of the much larger DOT 112J340W tank car volume. The volumes are shown in Table 3.8.

3.2.5.2 Center Of Gravity Height - The pressure vessel was mounted on a flat car, resulting in its center of gravity being slightly higher than that for the tank on an actual tank car. However, the flat car deck and the blocks placed on it to bring the total weight up to the tank car weight had a center of gravity considerably below the vessel centerline. The resultant c.g. height was not measured but was most likely slightly lower than that for an actual loaded tank car. In addition, a tank car is considerably stiffer in bending than a flat car. Movement of the tank head relative to the impacting coupler was much more noticeable in these tests than in the tests of actual tank cars because of this difference in stiffness.

3.2.5.3 Fluid Versus Rigid Mass - Most of the mass of a loaded tank car consists of the fluid inside the tank, free to slosh about within the constraints of tank geometry and outage when accelerations are applied. In the reaction vehicle used in these tests, the fluid mass is less than 25% of the total car mass. This has the effect of making the car more prone to puncture by increasing the effective mass of the car.

3.3 ACTUAL TANK CAR TESTS

The final phase of the test was conducted with actual tank cars. The test setup and instrumentation were the same as in the full-scale tests. These tests were intended to serve as an actual demonstration of the puncture resistance of a chlorine tank car. A clay slurry with a density of 12.3 pounds per gallon was used to approximate the chlorine lading density in the car filled to a 15% outage. The DOT 112J340W tank car was filled with water to a 6% outage. Water is heavier than LPG and the car weighed about 333,000 pounds or about 127% of normal weight.

The actual chlorine car was equipped with a stub sill reinforcing pad and bracket. The LPG car also had a reinforcing pad and bracket. On this LPG car the pad actually extended up the face of the tank head farther than on the chlorine car; however, the welds between the bracket and the pad and also between the pad and tank head were much lighter on the LPG car. No reinforcements, pads, or brackets, were used during the full-scale tests.

3.3.1 Test Specimen

Actual tank car impact tests were conducted on leased tank cars which were otherwise available for revenue service. When being tested, each tank car was backed up by three loaded freight cars. The tests were designed to model the 49 CFR 179.105-5 Tank Head Puncture Resistance requirement except that various impact speeds were used instead of the 18 mph specified in the requirement.

The test track, impactor car, ram fixture, and backup cars were the same as those used in the full-scale model tests described above. Figure 3.8 shows a typical test configuration if one substitutes an actual tank car for the reaction car. The impactor car and ram fixture are shown in Figure 3.9.

Three tank cars were used in these tests: two (2) DOT 105A500W tank cars representing DOT Class 105 chlorine tank cars; and one (1) DOT 112J340W representing DOT Class 112/114 LPG (propane) tank cars. The propane car was filled with water as required by 49 CFR 179.105. The chlorine cars were filled with kaolin clay slurry to simulate the high density of chlorine. Use of water would represent a less severe condition than that prescribed in the regulations. *Each tank was pressurized to 100 psig.*

3.3.2 Instrumentation

Instrumentation for the actual tank car impact tests was virtually identical to that for the full-scale model tests and is shown schematically in Figure 3.10. The discussion of instrumentation for those tests applies here as well except as discussed below. A summary of the test instrumentation parameters is listed in Table 3.12.

Surface temperature of the tanks varied between 53 and 77 °F.

The accelerometer on the impactor car was located on the car mainframe as in the last of the full-scale model tests, since those tests were performed prior to the actual tank car tests. The accelerometer on the reaction car was mounted on the manway cover plate at the center of the car.

Shape and depth of impact dents were measured using a vertical column mounted on the tank car tangential to the pre-dent head center as a guide and measuring horizontally at 7.5-inch vertical increments.

3.3.3 Test Variables

All parameters were held as close to the 49 CFR test parameters as possible. See Table 3.13 for a summary of scaling dimensions used.

Tank head thickness was measured with an ultrasonic digital thickness gage. The measurements indicated that the DOT 105A500W tank car heads were slightly thicker than the nominal value for that type of car, while the DOT 112J340W tank car heads were the usual thickness.

Impact location was set manually by adjusting the position of the ram structural support frame. Bolt spacing allowed only for 2-inch increments of adjustment. Average actual heights above the sill were 21.75 inches for DOT 105A500W tank car tests and 22 inches for DOT 112J340W tank car tests.

Impact speed was varied by changing the location on the track where the stationary impactor car was set free to roll under the influence of gravity towards the reaction car.

For a summary of the standard configuration parameters used see Table 3.14.

3.3.4 Test Matrix

Two impacts were planned for each tank car type, one at an impact speed just below, and one just above, the puncture threshold established in the earlier full-scale model impact tests.

The first DOT 105A500W tank car impact caused an unanticipated failure at the stub sill reinforcement at only 14.9 mph, so that three more impacts were made with the reinforcing member disabled. The first DOT 112J340W tank car impact, at 18.5 mph, did not puncture. The second impact was canceled because the 18 mph requirement had been met.

The resulting modified test matrix then became one test with the DOT 112J340W tank car and four with the DOT 105A500W tank cars, as shown in Table 3.15. The table also shows the maximum dent depth for each test and the estimated puncture velocity threshold based upon these tests. Since, for both car types, there were no punctures, the puncture threshold is estimated by utilizing the dent and puncture data from the full-scale model test results.

TABLE 3.12 TEST INSTRUMENTATION SUMMARY - ACTUAL TANK CAR IMPACT TESTS

Measurement Parameter	Frequency Response	Transducer Type/MFG	Total System Accuracy (+/-)	Comment
Mass, Test Cars	Static	Track Scale	0.14%, 35 lb	
Temperature, Tank	Static	Surface Thermocouple/Omega	5 °F	
Pressure, Tank	Static	Test Gage/Omega	0.5 psig	
Pressure, Tank	0-1 KHz	Strain Gage Transducer/Bell & Howell CEC 1000	1.8 psi	Assume 100 psi starting pressure
Displacement, Ram Coupler	12 Hz	Potentiometer/Celesco	0.13 in	+/- 5 inch full-scale
Position, Reactor/Backup Cars	> 2 Hz	Potentiometer/Celesco	2.1 in	Assume 250 inch full-scale range
Velocity, Impactor Car	200 Hz	Tachometer/Air Pax	0.04 mph	20 mph full-scale
Acceleration, Impactor Car, Reaction Car	500 Hz	Strain Gage Accelerometer/ENDEVCO	1.55 G	Assume 25 G range
Event Marker, PCM/Wayside Systems	100 Hz	Photocell/Warner	0 to 4 in	

TABLE 3.13 SCALING DIMENSION SUMMARY - ACTUAL TANK CAR IMPACT TEST

Measurement Parameter	Full-size Car Actual Value	Tested Value
Head Thickness, 105A500W Tank Car	0.813 in	0.844 in
Head Thickness, 112J340W Tank Car	0.688 in	0.688 in
Insulation Thickness, 105A500W Tank Car	4.0 in [Foam]	2.75-5.50 in within impact zone
Insulation Thickness, 112J340W Tank Car	0.5-1.0 in [Glass fiber]	0.5 in ceramic fiber
Head Shield Thickness, 112J340W Tank Car	0.5 in	0.5 in plate
Insulation Jacket, 105A500W Tank Car	0.125 in	0.125 in
Impactor Mass (Ram Car)	263,000 lb (+/- 5%)	265,150 lb
Reaction Car Weight	263,000 lb (+/- 5%)	257,350-261,000 lb* 333,000 lb**
Backup Car Weight	> 480,000 lb	483,300 lb, 3 cars total 497,700 lb, for one test (223,489 kg)
Tank Volume, 105A500W Tank Car	17,360 gal (nom)	17,300 gal
Tank Volume, 112J340W Tank Car	34,000 gal (nom)	33,500 gal

* DOT 105A500W Tank Car Service

** DOT 112J340W Tank Car Service

TABLE 3.14 STANDARD CONFIGURATION SUMMARY - ACTUAL TANK CAR IMPACT TESTS

Parameter	DOT 112J340W	DOT 105A500W
Head Thickness	0.688 in	0.844 in
Head Diameter	120 in	102 in
Insulation Material	Ceramic Fiber	Foam
Insulation Thickness	0.5 in	4 in
Insulation Jacket	none - head shield	0.125 in, steel
Head Shield	0.5 in, steel	none
Impact Height (Nominal)	22 in	21.75 in
Internal Pressure	100 psi	100 psi
Outage	6%	15.7%
Liquid Contents	Water	Water/Clay Slurry, 1.47 specific gravity

TABLE 3.15 DENT AND PUNCTURE RESULTS SUMMARY - ACTUAL TANK CAR IMPACT TESTS

Car Type-Test Series	Maximum Dent Depth	Impact Velocity
112-1 (DOT 112J340W)	19.0 in	18.5 mph
105-1 (DOT 105A500W)	Failure (see text)	14.9 mph
105-2 (DOT 105A500W)	13.875 in	15.5 mph
105-3 (DOT 105A500W)	16.375 in	16.6 mph
105-4 (DOT 105A500W)	17.0 in	17.5 mph

4 DISCUSSION OF TEST RESULTS

The overall objective of the test was to determine the relative puncture resistance of a nominally configured chlorine tank car as compared with a liquified propane gas tank car equipped with a 1/2-inch steel head shield. In addition, the 1/5-scale tests were designed to determine the effects of variations in several important parameters and to predict their performance in full-scale.

In order to evaluate the results of the 1/5-scale tests and predict the effect of the parametric variations in full-scale it is useful to consider a linear, elastic impact in terms of simple springs and masses. In Figure 4.1, a schematic of the test condition is presented where m_1 and k_1 are associated with the struck car and m_2 and k_2 with the impactor car. Assuming that the stiffness of the struck car is much less than the stiffness of the impactor car, effective stiffness (k_e) and effective mass (m_e) are $k_e = (k_1 \times k_2)/(k_1 + k_2) \approx k_1$, and $m_e = (m_1 \times m_2)/(m_1 + m_2)$. The kinetic energy (E) is $E = 1/2 m_2 v_{2i}^2$, where v_{2i} is the velocity at which impact occurs. The peak force is *peak force* $= v_{2i} \sqrt{k_1 m_2} = \sqrt{2Ek_1} = 2E/D_1$, where D_1 is the dent depth in the struck car. The flexibility of the tank head, whether the head is fixed or not, determines the value of the peak force.

In impacts of consequence, damage or dent depth resulting in tank car puncture involves plastic deformation of the struck car and is dependent upon the peak force and the energy absorbed. Linear relationships between peak force and dent depth no longer apply. For purposes of illustration, each of the two examples of impacted tank cars in Figure 4.2 is depicted as a simple, well behaved, nonlinear system with spring softening characteristics. The tank car with low stiffness (lower curve) should experience a large dent depth at a low critical force when the tank head is punctured. If the other tank car with the greater system stiffness can absorb the same energy, then failure will occur at a smaller dent depth and a higher critical force as shown.

Puncture starts as a local tearing or shearing when the critical force level is reached and the ultimate strength of the material is exceeded either at the point of impact or at some other severely stressed location in the dented region. The sharp edge of the striking coupler often produces a stress concentration and the critical force may become less dependent upon the impact energy than in the highly stressed, local region. Failure in a less than well behaved system can occur prematurely with the result that less energy is absorbed and the dent depth and critical force are smaller. This situation could be illustrated by Figure 4.2 if the more compliant tank car system were to reach the critical force level before the stiffer tank car system and therefore would absorb less energy.

In the interest of surviving increased impact velocities, conditions should be exploited that increase the dent depth and the critical force. A consideration when comparing results from tests conducted under

different conditions is how the relationship between dent depth and critical force level changes and is particularly important when the variations alter the stress distribution in the tank head. Initially, plastic deformation from an impact may be well behaved. Permanent denting may start as plate bending and, eventually, may include some degree of membrane stretching or shearing of the tank head as the dent grows. When the deformation is no longer well behaved, irregular and random folds and creases can develop. The ability to absorb energy diminishes as the ultimate strength is exceeded and the critical force and dent depth are approached. In tank car collisions, one way to reduce the severity of local stresses in the tank head at the impacting coupler is by blunting the contacting surfaces. The formation of a larger dent allows the car to move a greater distance so that the draft gear of backup cars and the brakes can absorb more of the impact energy. Head shields and insulation jackets will reduce the local stresses by blunting the coupler face and will spread the impact over a larger area. Since the formation of dents is the primary energy absorption mechanism, failure should not occur before maximum tank car deformation. Ideally, the values of critical force and dent depth at puncture should be maximum.

