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PHYSICAL RESPONSE OF FLAT STEEL PLATES TO DROP HAMMER IMPACTS

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A series of impact tests using the FRA/BRL Drop Hammer Facility was performed. The tests consisted of the creation of controlled damage to flat steel plates which had properties exceeding the minimum ASTM standards required for steel used in the construction of tank cars (ASTM A-515, Grade 70 steel). The plates responded in the form of dents which reflected the shapes and sizes of tups which were driven on to the plates and the sizes of dies on which the plates were placed. As expected, the shapes of the dents were similar to the

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) shapes of the tups and as the die diameters were increased from test to test, the amount of bending relative to the kinetic energy on impact increased. The depths of the dents increased as the kinetic energy of the tups increased and the diameters of the dies increased. A total of 73 tests were conducted with various hammer heights, tup shapes and sizes, and die diameters. The maximum dent depth as a function of impacting kinetic energy was shown to be a function which scales.

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INTRODUCTION

The Ballistic Research Laboratory (BRL) was under contract to the Federal Railroad Administration (FRA), Department of Transportation (DOT) to conduct a study dealing with the safety aspects of clearing wrecked tank cars loaded with hazardous materials under pressure. The key issue in this regard was to develop procedures which can enable personnel to make assessments in order to predict the level of safety for those involved in moving and/or unloading the damaged tank car. The historical data which supported the decision to research this subject includes the fact that 24 fatalities and 118 injuries have been sustained due to tank car ruptures during wreck-clearing operations. The worst occurred following a 23 car derailment at Waverly, Tennessee on February 24, 1978. (Ref. 1)[1] In that incident, a damaged tank car containing liquid petroleum gas (LPG) ruptured two days after the derailment while preparations for having its lading transferred were in progress. The lading was released and the ensuing fire killed 16 persons and injuried 43 others. Another incident occurred on April 18, 1979 at Crestiview, Florida, where several wreck-clearing personnel were exposed to anhydrous ammonia from a tank car which unexpectedly ruptured. (Ref. 2)[2] These incidents show that wreck-clearing crews, emergency response teams, and the public are in danger even after the initial hazards in a derailment involving hazardous materials are neutralized.

The solution to the problem will require advanced technology in at least two areas. One is the development of a data base which can serve as basic information describing how tank car materials respond to dynamic impacts. That is, once damage is sustained, what are the characteristics of the types of damage that can be used to predict potential rupture of the tank car? The other is to apply nondestructive evaluation (NDE) techniques on sample-damaged specimens in order to determine their effectiveness in locating flaws and their ability to identify specific types of flaws. These two in combination are necessary for developing an accurate procedure for evaluating a damaged tank car.

The work described in this report consisted of a series of impact tests using the FRA/BRL Drop Hammer Facility and was one of the efforts performed under the project entitled Tank Car Damage Assessment. The facility was used to create controlled damage to flat steel plates with properties similar to steel used in the construction of tank cars used to transport propane. The response of the plates to the impacts was in the form of dents which reflected the shapes and sizes of tups which were driven onto the plates and the sizes of dies on which the plates were placed. The objectives of these experiments were three fold. (1) One was to create in the plates actual flaws on which

[1] *"Railroad Accident Report - Derailment of Louisville and Nashville Railroad Company's Train No. 584 and Subsequent Rupture of Tank Car Containing Liquefied Petroleum Gas, Waverly, Tennessee, February 22, 1978," NTSB-RAR-79-1, U.S. National Transportation Safety Board, Washington, D.C. 20594, 8 February, 1979.*

[2] *"Railroad Accident Report — Louisville and Nashville Railroad Company Freight Train Derailment and Puncture of Hazardous Materials Tank Cars, Crestview, Florida, April 8, 1979," NTSB-RAR-79-11, U.S. National Transportation Safety Board, Washington, D.C. 20594, September 1979.*

various NDE techniques could be applied. This was to enable BRL to recommend those NDE techniques which can be used to assess the derailed tank car. (2) The second objective was to initiate the development of a data base which can be used directly in evaluating the integrity of a damaged tank car. (3) The third objective was to determine if this type of test data can be scaled to the actual conditions of a full scale tank car.

FRA/BRL DROP HAMMER FACILITY

The FRA/BRL Drop Hammer Facility was designed to enable one to inflict controlled damage on materials placed under the hammer. An overall view of the facility is shown in Figure 1. The hammer is a massive weight of 4,574 Kgm (10,084 lbs) which is raised vertically to some predetermined height depending on the amount of kinetic energy desired on impact. The hammer is raised by a cable attached to its top end with a special hook which allows the hammer to drop with a minimum of delay once the procedure is initiated. This mechanism is referred to as the quick release. To trigger the quick release, a pin is pulled from its initial position by a device called an actuator. The actuator pulls on the pin gradually due to a hydraulic pump hand worked by a technician. A device which records the velocity of the hammer is called the comb. The data generated by the comb and associated accelerometers are fed directly into a computer and serve as basic data from which calculations are performed.

A diagram of the interacting parts which create the damage is presented in Figure 2. The hammer does not impact the material directly, but has an object called a tup attached to the bottom end. The tup is threaded to the hammer and can be of arbitrary shape and size. In the figure, the striking surface of the tup is shown to be flat with the tip consisting of a layer of hardened steel. Below the flat surface of the tup, the diagram indicates the die which is also composed of hardened steel. The die is held in place by a die holder which lies in a recess carved in the heavy steel base on which the entire structure is attached. If the tup perforates a plate, it can pass through the opening in the die. In the tests described in this report, the cutting edge of the dies were rounded off to yield more realistic results.

There are important questions concerning the lack of realism in these tests. For one thing, the use of a die brings to mind immediately that there is no similar situation with respect to a tank car being punched by the coupler of another tank car or some other object as the tank car is overturned. On the other hand, our choice of using flat plates requires something such as a die in order to achieve depth in the dents. That is, a flat surface under the flat plate would be an even worse simulation and the damage sustained of less value. An alternative would be to construct three dimensional models but the cost of performing the tests would have risen greatly and perhaps the end results would not have been of a quality to warrent such an increase in expenditures. Another question concerns the fact the edges of the plates were not restrained as is the case when a portion of a tank car is impacted. Again, to restrain the edges to improve the simulation would have required a great deal of effort and since this was an exploratory portion of the program, such an expenditure was undesirable. Eventually, once these plates have been analyzed and other parallel portions of the program advanced, models can be designed and appropriate steps taken to include all of the characteristics of real tank car impacts.