Outside the region of linear elastic behavior, the deformation of the tank head will be affected by a combination of bending, stretching, and shearing that is not predictable by simple analysis and depends upon testing to establish the critical failure values of force and dent depth. The test procedures were based upon two conceptual models. The idea of a flexible stationary barrier was used in the drop tower arrangement for the 1/5-scale model tests and the idea of a flexible moveable barrier was used in the impactor car and ram test fixture for the full-scale model tests. In the flexible stationary model $m_1 = \infty$, so that $m_1 = m_2$. With linear modeling, the analysis for each test procedure predicts that the dent depths will have the same value. Also, the values for the peak forces and the energies will be the same. With nonlinear behavior the results will be similar only if the systems are well behaved.

Lading, because it comprises the major mass component of a fully laden tank car, along with tank car outage, will have a significant effect on any damage caused by an impact. Generally, the greater the lading in the impactor car, the greater will be the impact energy and the peak force. With no outage, a fully laden tank car is more liable to damage than a car with outage. A relatively small indentation of the tank head and the resultant fluid pressure increase can produce stresses that will rupture a tank wall. Allowance for gaseous headroom in the tank will tend to keep the peak tank pressure values low provided the percentage reduction in outage volume from impact is small. Such reductions which decrease the peak pressure have the effect of reducing the stiffness of the tank head, increasing the absorption energy, and raising the peak force. Another significant effect of outage is to introduce erratic forces, created by fluid sloshing, which decouple the mass of the fluid from the mass of the tank car. The result is an effective reduction of the combined mass tending to decrease the effective energy and the peak force. Changes in the location and the value of critical force can occur to increase the variability of test results. The tests conducted for this study considered fully laden tanks with some outage and did not study variations in tank car outage or the decoupling of fluid mass. Since the 1/5-scale drop tower tests are

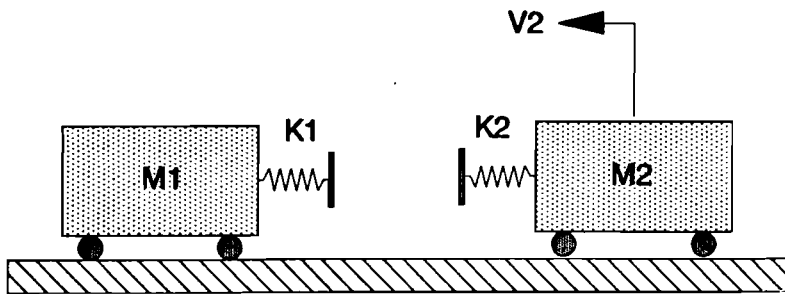


FIGURE 4.1 MODEL OF IMPACTING CARS

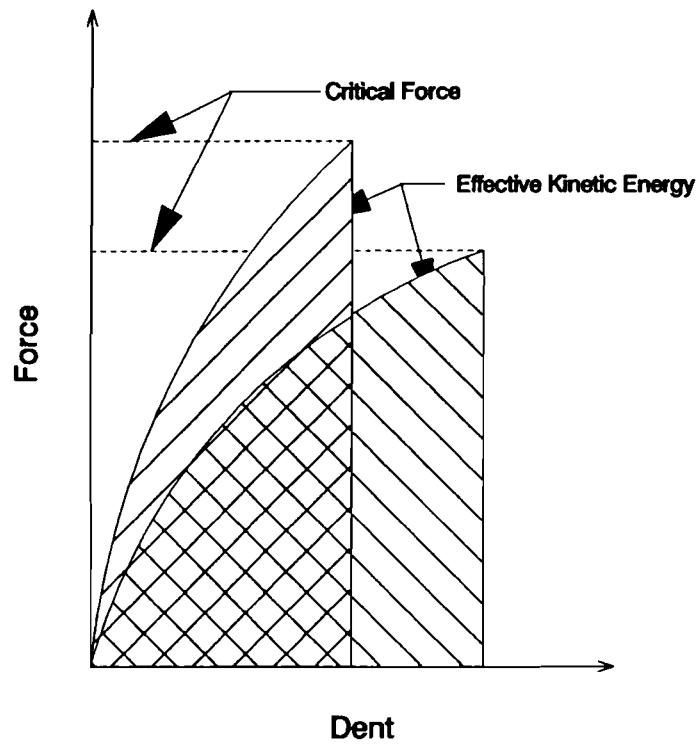


FIGURE 4.2 MODEL IMPACT RESPONSE

based on the flexible stationary model, the effect of the mass of a struck car and its lading could not be studied. An outage value of 10% was employed for the 1/5-scale and the full-scale model tests. The actual chlorine tank car tested had an outage of 15% and the actual LPG tank car tested had an outage of 6%.

The 1/5-scale drop tower tests generally do not predict full-scale performance directly because the impact mechanics are not scaled. In the drop tower test the head is fixed to a tank mounted vertically which cannot move under impact. This leads to a different energy and momentum transfer mechanism which under some circumstances can be important. Design and fabrication details such as the tank head mounting connections, variations in the head formation procedures, restricted coupler angle and relative deflection conditions produce strains which do not occur in the full-scale tests, and reduce the accuracy of the 1/5-scale model test results.

In general, the indentation of the head is related to head thickness, speed of impact, impacting mass, and whether the head is stationary or moveable. The presence of a head shield or insulation jacket affected whether the head would puncture at the impact speed but did not in general affect dent depth. In addition head puncture was influenced by small scale details of the striking coupler and its orientation relative to the tank head. Rounded corners of the coupler resulting from numerous impacts could cause the highly localized shear stress at the coupler's edge to be significantly reduced. Also a bending of the coupler shank during full-scale testing could cause variations producing more severe test conditions.

The primary failure mode for the tank heads in these low velocity impacts is plug formation by excessive shear forces along the upper edge of the impacting coupler. Two other failure modes were observed during the tests: a pinching failure in tension between the head and the cylindrical portion of the tank, and a shear failure at the reinforcing pad connecting the tank head to the stub sill. Generally, the modes of deformation of the 1/5-scale test model reproduced the modes experienced by the full-scale model at impact.

4.1 1/5-SCALE TESTS

The parameters studied in the 1/5-scale tests were impact location, jacket thickness, head shield presence, head thickness, internal pressure, and insulation type.

4.1.1 Impact Location

In the CFR specification defining required puncture resistance for certain pressure cars, the impact location above the sill is specified as either 21 inches or 31 inches, whichever is more severe. The 1/5-scale tests showed that the 21-inch location above the sill was the more severe test condition. In Figures 4.3 and 4.4, the dent shapes for tests near the puncture threshold are shown for the two impact

two impact locations. The dents for the 31-inch impacts are considerably larger as well as deeper. In Figure 4.5, the dent depth versus impact velocity for several test series is shown. Comparison of the test results for the 31-inch offset with the results for the nominal 21-inch offset show that for a given impact velocity the dent depth is greater for the 31-inch offset. The differences between dent depths range from 0.5 inch at an impact velocity (drop height) of 20 inches decreasing to 0.3 inch at 120 inches. The effect is that the tank head is considerably stiffer the closer the impact occurs to the tank head sill juncture. The stiffer head area allows the upper coupler edge to create a zone of high shear stress which eventually results in failure.

The puncture resistance for the DOT 112J340W tank car heads increased from about 10.6 mph at 21 inches to over 18 mph at 31 inches. For the chlorine car the puncture velocity threshold increased from 10.2 to about 15 mph. The absolute percentage increase in puncture velocity threshold would not be expected to be duplicated in full-scale; however, the trend that impacts closer to the tank head knuckle are more severe is expected to be true.

For the last drop in series D02, representative of the 31-inch offset impacts on the DOT 112J340W tank car heads, the dent was large enough to cause a failure of the tank in bending at the transition between the head and cylindrical portion of the tank. This type of failure cannot be mitigated with thicker head shields and requires some energy-absorbing system to reduce the dent size.

4.1.2 Jacket Thickness

Chlorine cars are equipped with insulation jackets which are made of 11-gage steel sheet metal. This steel jacket will blunt the edge of an impacting coupler. The effectiveness of this blunting is directly proportional to the thickness of the jacket as is shown in Figure 4.6 which plots the threshold puncture velocity versus jacket thickness.

Three 1/5-scale test series were performed to determine the effectiveness of varying the thickness of the steel jacket. Test series D03 was the nominal case, while series D04 and D05 had jackets of 1/4-inch and 3/8-inch respectively.

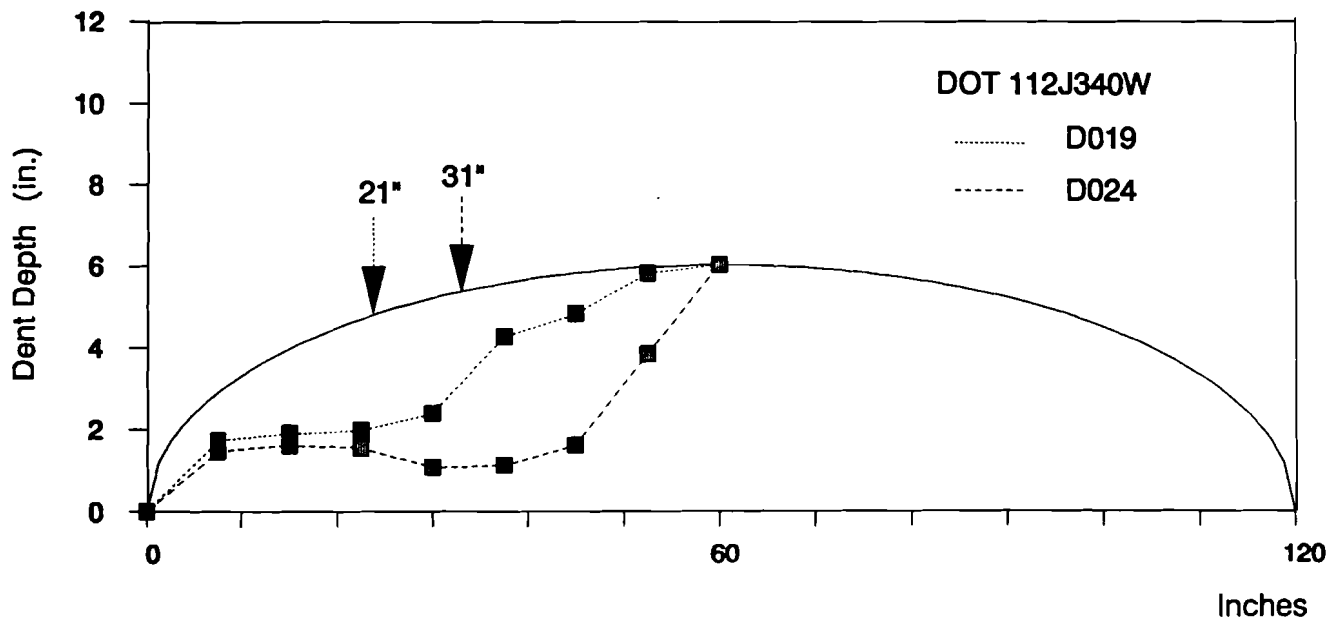


FIGURE 4.3 DENT SHAPE - DOT 112J340W TANK CAR

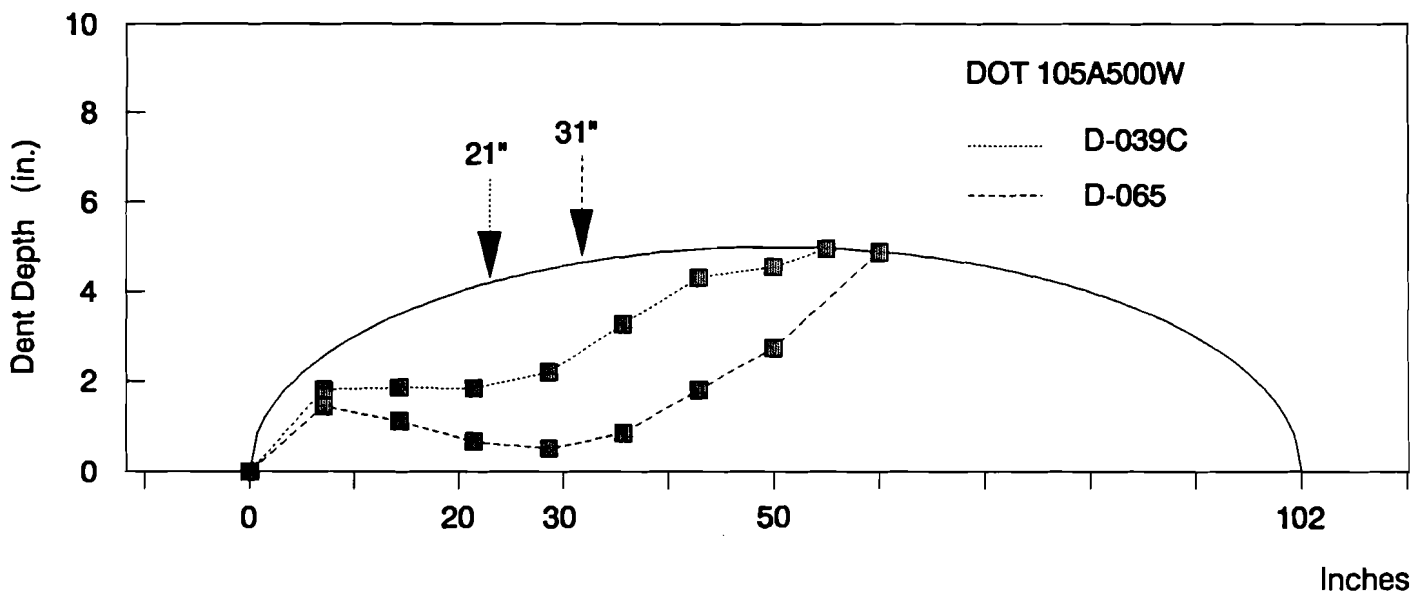


FIGURE 4.4 DENT SHAPE - DOT 105A500W TANK CAR

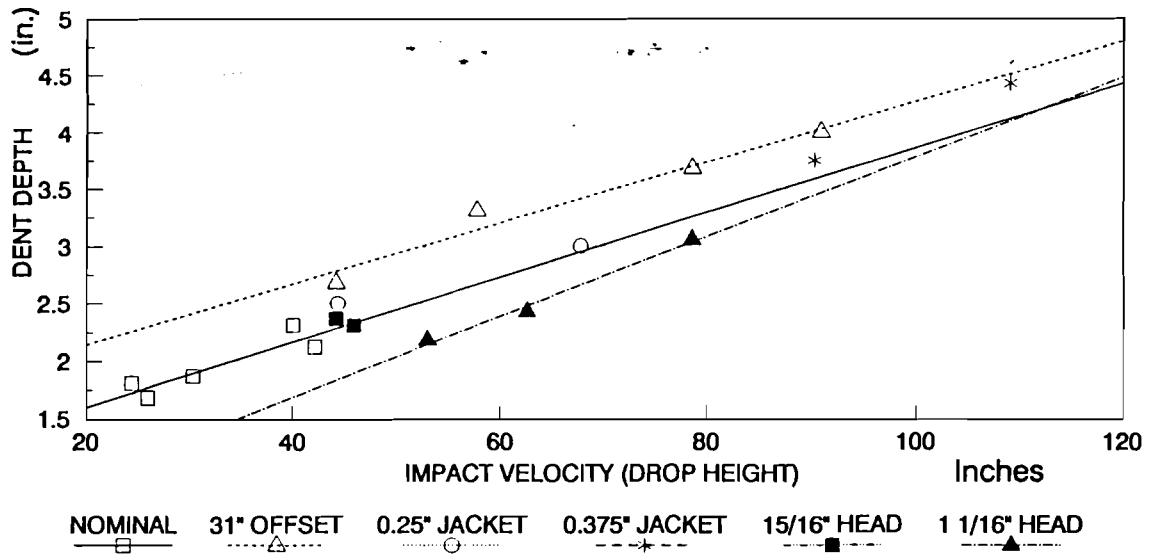


FIGURE 4.5 DENT DEPTH VS IMPACT VELOCITY

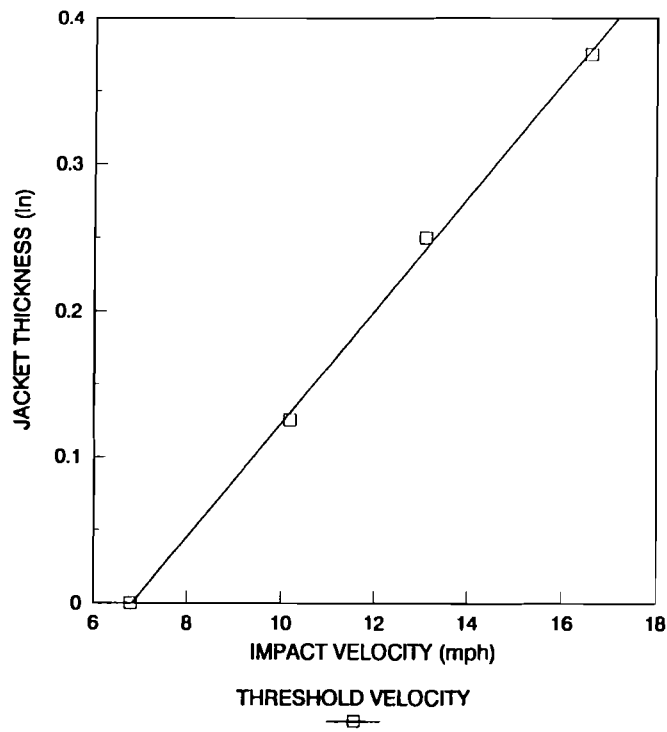


FIGURE 4.6 PUNCTURE RESISTANCE - JACKET THICKNESS VS IMPACT VELOCITY

Series D03X had no jacket. Interestingly, the dent depth is proportional to impact velocity and appears to be unaffected by jacket thickness. The dent depths for the cases with different jackets follow a straight line in Figure 4.5. This is expected as the jackets do little to absorb energy. The primary function is blunting which allows higher impact energies to be absorbed by the tank head.

4.1.3 Head Shield

The CFR requires that certain pressure cars be equipped with 1/2-inch thick head shields over the lower half of the tank head. Test series D01 modeled the nominal conditions of a DOT 112J340W pressure car in 1/5-scale. The series produced a threshold puncture resistance of only 10.6 mph. This low value, essentially equivalent to the chlorine car nominal configuration, was not expected. The head shield normally would blunt the coupler face sufficiently to produce a much higher threshold puncture velocity as was seen in the tests with thicker steel insulation jackets. The only reasonable explanation is that the DOT 112J340W tank car heads, having a larger diameter, required a much stiffer attachment bracket than the chlorine 1/5-scale tank heads which when coupled with the rigid test fixture produced a more severe test condition than is seen in full-scale. The test series D02, with impacts at the 31-inch offset location, produced the highest threshold puncture velocity of the test at 18 mph.

Although the 1/5-scale model tests with head shields reproduced the modes of deformation of the full-scale model, the test result values did not scale proportionally. Dent depths from the full-scale tests are much greater than would be predicted from the 1/5-scale tests as seen in Figure 4.7. It is especially confusing that the thicker jacket tests produced much higher comparative puncture threshold velocities. The results of this series of tests raise questions about the accuracy of the drop tower testing procedure.

In full-scale, impacts up to 22 mph were measured without puncturing a tank head equipped with a 1/2-inch steel head shield. No tests were conducted at speeds higher than 22 mph because the sills on the ram and reaction cars were not designed to withstand such high loadings.

4.1.4 Head Thickness

The effect of varying head thickness was investigated in the 1/5-scale test series D10 and D11. These series were compared with the baseline chlorine series, D03, using head thicknesses of 15/16-inch and 1-1/16 inch. The dent depth versus drop height for various test conditions is shown in Figure 4.5. The 15/16-inch thick head test results did not vary significantly from the nominal configuration results and fell just under the line fit for the nominal head thickness (extended using the varying jacket thickness results). However, the line for the 1-1/16 inch thick heads was substantially below the line for the nominal case. At a drop height of about 45 inches (\approx 10 mph), the difference between dent depths is 0.4 inch. In addition there was a significant increase in the threshold puncture resistance velocity at about 14 mph.

The effect of the thicker head was to increase the stiffness of the head, thus reducing the dent depths. However, the thicker tank head increased the critical force required to puncture. In addition, the process of buckling the thicker tank head absorbed more energy for the same size dent than the nominal case.

Of interest was the relative effectiveness of adding material to the tank head versus to the jacket. Both increased the threshold puncture resistance; however, comparing data in Tables 3.4 and 3.5 it is seen that increasing the jacket thickness produced the larger effect for the same amount of added steel.

Comparison of results between test series D03, D04 and D05 for tank heads of the same thickness when the jacket thickness is increased from 1/8 to 3/8-inch showed an increase in puncture velocity from 10.2 to 16.6 mph and an increase in dent depth from 2.7 to 4.6 inches. Comparison of results between test series D03, D10 and D11 for jackets of the same thickness when the tank head thickness is increased from 13/16 to 1-1/16 inch showed an increase in puncture velocity from 10.2 to 14.1 mph and an increase in dent depth from 2.7 to 3.4 inches. Results of changes in the jacket thickness show that the increase in puncture velocity was 25% greater and the increase in dent depth was 44% greater than the results of changes in head thickness. The relative benefits of adding steel to the jacket rather than the tank head would be expected to hold true in full-scale.

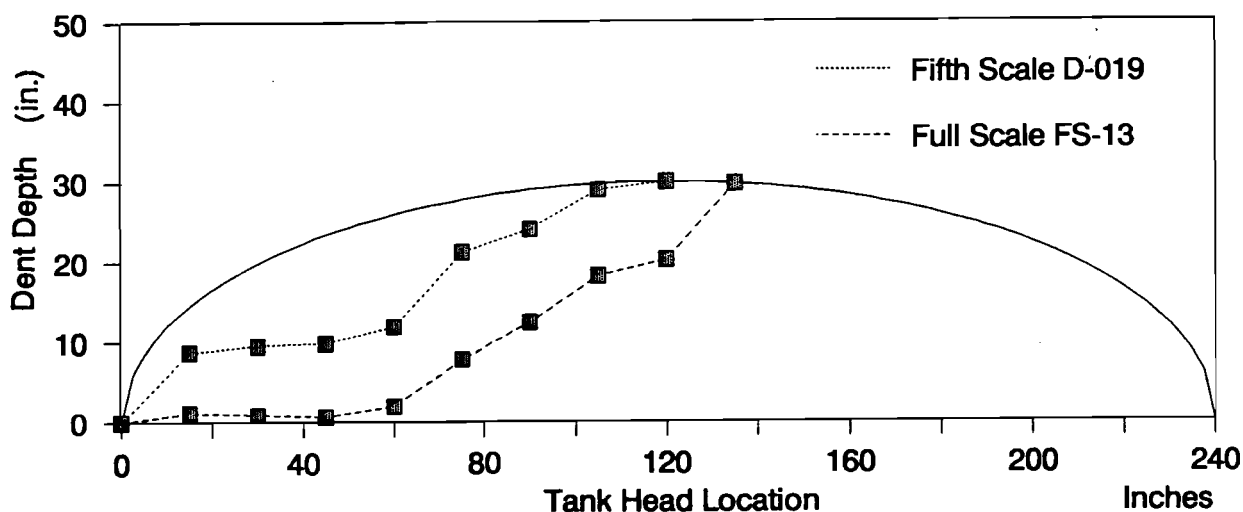


FIGURE 4.7 COMPARISON OF DENT SHAPES FOR FULL AND 1/5-SCALE TESTS

4.1.5 Internal Pressure

Chlorine is typically shipped cold with internal pressures less than 100 psi. However, occasionally internal pressures may reach 200 psi or more. Two 1/5-scale test series were designed to investigate the effect of varying internal pressure. Series D07 were conducted at 200 psi while series D08 were conducted at 50 psi.

The effect of internal pressure is complicated. The tank head is stiffened by the pressure which puts the head into a prestressed state inhibiting denting and allowing greater energy absorption for the same size dent. However, if the head is stiffened sufficiently, it becomes much more vulnerable to puncture because a high shear stress concentration will form at the coupler's edge. A very high pressure will produce a result similar to a 0% outage condition which was found to have a very low puncture resistance. Low internal pressure should be the least severe condition allowing a large dent to develop prior to reaching the critical shear stress at the coupler's edge. There may be a range of pressures which actually increases the puncture resistance of a tank car by stiffening the tank head just enough to absorb some energy while not producing the stress concentration. These effects deserve additional study and possibly full-scale testing to demonstrate the findings of the analyses.