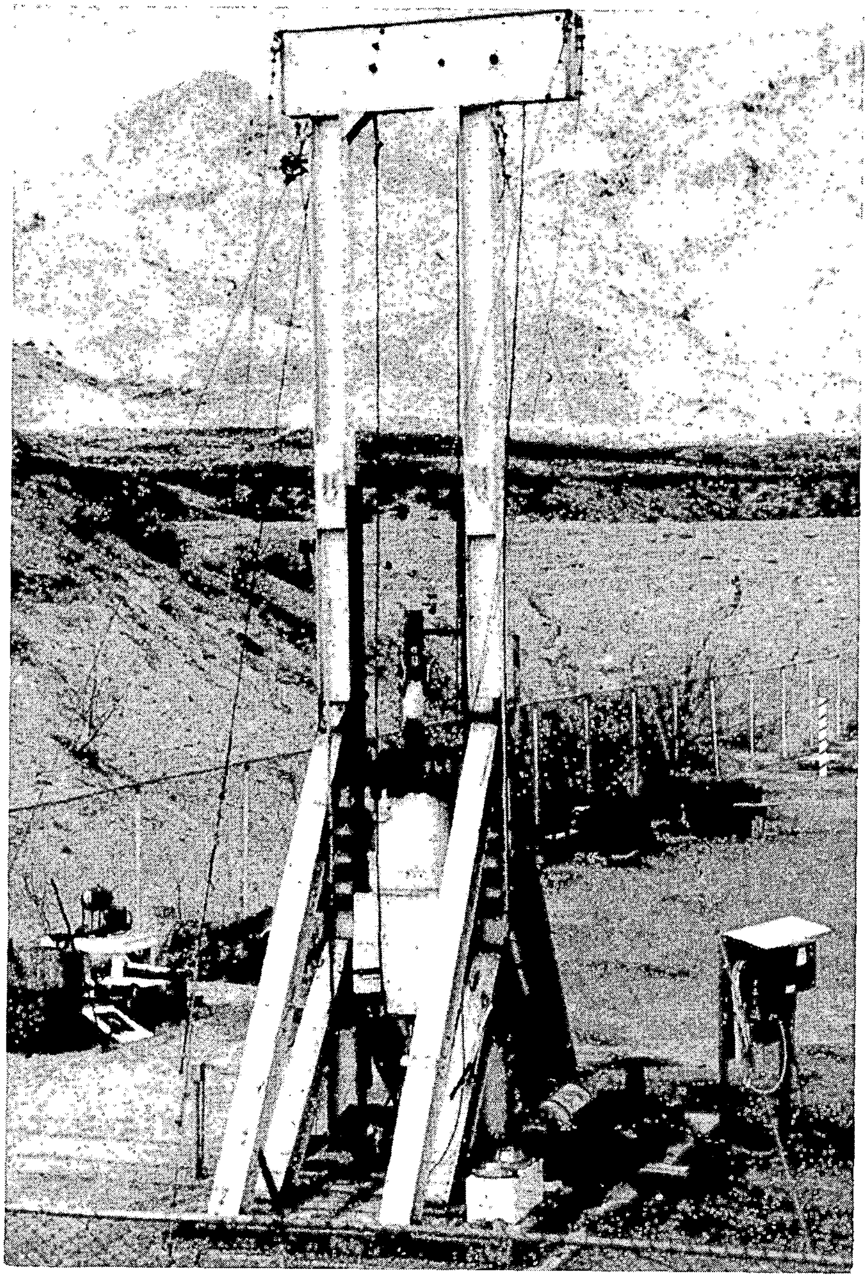

Figure 1: The FRA/BRL Drop Hammer Facility

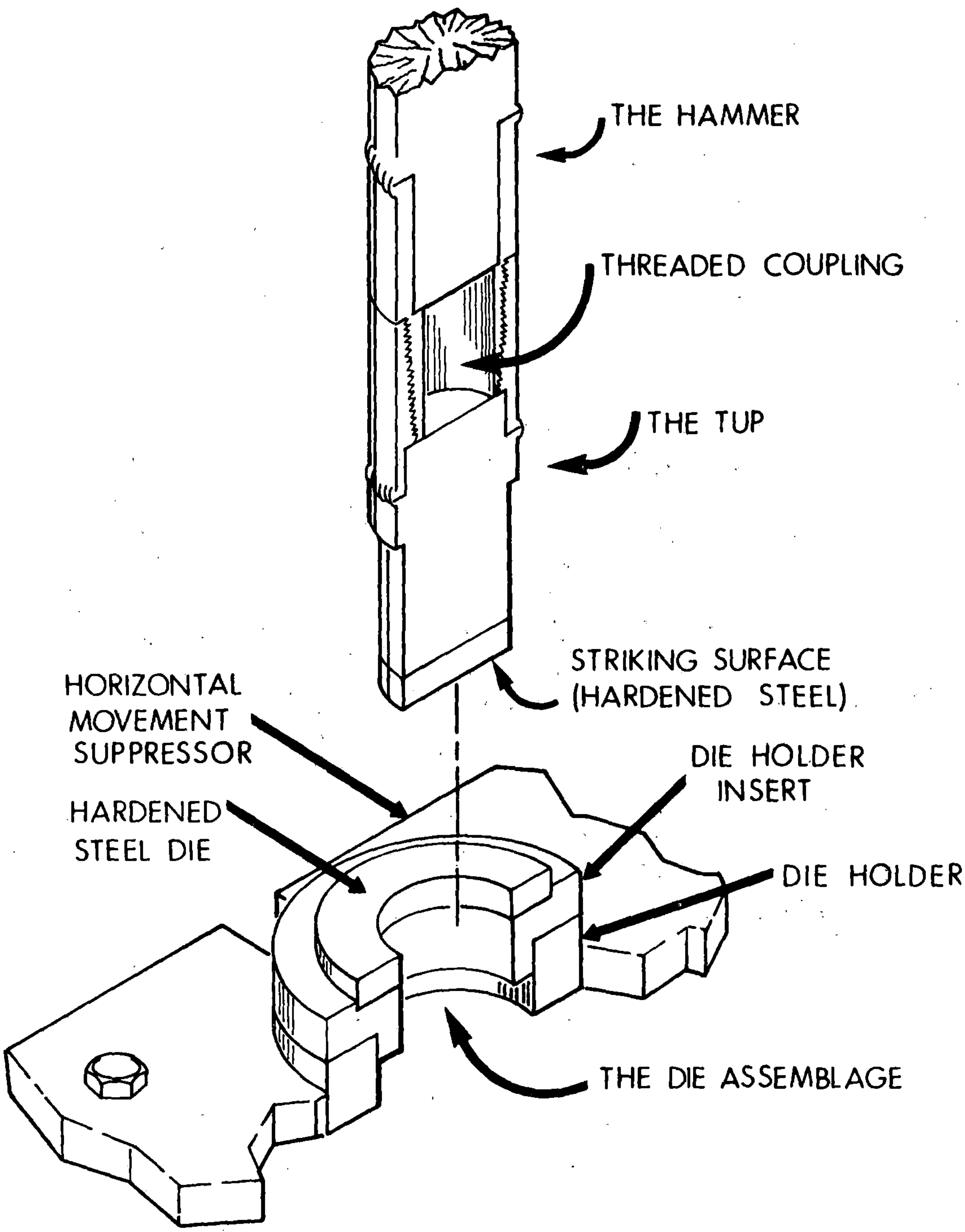

Figure 2: The Tup and Die Assemblage of the FRA/BRL Drop Hammer Facility

TEST PROCEDURES

The data generated was intended to be applicable to tank cars. Therefore, the plates used in the tests were made of steel which exceeded the minimum standards required in the construction of railroad cars. The steel was ASTM A515, Grade 70, with a minimum tensile strength of 4.9217×10^7 Kgs/meter^2 and a minimum elongation in 5.08 cm {2 inches} of 20 percent. The Brinell Hardness of each of the plates were measured and were included as the last three digits in the Identification Numbers {ID} which were written on the plates and attached to all of the various forms in which the data were recorded.

The tups used in the tests were of the following three sizes — 5.08 cm {2 inch}, 9.525 cm {3.75 inch}, and 13.97 cm {5.5 inch} diameters. In the largest size, both a flat tup and a hemispherical tup were used. In the other two sizes, there were only hemispherical tups. The four different die diameters used were 15.24 cm {6.0 inches}, 20.96 cm {8.25 inches}, 27.94 cm {11.0 inches}, and 34.93 cm {13.75 inches}. In addition to using various combinations of tup size and die diameters, various impact energies were used by raising the hammer to various heights. The plates were of all the same thickness of 0.9525 cm {3/8 inches} which is the thickness of the shell of the propane tank car.

The test data were recorded in two different ways. One was simply to photograph both sides of the plate following each of the tests. The other consisted of measuring the depth of the dent along a diagonal using a dial micrometer {DM}. A typical sample of a DM measurement is presented in Figure 3. The abscissa in the figure represents positions along the diagonal from one corner at zero to 86.35 cm {34 inches} indicated by the vertical line denoted as the "plate corner". The horizontal line drawn along the entire length of the diagonal to the "plate corner" and located at the zero value on the ordinate represents the original position of the surface points on the impact side of the plate. The drawing of the die in the figure was located by assuming that the die was centered on the deepest point in the dent as determined by the DM. The center of the tup was located on the same basis. In practice, while there was a deliberate effort to center the plate on the center of the die, this was not possible to do exactly. However, the variation in the placement of the plates had no affect on the quality or the usefulness of the data.

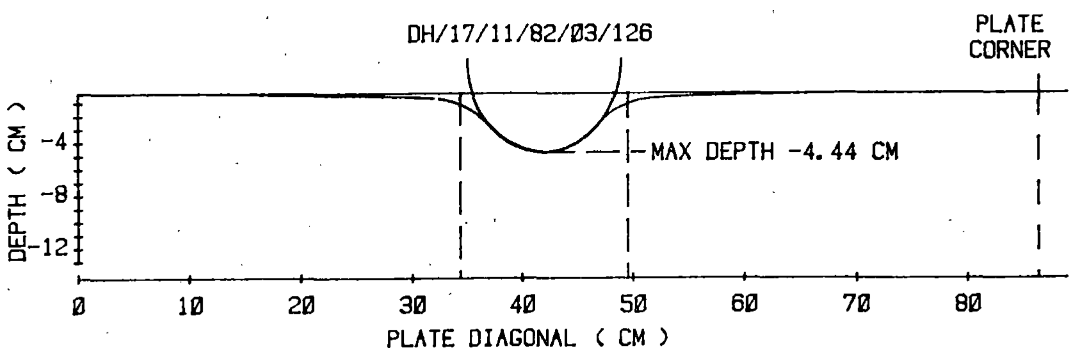

Figure 3: A Typical Example of the DM Dent Depth Plots

TEST DATA FOR THE FLAT 5.5 INCH TUP

In this series of impact tests, the shape of the tup was flat with a diameter of 14.0 cm (5.5 inches). The symbol for this tup size and shape is T_{LF} in the discussion which follows. A total of nine tests were performed using the T_{LF} tup and three dies of different diameters. A summary of the initial conditions of these tests is presented in Table 1.

TABLE 1:INITIAL CONDITIONS FOR TESTS USING THE 5.5 INCH FLAT TUP

Test No.	Identification Number	Tup Diameter (cm)	Tup Diameter (Inches)	Die Diameter (cm)	Die Diameter (Inches	Hammer Height (cm)	Hammer Height (Inches)
1.	DH-16-11-82-02-145	14.0	5.5	15.2	6.0	81.3	32.0
2.	DH-16-11-82-03-136	14.0	5.5	15.2	6.0	82.6	32.5
3.	DH-16-11-82-01-153	14.0	5.5	15.2	6.0	83.8	33.0
4.	DH-16-11-82-04-153	14.0	5.5	21.0	8.25	86.4	34.0
5.	DH-16-11-82-05-134	14.0	5.5	21.0	8.25	91.4	36.0
6.	DH-16-11-82-06-160	14.0	5.5	21.0	8.25	96.5	38.0
7.	DH-16-11-82-07-167	14.0	5.5	21.0	8.25	101.6	40.0
8.	DH-16-11-82-08-175	14.0	5.5	28.0	11.0	106.7	42.0
9.	DH-17-11-82-01-198	14.0	5.5	28.0	11.0	111.8	44.0

In the first three tests listed in Table 1, the die diameter was only 1.27 cm (0.5 inches) larger than the tup diameter. Past experience using this combination had previously shown that the primary failure mechanism would be shear in these tests. The reason is due to the fact that the bulk of the energy deposition is concentrated around the edge of the tup which causes a punching type action (Ref.3). Figure 4 presents the impact side and the bottom side of the plate for Test Number 1. Both photographs shows the flat impression reflecting the flat tup. There were no visible cracks on either side of the plate.