4.1.6 Insulation Type

Chlorine cars are nominally fitted with 4 inches of thermal insulation. The insulation may be a urethane foam or glass fiber and ceramic fiber combination. The consequences of this choice in terms of puncture resistance are small. The nominal 1/5-scale configuration test series were conducted with foam insulation while series D09 were conducted with glass fiber and ceramic fiber. The results show a slightly better performance for the foam. The foam acts as an energy absorber between the steel jacket and the impacting coupler. However, the amount of energy required to be absorbed during an impact is much greater than the foam can accommodate and the foam is almost instantly flattened. The glass fiber and ceramic fiber, especially in 1/5-scale, do not crush significantly nor do they significantly increase the blunting of the coupler face, which would account for the slightly lower threshold puncture resistance. A combination of energy absorbing material and a blunting material could prove to be the best alternative if the puncture resistance of a tank car must be increased.

4.2 FULL-SCALE TEST RESULTS

The full-scale phase of testing involved impacting full-scale tank heads attached to a special pressure vessel mounted to a flatcar. In all, nine tests were conducted: six tests with nominally configured chlorine heads and three with propane heads equipped with head shields.

4.2.1 DOT 105A500W Tank Car Heads

The first three chlorine heads tested were found to be 7/8-inch thick rather than the nominal 13/16-inch in the test matrix. The heads were used to bracket the puncture threshold with the assumption that the variation in head thickness would have very little effect on the results.

The calculated threshold puncture velocity for the full-scale tests was 15.1 mph. Two tests, FS-23 and FS-26, were conducted at this speed. FS-23 was a test with a 7/8-inch head. During the first three impacts the coupler was deforming, bending so that the jaw was more pronounced. This allowed the jaw

to contact the tank head early and initiate the failure in run FS-23.

Run FS-26 with a 13/16-inch thick head did not puncture. The threshold was lower than found in the actual tank car tests since the effective mass for the full-scale test was greater because the concrete blocks were rigidly attached to the flat car frame. In the actual tank car much of the mass of the car was the lading. With any outage, this fluid can slosh back and forth in the tank creating a dynamic loading which would reduce the effective mass at impact.

The dent size was larger than straight scaling would predict from the 1/5-scale tests. The result was expected since the 1/5-scale test with a fixed head tended to reduce the tank head denting and puncture resistance.

Basically the insulation and insulation jacket performed as they did in 1/5-scale, blunting the coupler slightly. An interesting motion noted during the tests was the vertical movement of the tank head which resulted from the bending of the tank car due to impact above the neutral axis of the flatcar. The coupler tore through the insulation jacket and insulation and then slid down the face of the tank head until the dent was formed. The dent formation and failure normally occur prior to the movement of the backup cars.

4.2.2 DOT 112I340W Tank Car Heads

Three tank heads were tested in the FS-1 series. FS-13 was at 23.4 mph and resulted in the initial phases of the head shield failure. The test also resulted in significant damage to both the flatcar and the ram car.

This threshold puncture velocity was well above the CFR required threshold of 18 mph even with the higher effective mass provided by the concrete blocks. In addition, the result was about 50% higher than the chlorine car, indicating the effectiveness of the 1/2-inch head shield. This again raises the question of why the 1/5-scale test with the head shield would produce such a low velocity failure. The full-scale results as scaled back would predict a puncture at somewhere near 15 mph depending on how the estimate is made.

4.3 ACTUAL TANK CAR TESTS RESULTS

The final phase of testing involved impacting actual tank cars. The chlorine cars used were leased from Union Tank Car (UTLX 81081 and 81083) and the LPG car was leased from General American Tank Car (GATX 93669).

4.3.1 Chlorine Car Test Results

Four impacts were conducted with the chlorine car at speeds between 15 and 18 mph. The first impact, 105-1, was at 15.1 mph and resulted in a failure at the stub sill attachment. This test is discussed in section 4.3.3. The highest velocity impact was test 105-4 at 17.5 mph, which did not result in a failure. The dent shapes for the three which did not fail are shown in Figure 4.8.

Figure 4.9 shows dent depths versus impact velocity for the 1/5-scale (scaled up), full-scale and actual tank car tests. Each series shifts the line fit to the right indicating that the actual tank car test was the least severe test condition. The actual car, even when filled with the clay slurry, has a lower effective mass than the full-scale car.

The tank head from test 105-4 showed some of the initial signs of failure, particularly the start of gouging along the top edge of the coupler. This condition along with the dent depth compared to the full-scale tests suggests that the car was very close to the puncture threshold.

4.3.2 LPG Car Tests Results

Only one test, 112-1, was conducted with the actual LPG car. The car was struck at 18.5 mph and did not puncture. In addition, the head shield was not near failure. Regarding comparison of the results with the full-scale tests, the relative masses are more difficult to compare because the actual car was filled with water which caused it to weigh much more than the car normally would weigh (333,000 pounds versus 263,000 pounds). In addition, the full-scale results do not fall on a straight line, which may be a result of the damage done to the sills of both the flat and ram cars.

The tests show that the nominally configured DOT 112J340W tank car equipped with a head shield has a puncture resistance well above the threshold specified in CFR.

4.3.3 Chlorine Car Stub Sill Attachment Failure

Tank cars are commonly equipped with reinforcing pads at the juncture of the tank shell and the stub sill. This pad often extends beyond the end of the cylindrical section of the tank shell and ends some distance up the tank face. This pad and the associated bracket help distribute the longitudinal loads transmitted through the couplers to the tank shell and aft to the coupler at the opposite end of the car. Figure 4.10 shows a sketch of the bracket and reinforcing pad design.

The first impact of an actual DOT 105A500W car was conducted in December 1986 at 14.9 mph, and resulted in a tank head failure at the stub sill reinforcing pad attachment. In subsequent tests the

reinforcing pad attachments to the tank head were cut away and the impact velocity was increased to 17.5 mph without tank head failure. The LPG car also had a reinforcing pad and bracket, although of a different design. This car was tested with the pad in place at 18.5 mph without head failure puncture.

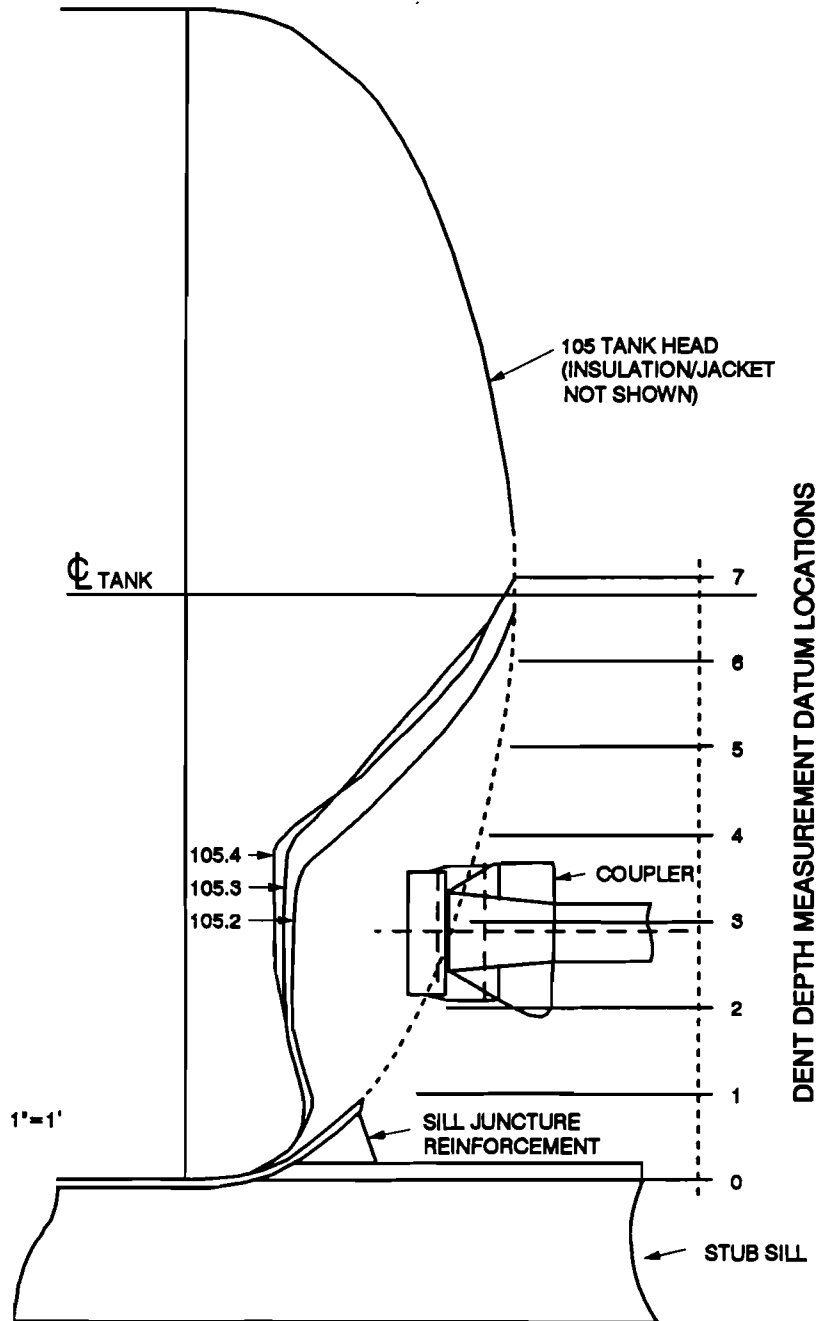
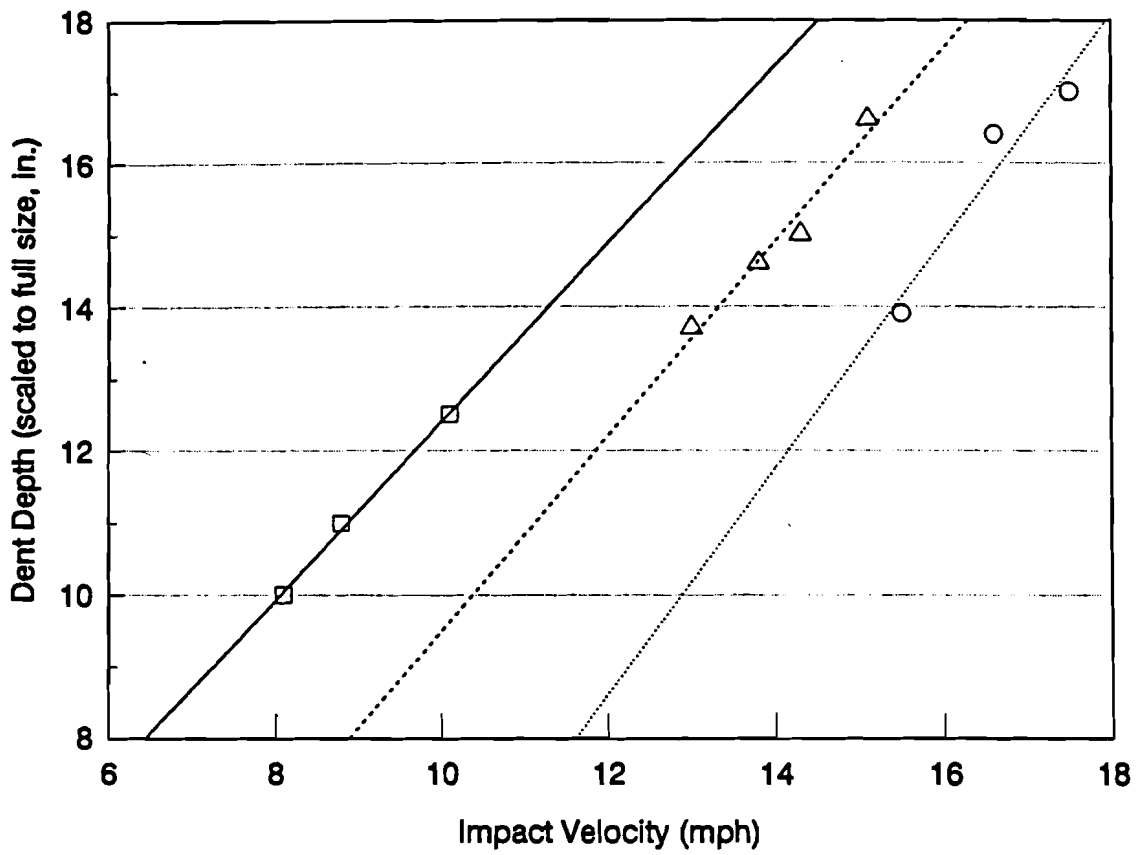


FIGURE 4.8 FULL-SIZE MEASUREMENT SCALE FOR DOT 105A500W TANK CAR DENT DEPTHS



Fifth Scale Full Scale Actual Tank Car
 —□— ····△···· ····○····

FIGURE 4.9 IMPACT VELOCITY VS DENT DEPTH

The chlorine car with the stub sill reinforcing pad and bracket in place probably would not withstand an 18 mph impact even if equipped with a 1/2-inch head shield. This bracket and pad combination significantly stiffens the tank head in the dent zone. The Association of American Railroads (AAR) Manual of Standards and Recommended Practices, Specifications for Tank Cars Part E13.00, Head-to-Sill Attachments [2], requires that on cars built after 1982 the weld between the bracket and reinforcing pad must fail prior to head failure. The pad itself, however, significantly stiffens the tank head, and the code does not specify that the weld between pad and the head fail prior to head failure. If the weld strength can be reduced between the pad and the head, the car may be able to withstand the prescribed impact test.