The DM measurements for Test Number 1 are presented in Figure 5. The diameter of the bottom of the dent, measured from the plot, is less than the diameter of the tup. This indicates that the tup's impacting surface failed to reach the bottom of the dent. However, the hammer bounces when the tup fails to perforate so that as the hammer rebounds, the plate probably contracted because of the elasticity of the plate material.

In Test Number 2, the height of the hammer was only 1.27 cm (0.5 inches) higher than in Test Number 1, but the tup completely sheared through the plate. The plate and the sheared out plug are presented in Figure 6. Since this test resulted in shear and the hammer height was only slightly higher than in Test Number 1, it appears likely that shear bands exist in the plate from Test Number 1. A verification of this will require an NDE analysis and/or a metallurgical fracture mechanical analysis on the plate. The plate in Test

[3] *Charles E. Anderson, Jr., en tal, "Analysis of the BRL/FRA Drop Hammer Facility," Final Report 6970/1, Southwest Research Institute, San Antonio, TX 78284, October 1982.*

Number 2 sustained some bending outside the diameter of the die, but it appears that the major portion of the energy was expended in the shearing process. Since the hammer height was even higher in Test Number 3, that test also produced a sheared out plug.

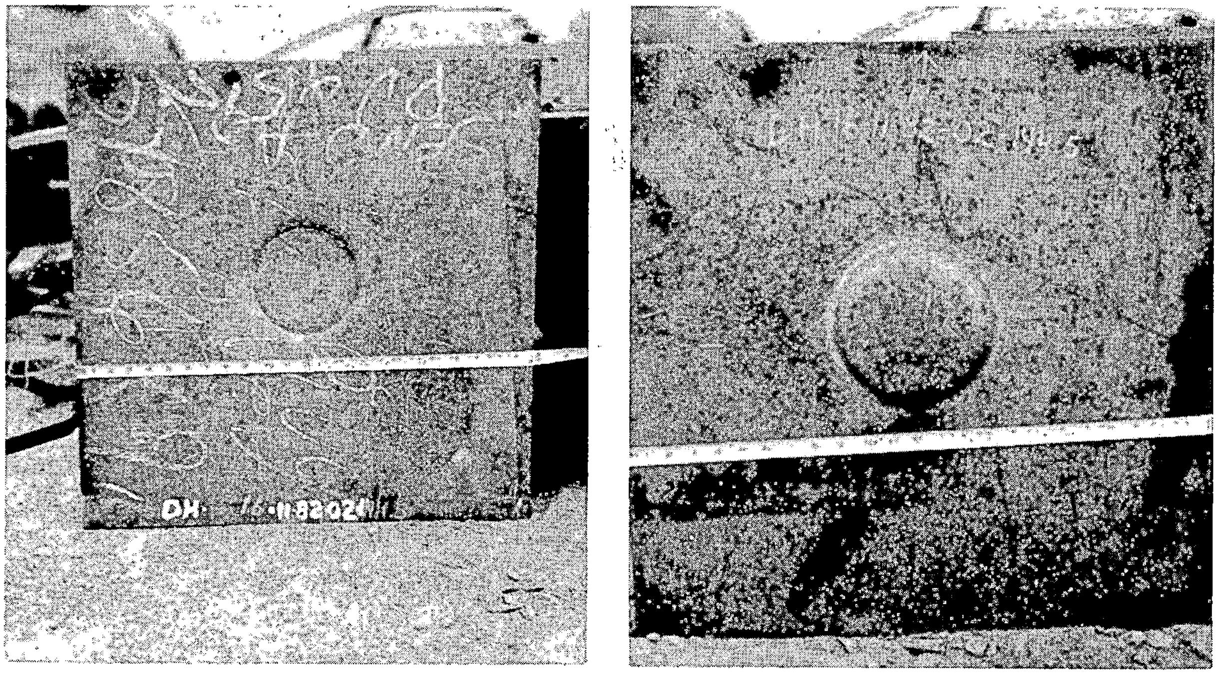

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Figure 4: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 1

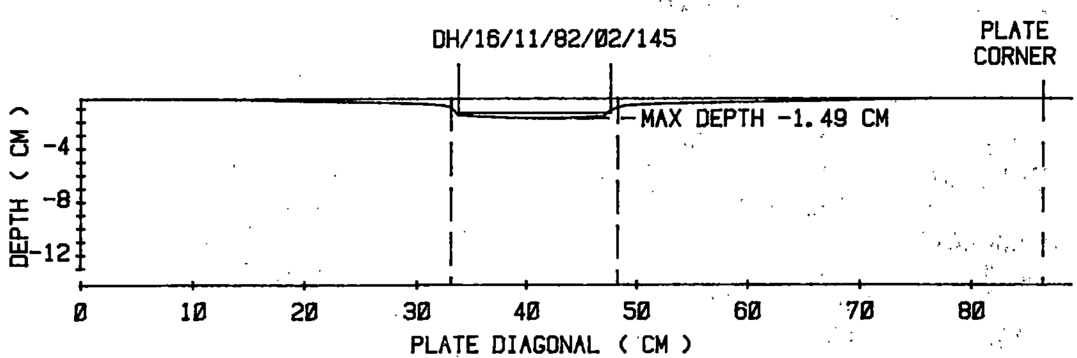

Figure 5: The DM Measurements of Impact Dent From Test Number 1

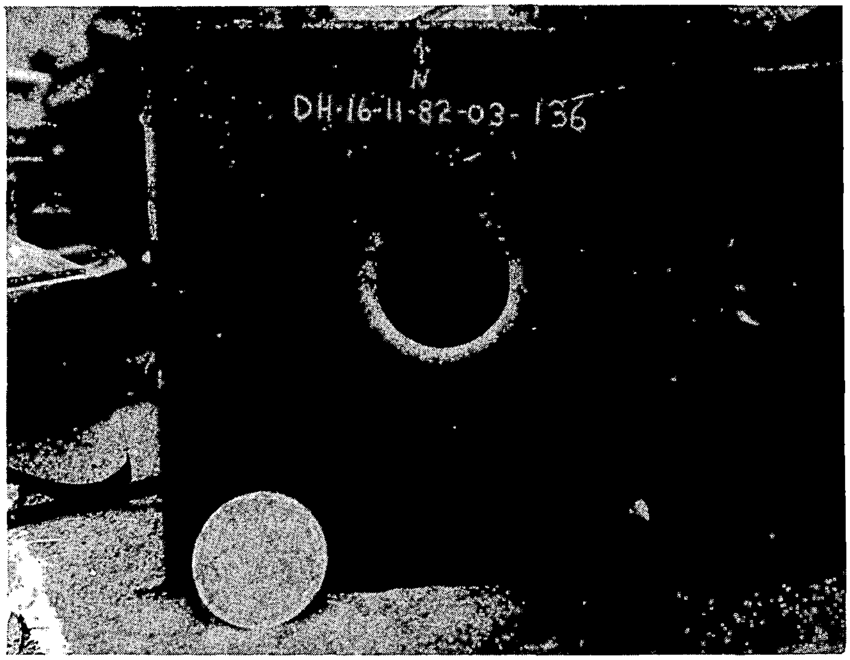

Figure 6: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 2

In the remaining tests there were no perforations, thus the dent depths for each were measured. In order to present the dent depth data on one plot, the potential energy of the hammer (hammer height) was divided by the presented area of the die. The results are presented in Figure 7. In general, for a specific kinetic energy (potential energy), the maximum depth of the dents increased as the die diameter was increased. This was attributed to an increase in the bending mode between the edge of the tup and the edge of the die. The curves were drawn merely to assist in visualizing the trend of the data.

TEST DATA FOR THE HEMISPHERICAL 5.5 INCH TUP

All of the remaining impact tests were performed using hemispherical tups. The largest tup diameter used was 13.97 cm (5.5 inches) and the symbolic designation for this shape and size is T_{LH}. It was anticipated that the penetrating capability of the T_{LH} tup would be greater than that demonstrated by using the T_{LF} tup since the initial area of contact between the tup and the plate would be a point. This therefore would cause the force per unit area to be far greater during the early portion of the tup-plate interaction. In addition, the response of the plate was expected to tend toward the bending mode and away from the shear mode which would tend to cause deeper dents.