There are three main areas of concern in terms of the effects of the stub sill reinforcing pad and bracket. The first is the effect on the puncture resistance and how the presence of the pads changes the mechanism of head failure. The second concern is whether 1/2-inch head shields protect against the failure mechanism created by the pads and brackets. The third concern is how many active cars have these pads and how significantly do the different observed designs reduce the puncture resistance of the tank car. At issue here is how to insure that the weld between the pad and the head fails prior to a failure of the tank car head itself.

In general terms, tank cars puncture when the shear stress at the coupler/tank head contact area exceeds the ultimate strength of the tank material. The force generating this stress is directly related to the impact velocity or impacting energy. Head shields and steel jackets reduce this stress by blunting the coupler face and spreading the impact force over a larger area. As this force is blunted larger dents are formed. The dent formation is the primary energy absorption mechanism. Other energy absorbing mechanisms could be effective; however, none were tested in this study. As the dents get larger and larger the mode of failure may change to one of bending rather than puncture, as was seen in the 1/5-scale, 31-inch offset tests.

If the tank head is restricted from motion in the dent zone, as is the case when the reinforcing pad is present, high stresses will occur at the restriction. The stub sill reinforcing pad on the chlorine car was attached to the tank head with a fairly heavy weld significantly stiffening the tank head in the dent zone. The result of the first test was a head failure above the bracket. The failure shown in Figure 4.11 had the characteristic "smile" often seen in previous investigations.

To evaluate the effect of the reinforcing pad, test results from the full-scale and actual tank car tests can be compared. The tests are not identical and some of these variations are apparent in the data; however, these are generally secondary effects. Perhaps the biggest difference is the relative effective masses of the various cars employed in the tests which cause a difference in the dent depths from test to test.

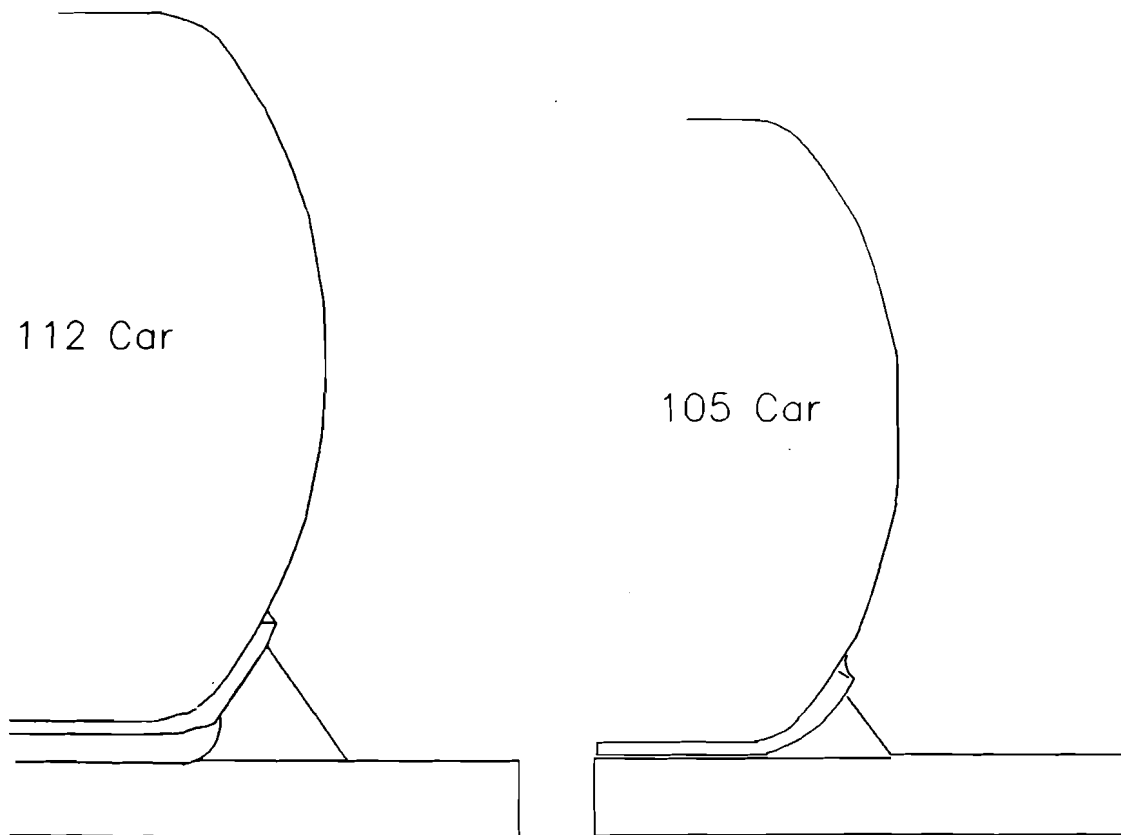


FIGURE 4.10 SKETCH OF BRACKET AND REINFORCING PAD ARRANGEMENT

In Figure 4.12 the dent shapes from the actual impact test for the DOT 105A500W tank car are shown. The pad and bracket were cut away for all these tests. The figure shows the approximate location of the bracket and pad which are well into the dent zone. In Figure 4.13, the dent labeled 105-4 is from an impact at 17.5 mph. This dent is compared to the dent from the full-scale test series FS-26 at 15 mph in Figure 4.13. Neither of these tests resulted in a tank puncture.

Similarly, the dent shape of the one actual impact of the LPG car is shown in Figure 4.14 compared to a similar impact in full-size. The LPG car was constructed with a reinforcing pad and bracket. During the impact the bracket failed first, allowing the head to dent. The weld between the tank head and the pad failed after nearly all of the dent had been formed. The dent shape shows the effect of the stiffened tank head in that the dent in the lower part of the head is much smaller.