A total of 24 impacts using the T_{LH} tup are listed in Table 2. For each of the die sizes, the hammer was raised to a height of 25.4 cm (10 inches) on the first drop and then the heights were increased in each following test until the tup perforated the plate (caused a severe crack). In Test Number 21, the hammer facility failed so no information was obtained. The tup perforated

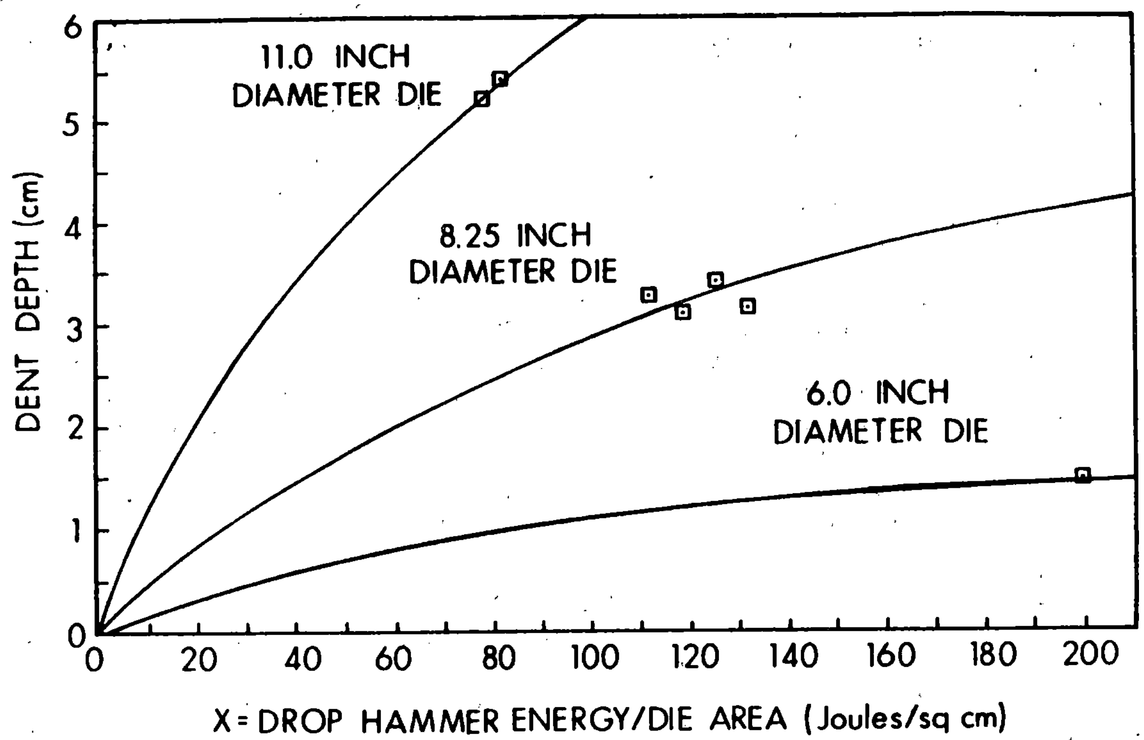

Figure 7: Dent Depth Summary of the 5.5 Inch Flat Tup Data

TABLE 2: INITIAL CONDITIONS FOR TESTS USING THE 5.5 INCH HEMISPHERICAL TUP

Test No.	Identification Number	Tup Diameter {cm}	Tup Diameter {Inches}	Die Diameter {cm}	Die Diameter {Inches}	Hammer Height {cm}	Hammer Height {Inches}
10	DH-26-04-83-03-160	14.0	5.5	15.2	6.0	25.4	10
11	DH-26-04-83-04-160	14.0	5.5	15.2	6.0	50.8	20
12	DH-17-11-82-02-131	14.0	5.5	15.2	6.0	96.5	38
13	DH-17-11-82-03-126	14.0	5.5	15.2	6.0	106.7	42
14	DH-26-04-83-05-160	14.0	5.5	15.2	6.0	127.0	50
15	DH-26-04-83-06-160	14.0	5.5	15.2	6.0	177.8	70
16	DH-26-04-83-01-160	14.0	5.5	21.0	8.3	25.4	10
17	DH-26-04-83-02-160	14.0	5.5	21.0	8.3	76.2	30
18	DH-18-11-82-09-149	14.0	5.5	21.0	8.3	127.0	50
19	DH-18-11-82-10-126	14.0	5.5	21.0	8.3	152.4	60
20	DH-18-11-82-11-149	14.0	5.5	21.0	8.3	177.8	70
21	DH-18-11-82-12-140	14.0	5.5	21.0	8.3	228.6	90
22	DH-25-04-83-20-160	14.0	5.5	28.0	11.0	25.4	10
23	DH-25-04-83-21-160	14.0	5.5	28.0	11.0	76.2	20
24	DH-25-04-83-22-160	14.0	5.5	28.0	11.0	127.0	50
25	DH-25-04-83-23-160	14.0	5.5	28.0	11.0	177.8	70
26	DH-25-04-83-16-160	14.0	5.5	35.0	14.0	25.4	10
27	DH-25-04-83-17-160	14.0	5.5	35.0	14.0	76.2	30
28	DH-25-04-83-18-160	14.0	5.5	35.0	14.0	127.0	50
29	DH-25-04-83-19-160	14.0	5.5	35.0	14.0	177.8	70
30	DH-26-04-83-15-160	14.0	5.5	35.0	14.0	203.2	80
31	DH-26-04-83-16-160	14.0	5.5	35.0	14.0	203.2	80
32	DH-27-04-83-01-160	14.0	5.5	35.0	14.0	203.2	80
33	DH-27-04-83-02-160	14.0	5.5	35.0	14.0	203.2	80

the plates on Test Numbers 15, 25, 32, and 33. The photographs of the impacted plates are presented in Figures 8 through 11. The impact side and the bottom side of the plate for Test Number 15, where the die diameter was 15.3 cm (6.0 inches) and the hammer height was 178.0 cm (70 inches), are presented in Figure 8. In that test a punched-out plug was achieved which lodged inside the die. The impact side and the bottom side of the plate for Test Number 25 are presented in Figure 9. The die diameter for this test was 28.0 cm (11.0 inches) and the hammer height was 178.0 cm (70 inches). The large crack generated probably started on one side of the bulge and propagated circumferencially toward the edges of the bulge. The impact sids and the bottom sides of the plates for Test Number 32 and 33 are presented in Figures 10 and 11 respectively. The die diameter was 35.0 cm (13.75 inches). The crack in each plate was similar to the one generated in the previous test discussed. For those tests in which die diameters greater than 15.2 cm (6.0 inches) were used, the data indicates that ductile cracks forms rather than shear plugs. The responses of the plates consist of initial crack formation and crack enlargement as the hammer height is increased (more kinetic energy on impact). The damage mechanism was probably severe thinning of the steel around the sides of the bulge as the tups penetrated and then the thinned metals separated by ductile fracture.

An example of the plate response to the tup when no perforation occurred is presented in Figure 12. The die diameter was 15.3 cm (6.0 inches). The shape and size of the tup and the diameter of the die was dominant in forming the geometry of the dent. Figure 13 presents an example of the DM plots for the tests where no severe cracking occurred. The dent depth as functions of the drop hammer energy/die diameter ratio (joules/sq. cm) data are presented in Figure 14. The curves indicate a gradual increase in the dent depth as the energy per area increased and the dent depth increased at a faster rate for the larger die diameters.

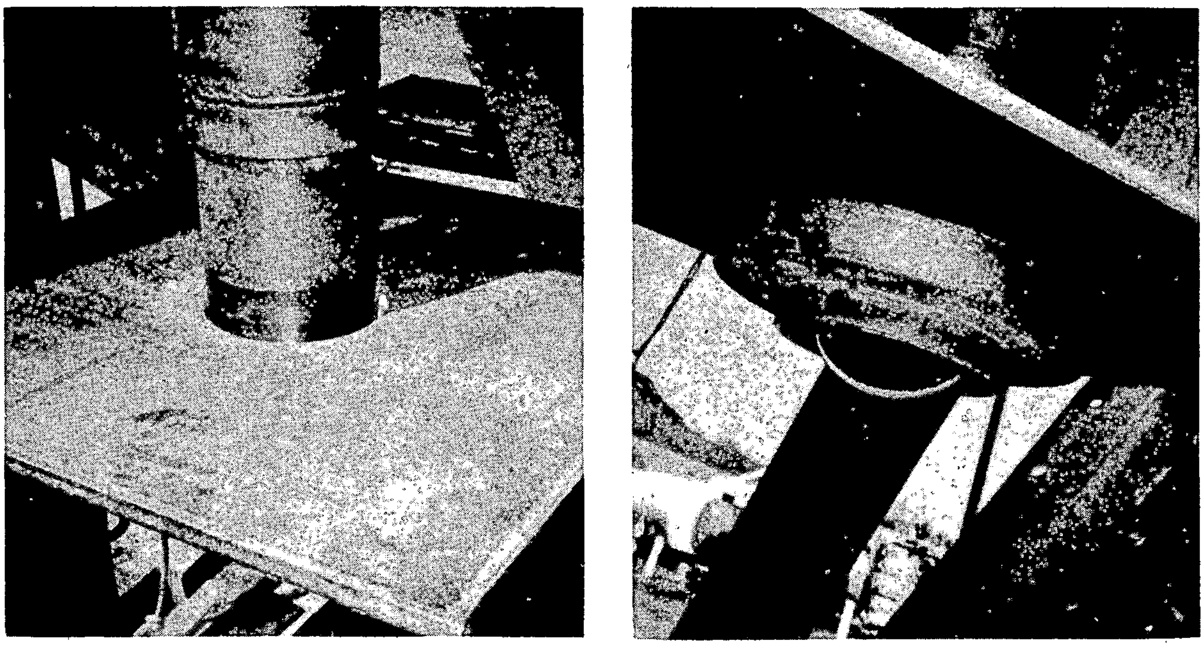

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Figure 8: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 15