**FIGURE 4.11 HEAD FAILURE AT SILL JUNCTURE REINFORCEMENT, TEST 105-1
(DOT 105A500W TANK CAR)**

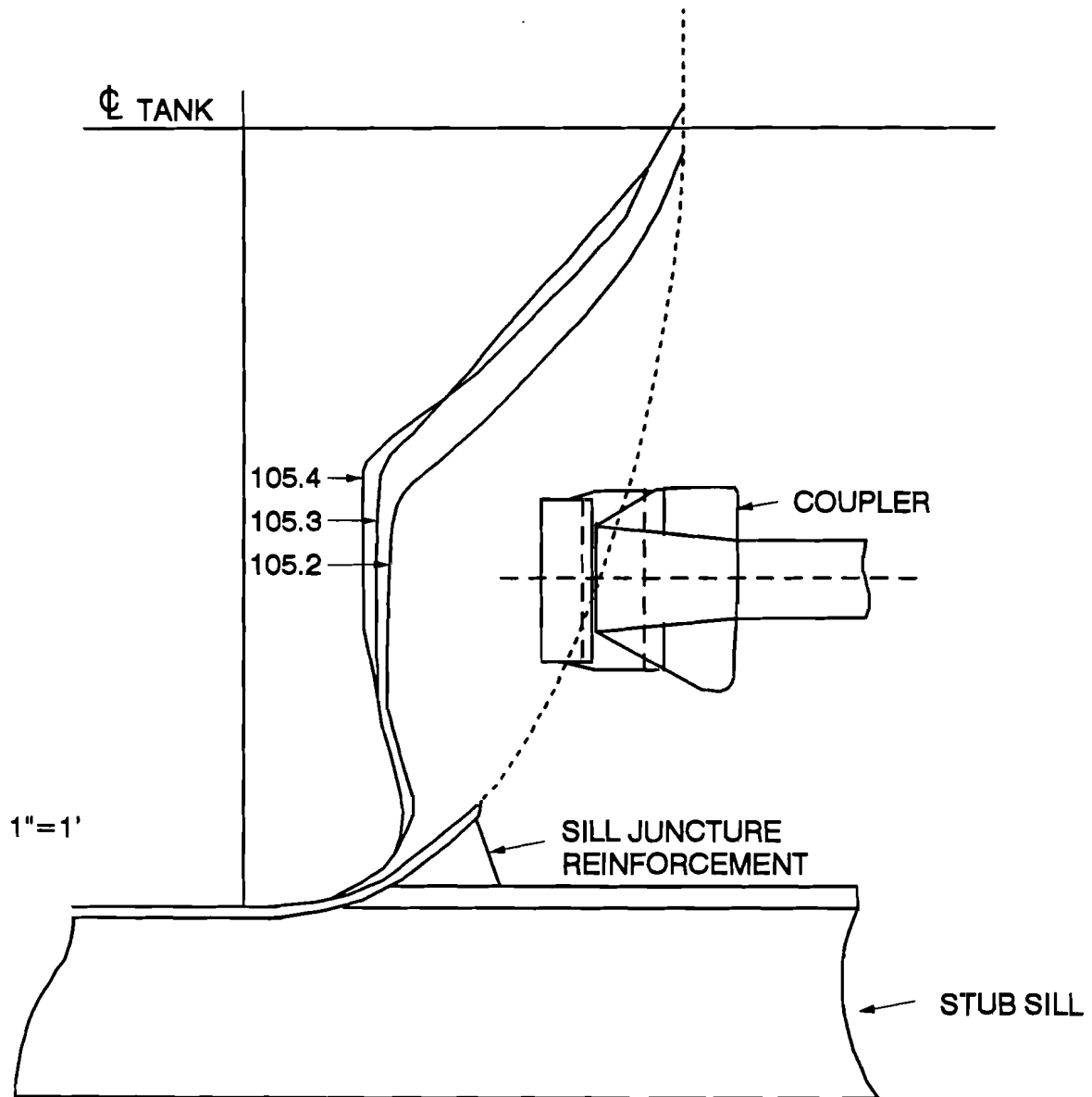


FIGURE 4.12 DENT SHAPES COMPARED - ACTUAL CHLORINE CAR WITH PAD

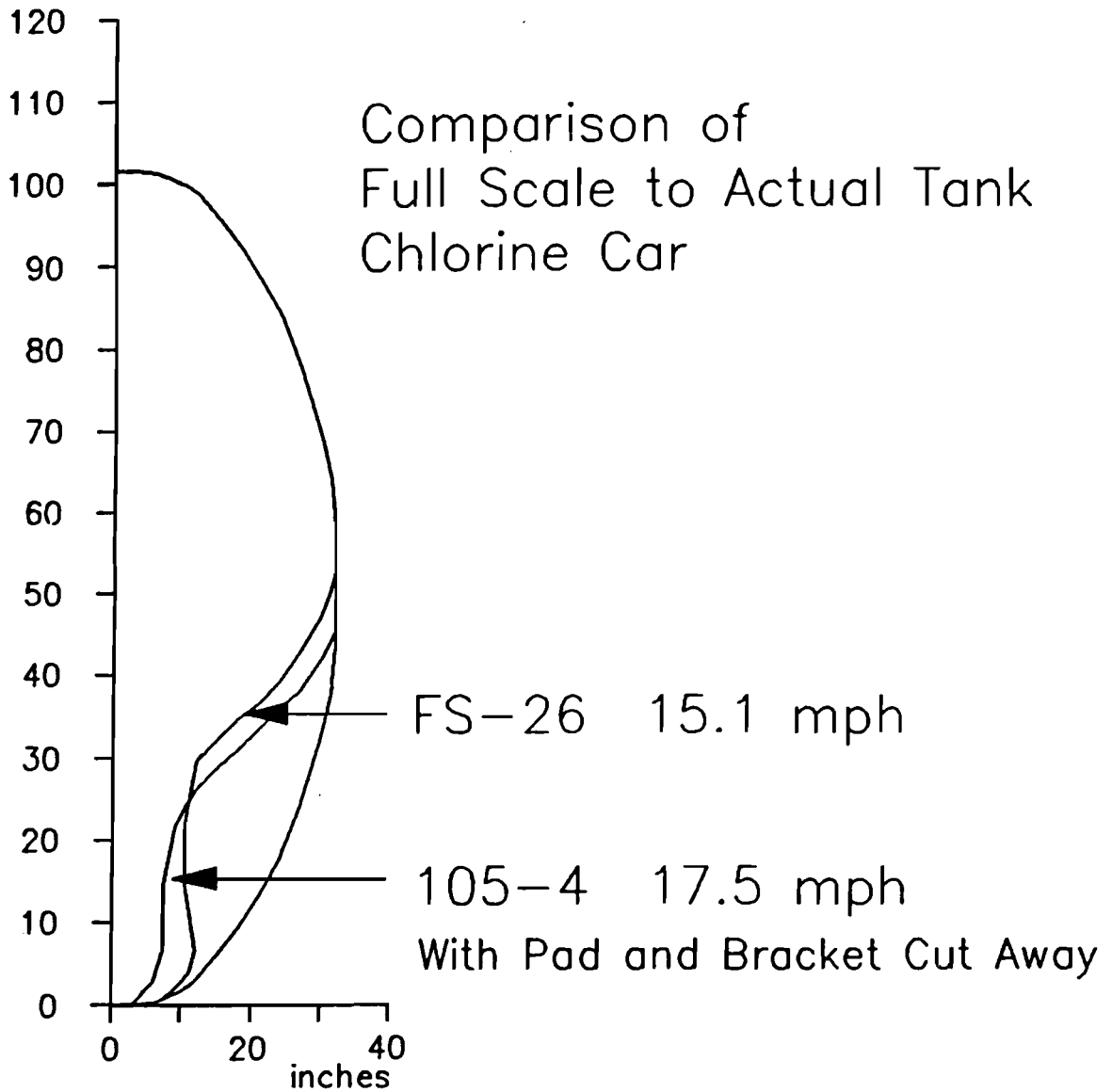


FIGURE 4.13 DENT SHAPES COMPARED - ACTUAL CHLORINE CAR AND FULL-SCALE CAR

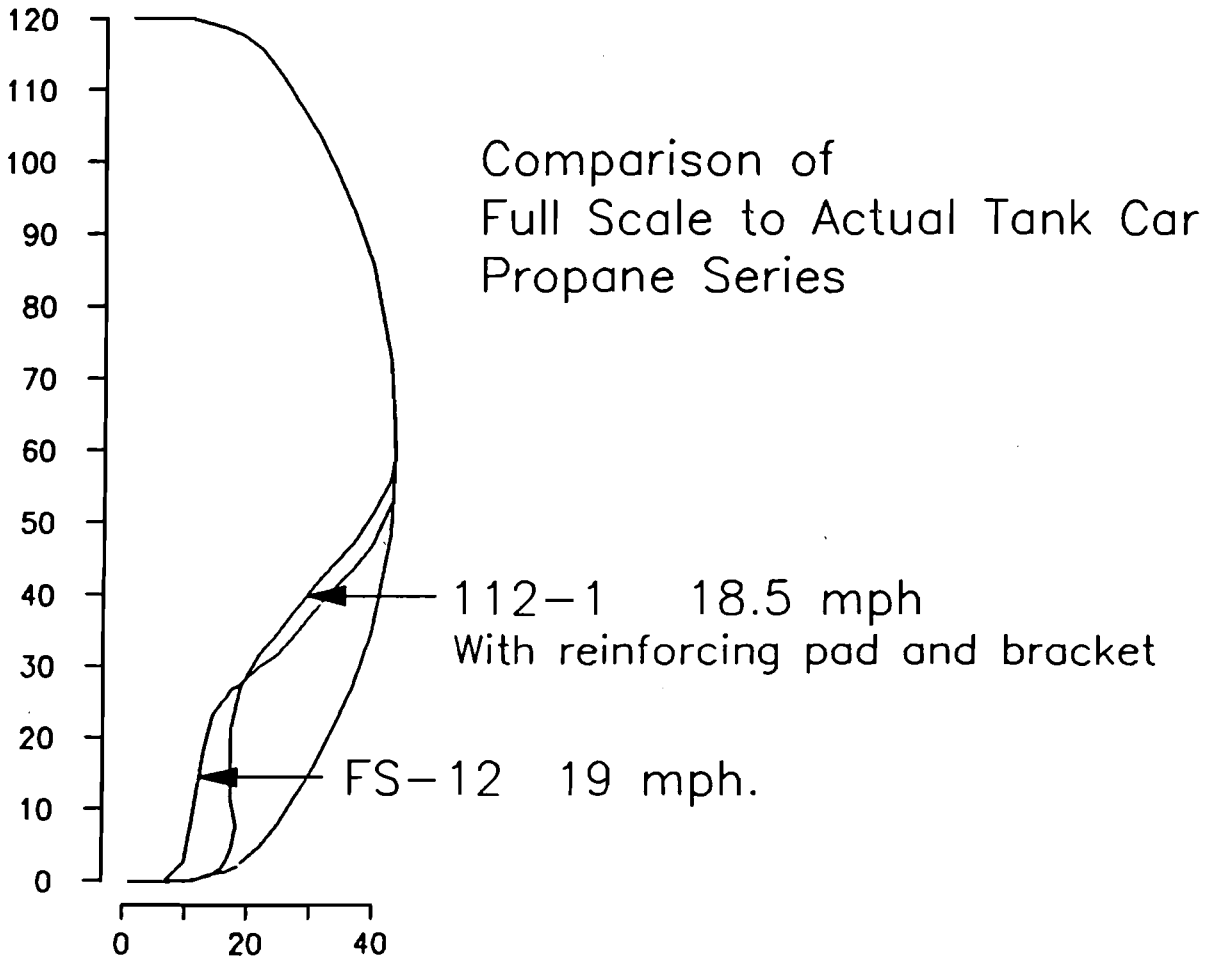


FIGURE 4.14 DENT SHAPES COMPARED - ACTUAL LPG CAR AND FULL-SCALE CAR

5 CONCLUSIONS

1. The chlorine car with the stub sill reinforcing pad and bracket did not pass the puncture resistance test as specified in the Code of Federal Regulations Title 49 Part 179.105-5 for the DOT 112J340W tank car.
2. With the stub sill reinforcing pad and bracket of the design tested, failure occurred at the reinforcing pad and not at the impacting coupler edges. Even if equipped with a 1/2-inch thick head shield, the chlorine car probably would not pass the puncture resistance requirements specified in the CFR.
3. With the stub sill reinforcing pad and bracket cut away, the chlorine car just meets the puncture resistance requirements specified in the CFR.
4. The test of the propane car with the bracket and reinforcing pad design, in combination with the head shield, showed that the puncture resistance of the car exceeds the requirements of the CFR.
5. The 1/5-scale tests indicate that thicker insulation jackets would substantially increase the puncture resistance of the chlorine car.
6. The 1/5-scale tests also indicate that thicker tank heads are less effective than thicker insulation jackets in increasing puncture resistance.
7. The effect of internal pressure is not clear as both lower and higher than nominal pressures produce higher puncture resistance thresholds.
8. The effect of the foam insulation is considered small.
9. The results from the 1/5-scale tests can not always be extrapolated to full-scale. The results of the 1/5-scale propane tank heads with head shields predict a much lower puncture resistance than that observed in full-scale. The usefulness of 1/5-scale drop tower tests must be evaluated.
10. The wording of the AAR's tank car specification does not ensure that the weld between the tank head and the reinforcing pad will fail before the head fails.

6 RECOMMENDATIONS

If the puncture resistance of DOT 105A600W cars is to be increased, adding thickness to the steel jacket would be more effective than using a thicker tank head.

The concept of 1/5-scale drop tower tests for evaluating puncture resistance should be reconsidered in light of results from the 1/5-scale LPG car with head shield. These tests would predict a marginal improvement in puncture resistance over the chlorine car with jacket, while the full-scale tests show a much greater improvement.

Further investigations should be conducted if the wording of the AAR's tank car specification related to the weld between the tank head and the reinforcing pad is to be clarified.

A relatively simple finite element analysis would be helpful in interpreting the pressure results. Of interest is the effect of the pressure on the stress distribution during the gross deformation which occurs during the dent.

APPENDIX A: 49 CFR 179.105-5, 179.106-2, and 179.200-6

Code of Federal Regulations, Title 49, "Transportation," Part 179, "Specification for Tank Cars,"
October 1987.

§ 179.105-5 Tank head puncture resistance.

(a) *Performance standard.* Each specification 112S, 112T, 112J, 114S, 114T, and 114J tank car shall be capable of sustaining, without loss of contents, coupler-to-tank head impacts within the area of the tank head described in § 179.100-23 at relative car speeds of 18 miles per hour when:

(1) The weight of the impact car is at least 263,000 pounds;

(2) The impacted tank car is coupled to one or more "backup" cars which have a total weight of at least 480,000 pounds and the hand brakes are applied on the first car; and

(3) The impacted tank car is pressurized to at least 100 psi.

(b) *Test verification.* Compliance with the requirements of paragraph (a) of this section shall be verified by full scale testing or by the alternate test procedures prescribed in paragraph (c) of this section. However, protective head shields that meet the requirements of § 179.100-23 or full tank head jackets that are at least ½-inch thick and made from steels specified in § 179.100-23(a)(1) need not be verified by testing.

(c) *Tank head puncture resistance test.* A tank head resistance system shall be tested under the following conditions:

(1) The ram car used shall weigh at least 263,000 pounds, be equipped with a coupler, and duplicate the condition of a conventional draft sill including the draft yoke and draft gear. The coupler shall protrude from the end of the ram car so that it is the leading location of perpendicular contact with the standing tank car.

(2) The impacted test car shall be loaded with water at six percent outage with internal pressure of at least 100 psi and coupled to one or more "backup" cars which have a total weight of 480,000 pounds with hand brakes applied on the first car.

(3) At least two separate tests shall be conducted with the coupler on the vertical centerline of the ram car. One test shall be conducted with the coupler at a height of 21 inches, plus-or-minus one-inch, above the top of the sill; the other test shall be conducted with the coupler height at 31 inches, plus-or-minus one-inch above the top of the sill. If the combined thickness of the tank head and any additional shielding material at any position over the area described in § 179.100-23 is less than the combined thickness on the vertical centerline of the car, a third test shall be conducted with the coupler positioned so as to strike the thinnest point.

(4) One of the following test procedures shall be applied:

	Minimum velocity of impact (in miles per hour)	Restriction
Minimum weight of ram car plus attached cars (in pounds):		
263,000	18	1 ram car only.
343,000	16	1 ram car or 1 ram car plus 1 rigidly attached car.
	Minimum velocity of impact (in miles per hour)	Restriction
686,000	14	1 ram car plus 1 or more rigidly attached cars.

(5) A test is successful if there is no visible leak from the standing tank car within one hour after impact.

[Amdt. 179-19, 42 FR 46314, Sept. 15, 1977]

§ 179.106-2 New cars.

(a) Each Specification 105A tank car built after February 28, 1981, shall be equipped with a coupler restraint system that meets the requirements of § 179.105-6.

(b) Each Specification 105S tank car built after August 31, 1981, shall be equipped with:

(1) A coupler restraint system that meets the requirements of § 179.105-6; and

(2) A tank head puncture resistance system that meets the requirements of § 179.105-5.

(c) Each Specification 105J tank car built after August 31, 1981, shall be equipped with:

(1) A coupler restraint system that meets the requirements of § 179.105-6;

(2) A tank head puncture resistance system that meets the requirements of § 179.105-5;

(3) A thermal protection system that meets the requirements of § 179.105-4; and

(4) A safety relief valve that meets the requirements of § 179.105-7.

(d) Each Specification 105 tank car shall be stenciled as prescribed in § 179.106-4.

[Amdt. 179-27, 46 FR 8012, Jan. 26, 1981]

§ 179.200-6 Thickness of plates.

(a) The wall thickness after forming of the tank shell, dome shell, and of 2:1 ellipsoidal heads must be not less than specified in § 179.201-1, nor that calculated by the following formula:

$$t = Pd/2SE$$

where:

- d* = Inside diameter in inches;
- E* = 0.9 Welded joint efficiency; except *E* = 1.0 for seamless heads;
- P* = Minimum required bursting pressure in p.s.i.;
- S* = Minimum tensile strength of plate material in p.s.i. as prescribed in § 179.200-7;
- t* = Minimum thickness of plate in inches after forming.