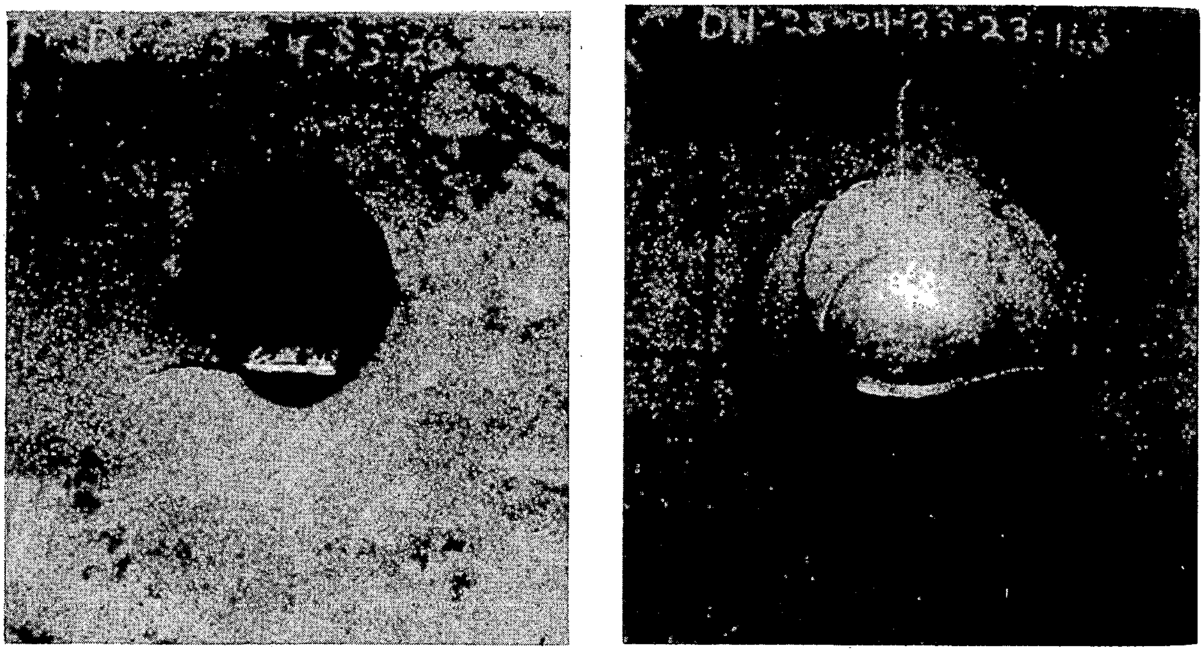

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Figure 9: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 25

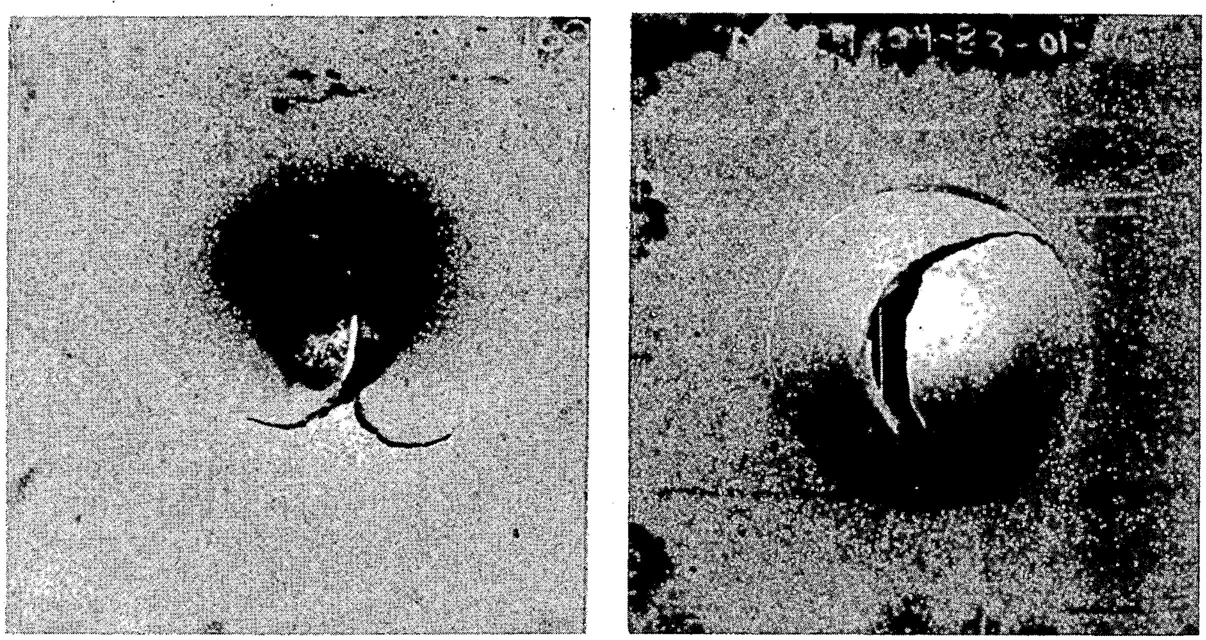

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Figure 10: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 32

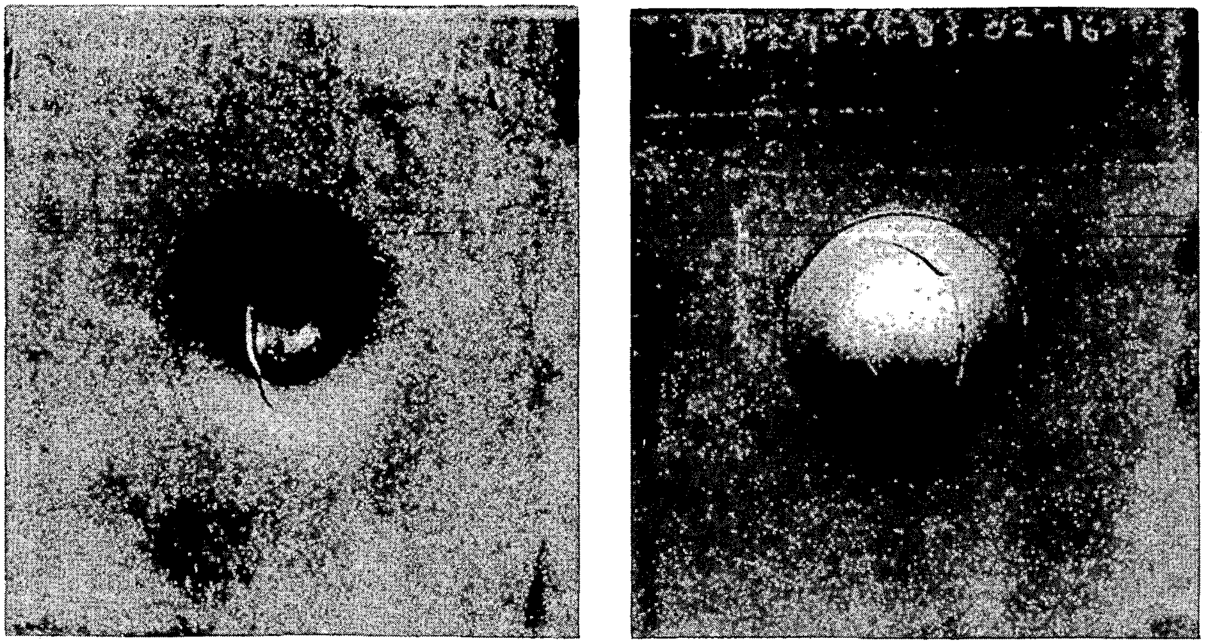

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Figure 11: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 33

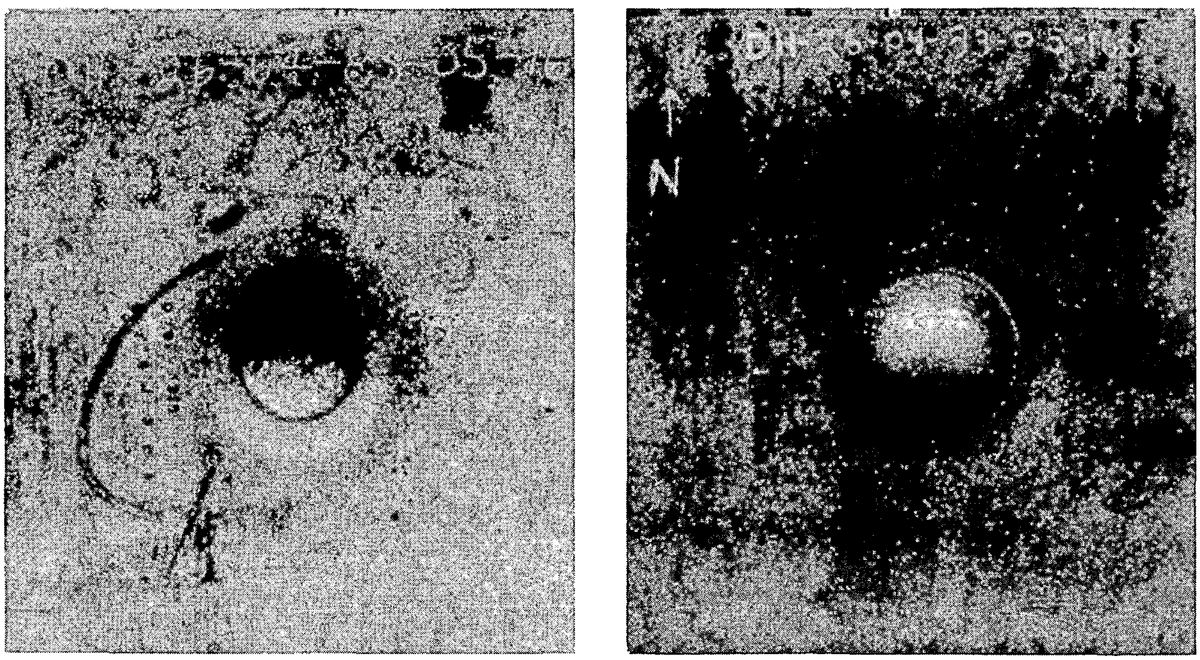

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Figure 12: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 14