(b) The wall thickness after forming of 3:1 ellipsoidal heads must be not less than specified in § 179.201-1, nor that calculated by the following formula:

$$t = Pd/2SE \times 1.83$$

where:

- d* = Inside diameter in inches;
- E* = 0.9 Welded joint efficiency; except *E* = 1.0 for seamless heads;
- P* = Minimum required bursting pressure in p.s.i.;
- S* = Minimum tensile strength of plate material in p.s.i. as prescribed in § 179.200-7;
- t* = Minimum thickness of plate in inches after forming.

(c) The wall thickness after forming of a flanged and dished head must be not less than specified in § 179.201-1, nor that calculated by the following formula:

$$t = 5PL/6SE$$

where:

- E* = 0.9 Welded joint efficiency; except *E* = 1.0 for seamless heads;
- L* = Main inside radius to which head is dished, measured on concave side in inches;
- P* = Minimum required bursting pressure in p.s.i.;
- S* = Minimum tensile strength of plate material in p.s.i. as prescribed in § 179.200-7;
- t* = Minimum thickness of plate in inches after forming.

(d) If plates are clad with material having tensile strength properties at least equal to the base plate, the cladding may be considered a part of the base plate when determining thickness. If cladding material does not have tensile strength at least equal to the base plate, the base plate alone must meet the thickness requirements.

(e) For a tank constructed of longitudinal sections, the minimum width of bottom sheet of the tank must be 60 inches measured on the arc, but in all cases the width must be sufficient to bring the entire width of the longitudinal welded joint, including welds, above the bolster.

(f) For a tank built of one piece cylindrical sections, the thickness specified for bottom sheet must apply to the entire cylindrical section.

(g) See § 179.200-9 for thickness requirements for a compartmented tank.

[Amdt. 179-10, 36 FR 21349, Nov. 6, 1971]

APPENDIX B: SUMMARY TABLES OF TEST RESULTS

Series 01 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
011	102.6	270.6	3.06	29.2	P
012	78.56	234.6	2.75	-22.4	P
013	40.06	166.1	2.53	-23.2	NP
013-2	57.75	198.7	3.53	-26.4	NP
014	76.75	218.3	3.81	26.0	P
015	60.12	205.2	3.12	24.4	P
016	55.81	195.5	4.12	-31.6	P
017	50.75	188.9	2.65	22.4	P
018	46.75	182.4	3.00	23.2	P
019	43.37	172.6	2.7	21.2	NP

CLASS 112/114 TANK CAR BASELINE TESTS

Series 02 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
021	62.62	208.5	3.40	24.0	NP
022	78.56	234.6	3.75	26.4	NP
023	96.31	260.6	4.06	30.0	NP
024	115.8	283.4	4.43	32.0	NP
025	137.1	309.5	4.75	36.0	NP

CLASS 112/114 TANK CAR 31 INCH IMPACT LOCATION TESTS

Series 03 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
036	24.43	130.1	1.81	21.8	NP
037	26.00	136.8	1.68	20.6	NP
037-2	28.00	140.1	1.93	20.2	NP
038	30.37	143.3	1.87	23.8	NP
038-2	35.00	156.+	-	23.0	NP
039	75.25	234.6	-	26.0	P
039A	57.75		2.87	-	P
039B	44.37	175.9	2.43	28.0	P
039C	40.00	166.1	2.31	-26.0	NP
039C-2	42.12	169.4	2.43	22.0	NP
039D	42.12	169.4	2.12	21.2	P
039X-1	16.93	-	1.56	-	NP
039X-2	20.06	-	1.81	-	P

CLASS 105 TANK CAR BASELINE TESTS

Series 04 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
041	44.31	175.9	2.50	-	NP
041-2	57.57	202.0	2.87	-	NP
042	67.75	215.0	3.00	-	NP
042-2	83.87	237.8	-	-31.2	P
043	73.18	228.0	-	-	P
044	70.37	221.5	3.81	-	P

CLASS 105 TANK CAR 3/8-INCH JACKET THICKNESS TESTS

Series 05 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
051	90.25	254.0	3.75	34.0	NP
052	109.10	273.7	4.43	-	NP
053	122.60	289.9	5.12	-36.8	P
054	115.80	283.4	5.25	30.0	P
055	112.40	280.2	5.18	30.8	P

CLASS 105 TANK CAR 1/8-INCH JACKET THICKNESS TESTS

Series 06 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
061	44.18	179.2	2.68	24.4	NP
062	57.75	202.0	3.31	30.8	NP
063	78.56	257.4	3.68	-	NP
064	102.60	267.1	4.37	36.0	P
065	90.87	260.6	4.00	-30.8	NP
066	94.00	257.4	4.31	32.8	P

CLASS 105 TANK CAR 21 INCH IMPACT LOCTAION TESTS

Series 07 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
071	40.06	166.1	2.25	21.2	NP
072	53.00	195.5	2.75	-29.2	NP
073	62.62	208.5	3.06	30.4	NP
074	73.06	224.8	4.87	-28.8	P
075	67.75	218.3	5.25	24.0	P
076	64.62	-	3.43	-27.6	P

CLASS 105 TANK CAR 50 PSI PRESSURE TESTS

Series 08 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
081	44.18	172.6	2.62	20.8	P
082	42.50	169.4	2.68	18.4	NP
083	44.18	175.9	2.75	20.8	NP
084	48.50	182.4	2.81	20.8	P

CLASS 105 TANK CAR 100 PSI PRESSURE TESTS

Series 09 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
091	44.18	175.9	2.56	22.8	P
092	36.18	159.6	2.25	20.0	NP
092-2	40.06	166.1	2.43	22.8	P
093	38.50	162.9	3.62	16.0	P
094	36.93	159.6	5.00	-13.2	P
095	34.06	156.4	2.25	18.8	P
096	31.06	144.3	2.25	18.8	NP
097	33.93	159.6	2.37	-	NP
098	38.12	166.1	2.62	18.8	NP

CLASS 105 TANK CAR INSULATION TESTS

Series 10 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
101	78.06	231.3	3.37	31.0	P
102	62.62	208.5	3.18	26.0	P
103	48.50	182.4	2.37	23.2	P
104	44.18	175.9	2.37	24.8	NP
105	45.87	175.9	2.31	24.0	NP
106	47.18	182.4	2.62	21.2	-
107(A)	25.62	-	1.37	-	P
108(B)	22.56	-	1.68	-	P

CLASS 105 TANK CAR 15/16-INCH HEAD THICKNESS TESTS

Series 11 (#)	Drop Height (in.)	Impact Speed (in./s)	Dent Depth (in.)	Max. Accel. (g)	Result (P/NP)
111	53.00	192.2	2.18	29.2	NP
112	62.62	211.7	2.43	-33.2	NP
113	78.56	234.6	3.06	-37.6	NP
114	96.31	260.6	2.81	-37.6	P
115	84.25	-	3.25	30.4	P
116	81.37	241.1	3.93	30.4	P

CLASS 105 TANK CAR 1-1/16 INCH HEAD THICKNESS TESTS

Series 105 (#)	Tank Car	Peak Pressure (psig)	Impact speed (mph)	Dent Depth (in)	Avg. Accel. (g)	Result (P/NP)
105-1	UTLX 81081	-	14.9	-	-	P
105-2	UTLX 81083	108	15.5	13.88	-4.81*	NP
105-3	UTLX 81083	108	16.6	16.38	-	NP
105-4	UTLX 81081	-	17.5	17.00	-	NP

ACTUAL DOT 105A500W TANK CAR TESTS

* Maximum Average deceleration of ram car main frame

Series 112 (#)	Tank Car	Peak Pressure (psig)	Impact speed (mph)	Dent Depth (in)	Avg. Accel. (g)	Result (P/NP)
112-1	GATX 93669	103	18.5	19	-4.81*	NP

ACTUAL DOT 112J340W TANK CAR TESTS

* Maximum Average deceleration of ram car mainframe

Series FS-10 (#)	Peak Pressure (psig)	Impact speed (mph)	Dent Depth (in)	Avg. Accel. (g)	Result (P/NP)
FS-11	-	16.0	17.8	-	NP
FS-12	183	19.0	21.3	-16.0*	NP
FS-13	135	23.4	24.2	-	NP

DOT 112J340W FULL-SCALE MODEL TESTS

* Tank Top, Longitudinal

Series FS-20 (#)	Peak Pressure (psig)	Impact speed (mph)	Dent Depth (in)	Avg. Accel. (g)	Result (P/NP)
FS-21	120	113.0	13.7	-	NP
FS-22	150	17.0	-	-	P
FS-23	120	15.1	-	-	P
FS-24	125	14.3	15.0	-	NP
FS-25	130	13.8	14.6	-	NP
FS-26	149	15.1	16.6	-	NP

DOT 105A500W FULL-SCALE MODEL TESTS

APPENDIX C: SAMPLE TEST LOGS



Transportation Test Center
 Box 11130
 Pueblo, Colorado 81001
 303.545-5660



ASSOCIATION
 OF AMERICAN
 RAILROADS
 Research and Test
 Department

CHLORINE TANK CAR PUNCTURE

Resistance Tests
 Full Scale/Full Size Test Log

1. Tank Head Type DOT 112J340W (GATX 93669) I.D. No. 112-1
 2. Test Date and Time 4/16/87, 3:30 P.M.
 3. Test Personnel M. White, D. Kido, W. Martinez
 4. Tank Shell Temperature 53.3°F Air Outage 6%, 14"
 5. Reaction Car Weight 333,000#
 6. Ram Car Weight 265,150# Coupler Height 22-22 1/4"
 7. Pressure Change; Gage pressure the next morning was 90 psi
 Static Gage Pressure, Initial 99 Post 97
 PT #1 (Top), Initial 93.07 Peak 102.7 Final 91.47
 PT #2 (End), Initial _____ Peak _____ Final _____
 PT #3 (Side), Initial 98.47 Peak 125.9 Final 96.86
 8. Max. Velocity 18.5 mph Distance Traveled 1700
 9. Did Tank Puncture? Yes _____ No X
 10. Car Displacement; Distance from ALD to impact point is 14 5/8"
 (Static Measurement)
 Reaction Car (16' - 4") Backup Car #1 (16' - 4")
 Backup Car #2 (16' - 3") Backup Car #3 195.9" (16' - 2 1/2")
 11. Dent Depth Reading, Inch #1 1 7/8" #2 1 3/2" #3 1 7/8" #4 1 8 1/2" #5 1 3 1/4" #6 7 5/8"
 #7 2 1/8" Max. 19" (17 1/2" tangent to original surface profile)
 12. Data Menu Disc Location I.D. (IBM PC) #26
 13. Data Menu Disc Location I.D. (PCM) _____
 14. Remarks Car was filled with water to a 14" air outage condition using the tank cars gaging device.
- Weather Conditions - Aprox. 80°F. Clear, 0-5 mph breeze out of the West (Track runs north to south).
- No noticeable air leaks after pressurizing the tank car.

Car brake line was pressurized for over 30 minutes and put into emergency at 2:05 p.m. All four hand brakes were applied.

The same coupler used on 105-2 was used for this impact. The coupler shank was bent upward after impact. Height of the top-of-ram next to the draft key retainer was 68 1/8" prior to impact, 68 1/2" after impact.

Three velocity measuring devices were used on this impact.

Speed Gun	18.0 mph
Wayside ALD/timer	18.3 mph
Ram tach./PCM	18.5 mph

Maximum average deceleration of ram car mainframe was 4.81G.

$$F = ma = (w/g)a = 265,150(4.81) = 1,275,000 \text{ lbs. force}$$

The following instrumentation problems were encountered:

1. The ALD trigger system did not show a pulse on the PCM system.
2. Started losing data after impact on the PCM system due to a pinched cable to the ram car antenna. Data is questionable between 9.79 and 9.91 seconds on the printout.
3. Position transducer data from the reaction car is unusable. Strings from the position transducers on Backup Cars 1 and 2 pulled loose on impact. Data from Backup Car 3 looks good.

The head shield failed by shear/tearing along the outside of the coupler jaw and top edge of the knuckle contact areas. The reinforcing web between the tank head and stub sill tore loose from the sill and collapsed with the head dent formation. Tank head did not show significant stress conditions in the area of impact that would indicate a near failure condition.