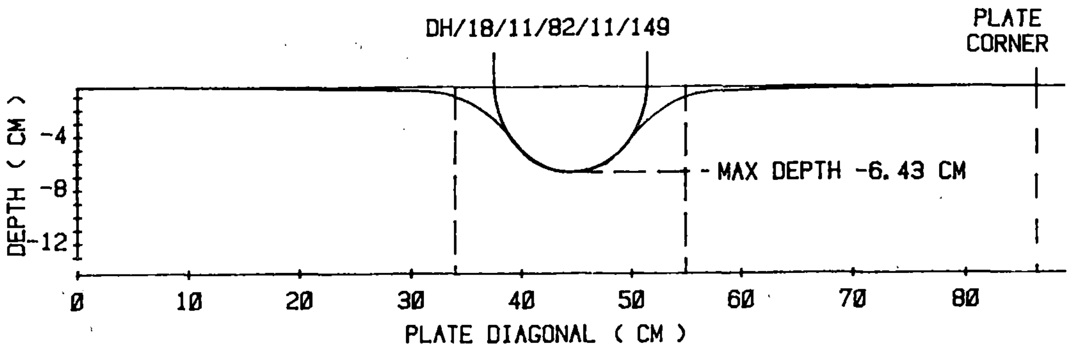


Figure 13: The DM Measurements of Impact Dent From Test Number 20

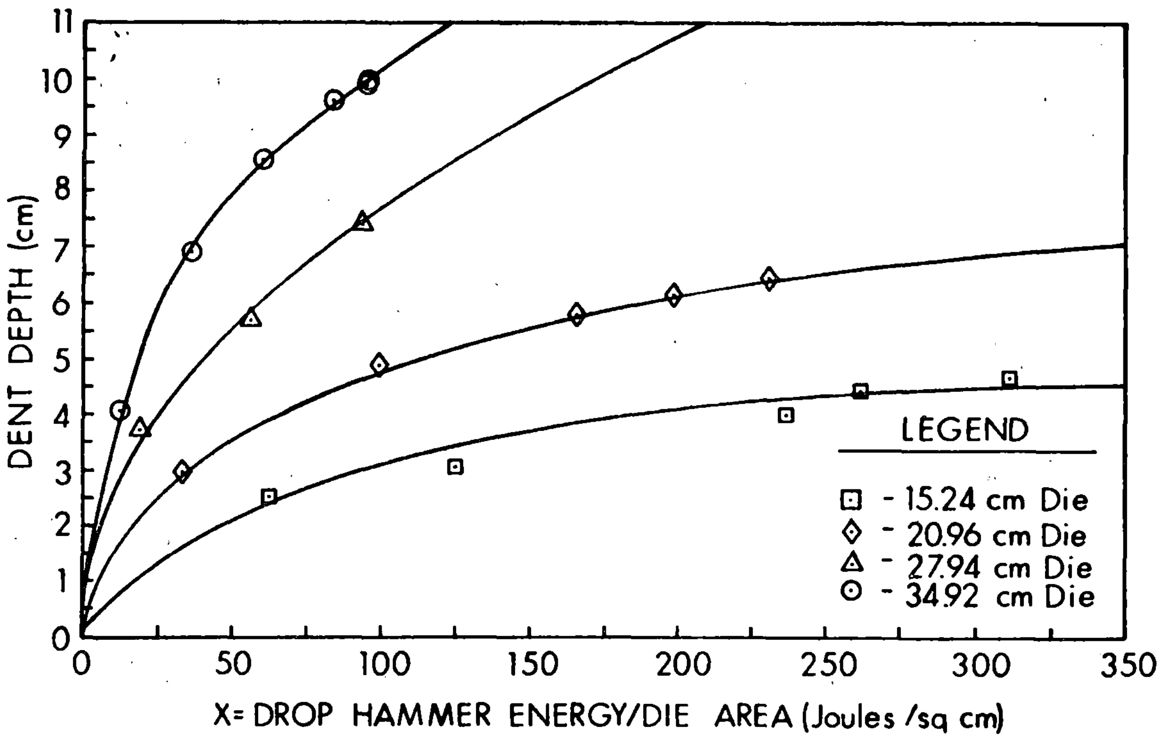


Figure 14: Dent Depth Summary of the 5.5 Inch Hemispherical Tup Data

TEST DATA FOR THE HEMISPHERICAL 3.75 INCH TUP

The next group of tests were done using a hemispherical tup with a maximum diameter of 9.5 cm (3.75 inches). The symbol designation for this tup is T_{MH}. In general, it was expected that the response by the plates to impacts using the T_{MH} tup would be similar to the results using the larger size tup, but that the depths would be greater with respect to the hammer height. The initial conditions for the 15 tests using this tup are listed in Table 3.

TABLE 3: INITIAL CONDITIONS FOR TESTS USING THE 3.75 INCH HEMISPHERICAL TUP

Test No.	Identification Number	Tup Diameter (cm)	Tup Diameter (Inches)	Die Diameter (cm)	Die Diameter (Inches)	Hammer Height (cm)	Hammer Height (Inches)
34	DH-25-04-83-01-160	9.6	3.75	15.2	6.0	25.4	10.0
35	DH-25-04-83-02-160	9.6	3.75	15.2	6.0	50.8	20.0
36	DH-25-04-83-03-160	9.6	3.75	15.2	6.0	76.2	30.0
37	DH-25-04-83-04-160	9.6	3.75	15.2	6.0	101.6	40.0
38	DH-25-04-83-05-160	9.6	3.75	21.0	8.25	25.4	10.0
39	DH-25-04-83-06-160	9.6	3.75	21.0	8.25	50.8	20.0
40	DH-25-04-83-07-160	9.6	3.75	21.0	8.25	76.2	30.0
41	DH-25-04-83-08-160	9.6	3.75	21.0	8.25	101.6	40.0
42	DH-25-04-83-09-160	9.6	3.75	28.0	11.0	25.4	10.0
43	DH-25-04-83-10-160	9.6	3.75	28.0	11.0	50.8	20.0
44	DH-25-04-83-11-160	9.6	3.75	28.0	11.0	76.2	30.0
45	DH-25-04-83-12-160	9.6	3.75	35.0	13.75	25.4	10.0
46	DH-25-04-83-13-160	9.6	3.75	35.0	13.75	50.8	20.0
47	DH-25-04-83-14-160	9.6	3.75	35.0	13.75	76.2	30.0
48	DH-25-04-83-15-160	9.6	3.75	35.0	13.75	101.6	40.0

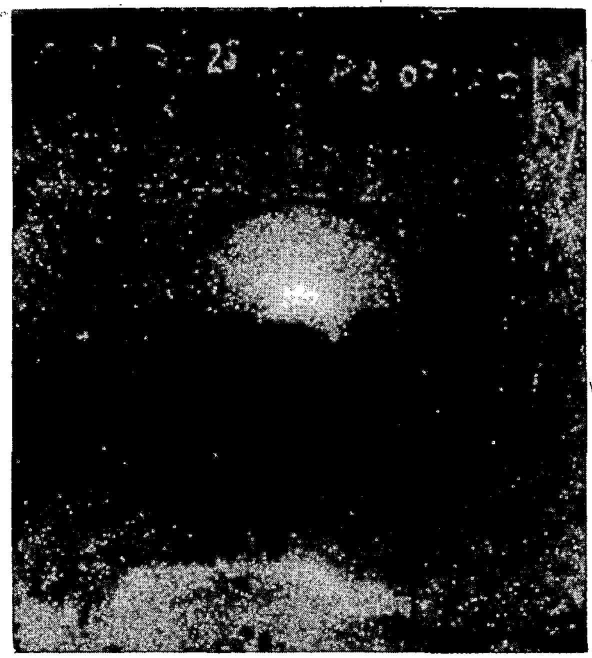
Figure 15 presents a view of the impact side and the bottom side of a sample impacted plate using the T_{MH} tup. The response of the plate was similar to that obtained for the larger hemispherical tup. Figure 16 presents a sample of the DM measurements for this group of tests which also is similar to the previously discussed group. The dent depth as functions of drop hammer energy/die area (joules/sq. cm) are presented in Figure 17. The trends are similar to the previous group's results but the dent depths are greater as anticipated.

TEST DATA FOR THE HEMISPHERICAL 2.0 INCH TUP

The remaining tests were performed using a 5.08 cm (2 inch) diameter hemispherical tup designated with the symbol T_{SH}. It was expected that the depth of the dents as functions of hammer height would increase significantly due to the much greater energy/area concentration. The initial conditions for these tests are summarized in Table 4.

An example of one of the tests, where a 15.2 cm (6.0 inch) diameter die was used is presented in Figure 18. The imprint of the perimeter of the die is visible in both photographs. Figure 19 presents a sample DM measurement plot for Test Number 61 where a 21.0 cm (8.3 inch) diameter die was used. In general, the plates experienced a great deal of bending due to the relatively large distance between the edge of the die and the tup.

In practically all of the T_{SH} tup tests, visible cracks were observed on the bottom side of the plates at or near the apex of the bulges. The seriousness of this type of crack with respect to a tank car rupture cannot be estimated at the present. However, the data indicates that for a bend with a radius of curvature of 2.54 cm (1.0 inches) and a dent depth of 3.81 cm (1.5



IMPACT SIDE BOTTOM SIDE

Figure 15: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 40

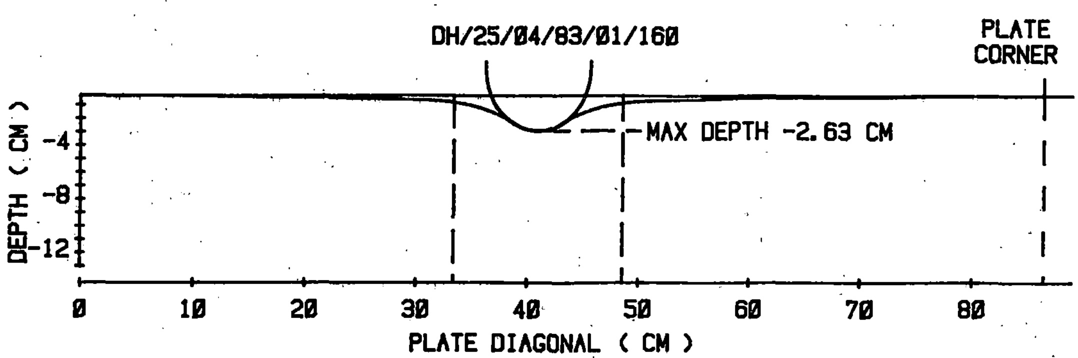


Figure 16: The DM Measurements of Impact Dent From Test Number 34

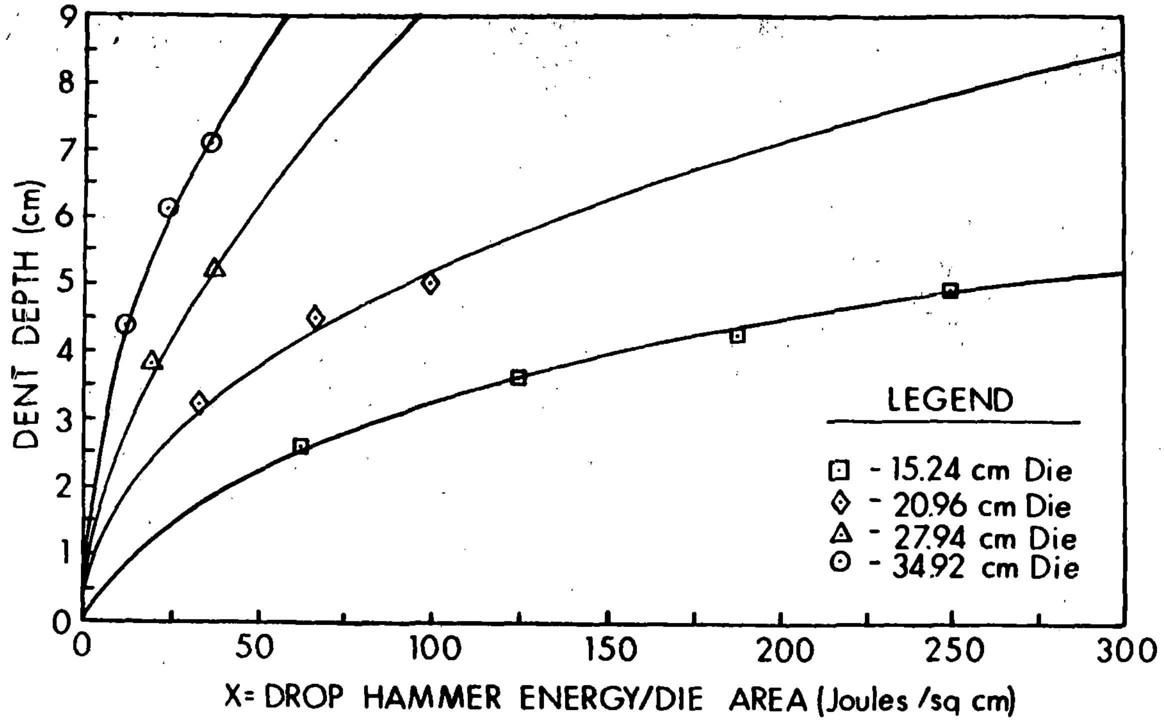


Figure 17: Dent Depth Summary for the 3.75 Inch Hemispherical Tup Data

TABLE 4: INITIAL CONDITIONS FOR TESTS USING THE 2.0 INCH HEMISPHERICAL TUP

Test No.	Identification Number	Tup Diameter {cm}	Tup Diameter {Inches}	Die Diameter {cm}	Die Diameter {Inches}	Hammer Height {cm}	Hammer Height {Inches}
49	DH-26-04-83-07-160	5.1	2.0	15.2	6.0	10.2	4.0
50	DH-26-04-83-08-160	5.1	2.0	15.2	6.0	20.3	8.0
51	DH-17-11-82-04-140	5.1	2.0	15.2	6.0	30.5	12.0
52	DH-17-11-82-05-167	5.1	2.0	15.2	6.0	33.0	13.0
53	DH-17-11-82-06-167	5.1	2.0	15.2	6.0	35.6	14.0
54	DH-17-11-82-09-147	5.1	2.0	15.2	6.0	38.1	15.0
55	DH-17-11-82-07-167	5.1	2.0	15.2	6.0	40.6	16.0
56	DH-17-11-82-08-136	5.1	2.0	15.2	6.0	43.2	17.0
57	DH-26-04-83-09-160	5.1	2.0	21.0	6.0	10.2	4.0
58	DH-26-04-83-10-160	5.1	2.0	21.0	8.3	20.3	8.0
59	DH-18-11-82-01-179	5.1	2.0	21.0	8.3	30.5	12.0
60	DH-17-11-82-12-171	5.1	2.0	21.0	8.3	33.0	13.0
61	DH-17-11-82-11-157	5.1	2.0	21.0	8.3	40.6	16.0
62	DH-17-11-82-10-167	5.1	2.0	21.0	8.3	45.7	18.0
63	DH-26-04-83-11-160	5.1	2.0	28.0	11.0	10.2	4.0
64	DH-26-04-83-12-160	5.1	2.0	28.0	11.0	20.3	8.0
65	DH-18-11-82-04-160	5.1	2.0	28.0	11.0	30.5	12.0
66	DH-18-11-82-03-179	5.1	2.0	28.0	11.0	33.0	13.0
67	DH-18-11-82-02-171	5.1	2.0	28.0	11.0	35.6	14.0
68	DH-26-04-83-13-160	5.1	2.0	35.0	13.8	10.2	4.0
69	DH-26-04-83-14-160	5.1	2.0	35.0	13.8	20.3	8.0
70	DH-18-11-82-08-167	5.1	2.0	35.0	13.8	33.0	13.0
71	DH-18-11-82-05-171	5.1	2.0	35.0	13.8	35.6	14.0
72	DH-18-11-82-07-163	5.1	2.0	35.0	13.8	35.6	14.0
73	DH-18-11-82-06-160	5.1	2.0	35.0	13.8	38.1	15.0

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Figure 18: Steel Plate Response to 2.0 Inch Hemispherical Tup in Test Number 55

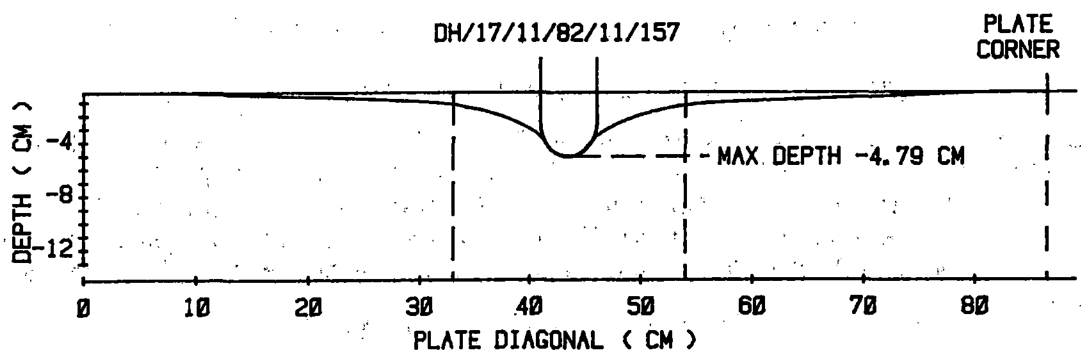


Figure 19: The DM Measurements of Impact Dent From Test Number 61

inches} to 6.35 cm {2.5 inches}, there will be surface cracking on the inside of the tank car. This is an example of how these data can be used in assessing a damaged tank car. Such a correlation can be expanded to include other flaw data obtained by using NDE techniques. Figure 20 presents a plot of the dent depth as functions of drop hammer energy/die area {joules/sq. cm}. Again, these curves are similar to those obtained from test data obtained using the larger diameter tups.