Transportation Test Center

Box 11130
Pueblo, Colorado 81001
303-545-5660



ASSOCIATION
OF AMERICAN
RAILROADS
Research and Test
Department

CHLORINE TANK CAR PUNCTURE

Resistance Tests
Full Scale/Full Size Test Log

1. Tank Head Type DOT 105A500W (UTLX 81081) I.D. No. 105-1
2. Test Date and Time 12/3/86, 12:00
3. Test Personnel M. White/C. Bachhuber/B. Kreusch/D. Kido
4. Tank Shell Temperature 62.3 ° F Air Outage 17.4%
5. Reaction Car Weight 259,100# (Georgia)
257,750# (TTC)
6. Ram Car Weight 261,250# (TTC) Coupler Height 21 3/8"
7. Pressure Change;
 Static Gage Pressure, Initial 100 psig Post _____
 PT #1 (Top), Initial 103.6 Peak _____ Final _____
 PT #2 (End), Initial ----- Peak ----- Final -----
 PT #3 (Side), Initial 49.15 Peak _____ Final _____
8. Max. Velocity 14.9 Distance Traveled 1275'
9. Did Tank Puncture? Yes X No _____
10. Car Displacement; (Static Measurement)
 Reaction Car (27'-1½") Backup Car #1 (27'-1½")
 Backup Car #2 (27'-2") Backup Car #3 (27'-1")
11. Dent Depth Reading, Inch #1 _____ #2 _____ #3 _____ #4 _____ #5 _____ #6 _____
 #7 _____ Max. _____ Distance from LCD to impact point is 7½"
12. Data Menu Disc Location I.D. (IBM PC) _____
13. Data Menu Disc Location I.D. (PCM) _____
14. Remarks Car filled with 177,800# of clay slurry (RC-32) with 52.4% solid,
~ 12.4 #/gal. density.

Puncture occurred at the center sill, reinforcing pad juncture with the
tank head. The failure was a horizontal tear along the top edge of the reinforc-
ing pad weld. Web reinforcing of the pad prevented yielding of the pad with

head dent formation.

The reaction car (chlorine tank car) would not hold brake air pressure to maintain brake setting. The hand brake was set (1 truck) to compensate for lack of air brakes. The backup cars were put into emergency brake setting with the hand brake applied to the last backup car.



Transportation Test Center

Box 11130
Pueblo, Colorado 81001
303.545-5660



ASSOCIATION
OF AMERICAN
RAILROADS
Research and Test
Department

CHLORINE TANK CAR PUNCTURE

Resistance Tests
Full Scale/Full Size Test Log

1. Tank Head Type DOT 105A5COW (UTLX 81083) I.D. No. 105-2
2. Test Date and Time 4/15/87, 3:25 P.M.
3. Test Personnel M. White/D. Kido/D. Graff/W. Martinez
4. Tank Shell Temperature 56.2°F Air Outage 17.4%
5. Reaction Car Weight 262,700# (Georgia)
257,350# (TTC)
6. Ram Car Weight 265,150# Coupler Height 21 3/4"
7. Pressure Change;

Static Gage Pressure, Initial	<u>97.5</u>	Post	<u>99.0</u>
PT #1 (Top), Initial	<u>98.3</u>	Peak	<u>108.3</u>
		Final	<u>100.3</u>
PT #2 (End), Initial		Peak	
		Final	
PT #3 (Side), Initial		Peak	
		Final	
8. Max. Velocity 15.5 mph Distance Traveled 1200 ft.
9. Did Tank Puncture? Yes _____ No X
Distance from ALD to impact point is 12"
10. Car Displacement; (Static Measurement)
Reaction Car (14' - 1") Backup Car #1 (14'-0")
Backup Car #2 (14' - 0") Backup Car #3 165" (14' - 0")
11. Dent Depth Reading, Inch #1 5" #2 11 1/2" #3 13 3/4" #4 13" #5 7 1/8" #6 1 7/8"
#7 -0- Max. 13 7/8"
12. Data Menu Disc Location I.D. (IBM PC) #25
13. Data Menu Disc Location I.D. (PCM) _____
14. Remarks Car was filled with aprox. 180,500# of clay slurry (RC-32) with
52.2% solids, 12.3 #/gal. density.

Weather Conditions - 77°F ambient air, clear, slight breeze 0-5
mph out of the N.W. (Track runs north to south)

The tank car was leaking air at the manway flanges.

All four hand brakes were set with draft gears compressed. Visual inspection prior to impact showed that all brake cylinders were extended except for Backup Car #1.

A new coupler was installed on the ram prior to impact. A slight bend downward was noted on the ram coupler shank after impact.

Height of the top of ram next to the draft key retainer was 68 7/8" prior to impact, 68 1/8" after impact.

The wayside ALD/timer system indicated a 15.5 mph speed for the ram car prior to impact.

The position transducers on the reaction car and Backup Cars 1 & 2 failed during impact because of bracket separation.

The tank car was prepared for testing by separating the tank head from the sill reinforcing pad. The weld between the head and pad was cut away by grinding. See photos 87-642 and 87-645. During impact, the head separated from the pad, leaving a maximum 5 1/4" gap. Separation was approximately 8" along the outside edges of the pad.

The tank head was stamped with the following information:

ICC 105-A500W
AAR-TC-128-B
C.T.C.-3074-6
TEST DATE - 10 15 68
CAPACITY 144679
INSP.



Transportation Test Center

Box 11130
Pueblo, Colorado 81001
303.545-5660



ASSOCIATION
OF AMERICAN
RAILROADS
Research and Test
Department

CHLORINE TANK CAR PUNCTURE

Resistance Tests
Full Scale/Full Size Test Log

1. Tank Head Type DOT 105A500W (UTLX 81083) I.D. No. 105-3
 2. Test Date and Time 4/29/87
 3. Test Personnel M. White/D. Kido/W. Martinez
 4. Tank Shell Temperature 59.5°F Air Outage 17.4%
 5. Reaction Car Weight 262,700# (Georgia), 257,350# (TTC)
 6. Ram Car Weight 265,150# Coupler Height 22" - 22½"
 7. Pressure Change;

Static Gage Pressure, Initial	<u>99.0</u>	Post	<u>101</u>
PT #1 (Top), Initial	<u>99.49</u>	Peak	<u>107.5</u>
		Final	<u>101.0</u>
PT #2 (End), Initial	<u>-----</u>	Peak	<u>-----</u>
		Final	<u>-----</u>
PT #3 (Side), Initial	<u>-----</u>	Peak	<u>-----</u>
		Final	<u>-----</u>
 8. Max. Velocity 16.6 mph Distance Traveled 1420 ft.
 9. Did Tank Puncture? Yes ----- No X
 10. Car Displacement; Distance from ALD to impact is 11½"
(Static Measurement)
Reaction Car 213.5" (17'-4") Backup Car #1 212.2" (17'-2½")
Backup Car #2 ----- (17'-2") Backup Car #3 210.3" (17'-1½")
 11. Dent Depth Reading, Inch #1 4 1/4 #2 10 1/8 #3 14 1/2 #4 16 1/4 #5 11 1/4 #6 5 5/8
#7 5/8 Max. 16 3/8
 12. Data Menu Disc Location I.D. (IBM PC) -----
 13. Data Menu Disc Location I.D. (PCM) -----
 14. Remarks This was the second impact on UTLX 81083 (B end). Clay slurry conditions were the same as impact 105-2. Sill reinforcing pad was modified the same as impact 105-2.
- Weather Conditions - Partly Cloudy, 73°F ambient air, slight breeze out of the SE 0-5 mph. (track runs north to south).

No tank car air leaks. Manway was regasketed from impact 105-2.

Wayside ALD system showed an impact speed of 16.3 mph.

A new coupler was used on the ram.



Transportation Test Center

Box 11130
Pueblo, Colorado 81001
303.545-5660



ASSOCIATION
OF AMERICAN
RAILROADS
Research and Test
Department

CHLORINE TANK CAR PUNCTURE

Resistance Tests
Full Scale/Full Size Test Log

1. Tank Head Type DOT 105 A500W (UTLX 81081, B-End) I.D. No. 105-4
2. Test Date and Time August 20, 1987 3:25 P.M.
3. Test Personnel M. White - D. Kido - W. Martinez
4. Tank Shell Temperature 77.1 Air Outage 15.1%
5. Reaction Car Weight 261,100 # (TTC)
6. Ram Car Weight 265,150 # Coupler Height 21 3/4"
7. Pressure Change;

Static Gage Pressure, Initial	<u>100.0</u>	Post	<u>102.0</u>
PT #1 (Top), Initial	<u>97.52</u>	Peak	<u>- - - -</u>
		Final	<u>- - - -</u>
PT #2 (End), Initial	<u>- - - -</u>	Peak	<u>- - - -</u>
		Final	<u>- - - -</u>
PT #3 (Side), Initial	<u>- - - -</u>	Peak	<u>- - - -</u>
		Final	<u>- - - -</u>
8. Max. Velocity 17.5 mph Distance Traveled 1575 ft.
9. Did Tank Puncture? Yes - No X
10. Car Displacement; (Static Measurements - distance exceeded position on transducers.)

Reaction Car	<u>31' 2"</u>	Backup Car #1	<u>31' 0.1/4"</u>
Backup Car #2	<u>30' 10 1/2"</u>	Backup Car #3	<u>36' 11"</u>
11. Dent Depth Reading, Inch #1 5 #2 11 5/8 #3 15 1/8 #4 17 #5 10 1/4 #6 4 5/8
#7 1/2 Max. 17 Distance from ALD to Impact is 9 1/2".
12. Data Menu Disc Location I.D. (IBM PC) -
13. Data Menu Disc Location I.D. (PCM) -
14. Remarks This was the second impact on UTLX 81081. The punctured "A" end was repaired by welding a new head over the top of the existing head. Clay slurry was transferred from UTLX 81083 to UTLX 81081, except for approximately 3 1/2" of clay sediment on the bottom of 81083. An additional 5 1/2" of water was added to 81081 to bring the fill height to 80". Sill reinforcing pad and insulation jacket was

14. (continued)

modified the same as Impact 105-3.

Weather conditions - Partly cloudy, 96° F. ambient air, wind out of the east, southeast at approximately 11 mph during the impact run. Speed runs earlier in the day were reaching 18.0 mph from the release point.

Wayside ALD system showed a speed just prior to impact of 17.4 mph.

A new coupler was installed prior to impact. Static measurements prior to and after impact indicated that the coupler shank was bent upward, with the coupler head at the knuckle raising 7/16" upward from its initial position. Changes in lateral and rotational directions were negligible.

The reaction car and backup cars were put into emergency brake setting approximately 30 minutes prior to impact. The hand brakes were set on the three backup cars. All brakes visually appeared to be operational except for the "A" end of backup car #3.

Car travel for the reaction car/backup cars exceeded the length of the position transducers. Three of the emergency release devices protected the position transducers with one failing. The wayside data collection system did not collect data from the pressure transducer.

Three different backup cars were used on the test than the previous tests. Weights for the cars were as follows:

	<u>Car #</u>	<u>GVW</u>
Backup Car #1	UP-41303	159,850 #
" " #2	UP-41331	170,450 #
" " #3	UP-41318	162,400 #
		<hr/>
		492,700 #
Required weight	480,000 #	+ 4.5%
		- 0

REFERENCES

1. Code of Federal Regulations, Title 49, "Transportation," Part 179, "Specifications for Tank Cars," October 1987.
2. Manual of Standards and Recommended Practices, Section C - Part III "Specifications for Tank Cars, Specification M-1002," Association of American Railroads, January 1983.
3. Phillips, E. A. and L. Olsen, "Final Phase O5 Report on Tank Car Head Study," RPI-AAR Tank Car Safety Research Project, RA-05-1-17, July 1972.
4. Orringer, O. and Tong, P., "Results and Analysis of Switchyard Impact Tests," DOT Transportation Systems Center, FRA/ORD-80-6, January 1980.
5. White, M., "1/5-scale Model Test Report Chlorine Tank Puncture Resistance Test Program," Association of American Railroads, Transportation Test Center, 86-47574-074, March 1987.
6. White, M., "Full-scale Model Test Report Chlorine Tank Puncture Resistance Test Program," Association of American Railroads, Transportation Test Center, 87-47574-093, March 1987.
7. White, M., "Full-size Test Report Chlorine Tank Puncture Resistance Test Program," Association of American Railroads, Transportation Test Center, 87-47574-104, December 1987.
8. Shang, J. and Everett, J., "Impact Vulnerability Of Tank Car Heads," General American Research Division, General American Transportation Corporation.

•

•

•

•