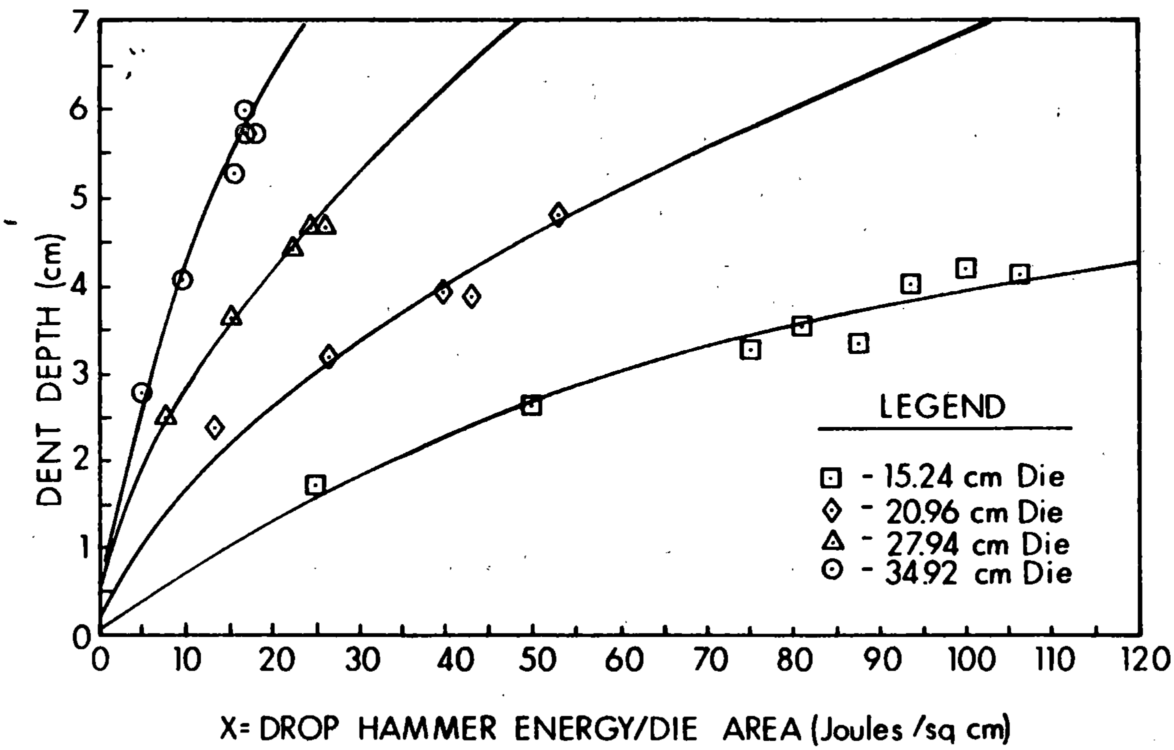


Figure 20: Dent Depth Summary for the 2.0 Inch Hemispherical Tup

SCALING OF THE DENT DEPTH VERSUS ENERGY

As with any test program, in the event the data scales, a great deal of future test reduction may be realized. Consequently, an attempt to scale the dent depth as a function of drop hammer energy was pursued. The results of this effort are presented in Figure 21. As Figure 21 shows, the scaling was done by nondimensionalizing the X and Y terms. These terms are defined as follows:

$$X = \{\{ E / S \} * \{ D_T / D_D \}\}^{0.5}$$

and

$$Y = \{ DD / d \} * \{ D_T / D_D \}^{0.25}$$

where:

DD is depth of dent {cm},
d is plate thickness {1.5875 cm = 5/8 inches},
D_D is die diameter {cm},
E is plate density times tup velocity squared {kg/m-sec^2},

S is ultimate strength of plate material {4.5 x 10^6 kg/m-sec^2}= 65,000 psi}
and the density of the steel was assumed to be equal to 7.78 gm/cc.

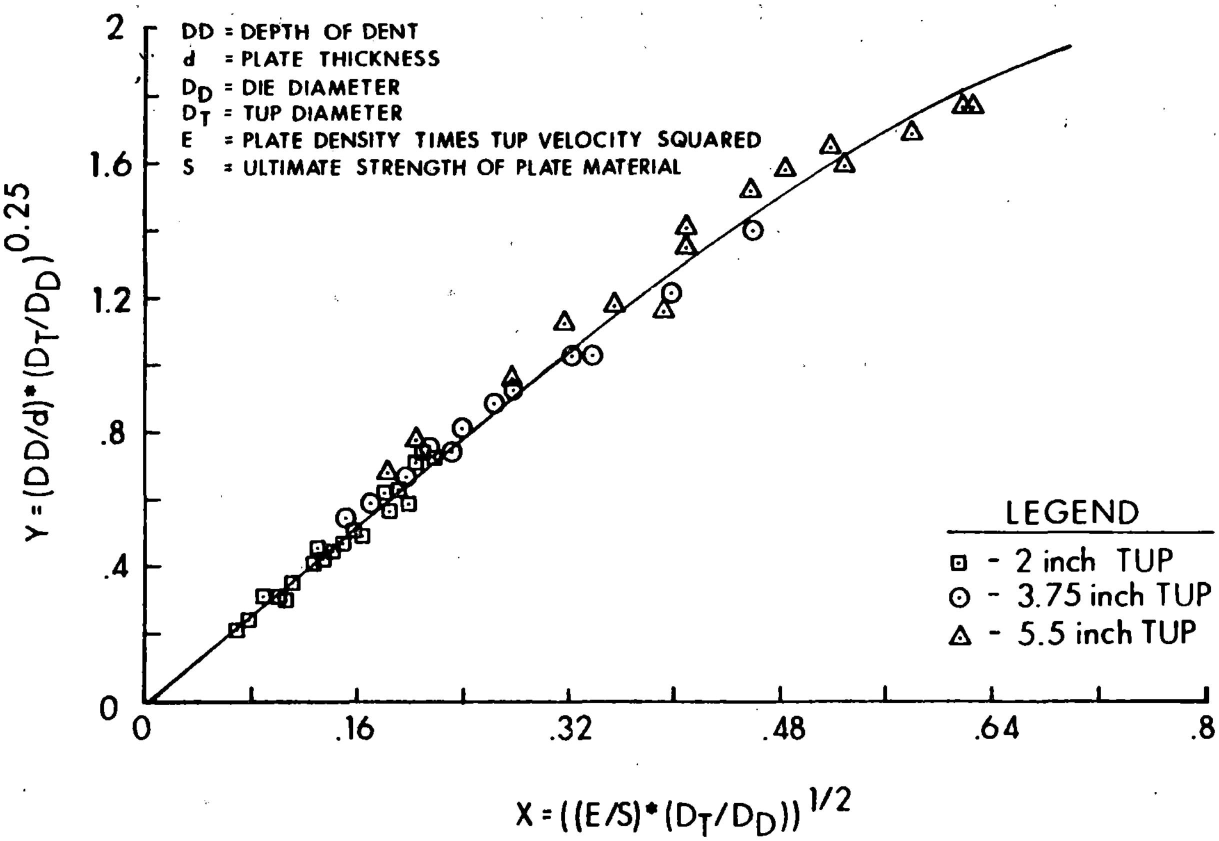


Figure 21: Summary of Dent Depth Versus Energy for the Hemispherical Tup Impact Data

These scaling relations were obtained using nondimensionalizing techniques in a totally empirical way. The most important aspect of this exercise is that the result shows that there is a high probability that these kinds of test data can be scaled. Additional work is required in the form of data generation for other initial conditions. For example, it would be very useful if expressions could be developed for scaling to other plate thicknesses and materials.

SUMMARY

The discussion indicates that tank car type steel is very ductile and that brittle fracture can only be expected after the material has experienced a great deal of strain hardening. It was shown that for 3.81 cm {1.5 inch} to 6.35 cm {2.5 inch} deep dents with a radius of curvature of 2.54 cm {1 inches}, ductile cracking can be expected on the inside surface of a dented tank car with a shell constructed with steel used in this program. The data indicates that the depth of the dent measured from the original surface of the plate increases as the radius of the die increases for corresponding values of hammer heights. Also, the depths of the dents are greater for hemispherical tups than for flat tups for corresponding hammer heights. However, the chance of shear is much greater for the flat tup {with a relatively sharp cutting edge} than for a hemispherical tup with the same diameter.

The dent depth as a function of impact energy {hammer height} scales according to the ratio of tup diameter to die diameter. However, the scaling relations obtained are preliminary and additional work is required to generate scaling procedures useful for assessing damaged tank cars. The information presented in this report will be useful in resolving the general problem, but the most important data to be gained from the impacted plates will be obtained using NDE techniques and parallel evaluations using metallurgical and fracture mechanical procedures.

ACKNOWLEDGEMENT

The authors would like to acknowledge Mr John A. Zook of the Ballistic Research Laboratory for his contribution in the development of the scaling procedure presented in this report.

LIST OF SYMBOLS

BRL — Ballistic Research Laboratory

FRA — Federal Railroad Administration

DOT — Department of Transportation

LPG — Liquid Petroleum Gas

NDE — Nondestructive Evaluation

ASTM — American Society for Testing and Materials

DM — Dial Micrometer

T_{LF} — The 5.5 Inch Diameter - Flat Tup

DF — Drop Hammer

T_{LH} — The 5.5 Inch Diameter - Hemispherical Tup

T_{MH} — The 3.75 Inch Diameter - Hemispherical Tup

T_{SH} — The 2.0 Inch Diameter - Hemispherical Tup

DD — Depth of Dent

d — Plate Thickness

D_D — Die Diameter

D_T — Tup Diameter

E — Plate Density Times the Tup Velocity Squared

S — Ultimate Strength of Plate Material

APPENDIX A

SUMMARY OF INITIAL CONDITIONS OF IMPACT TESTS

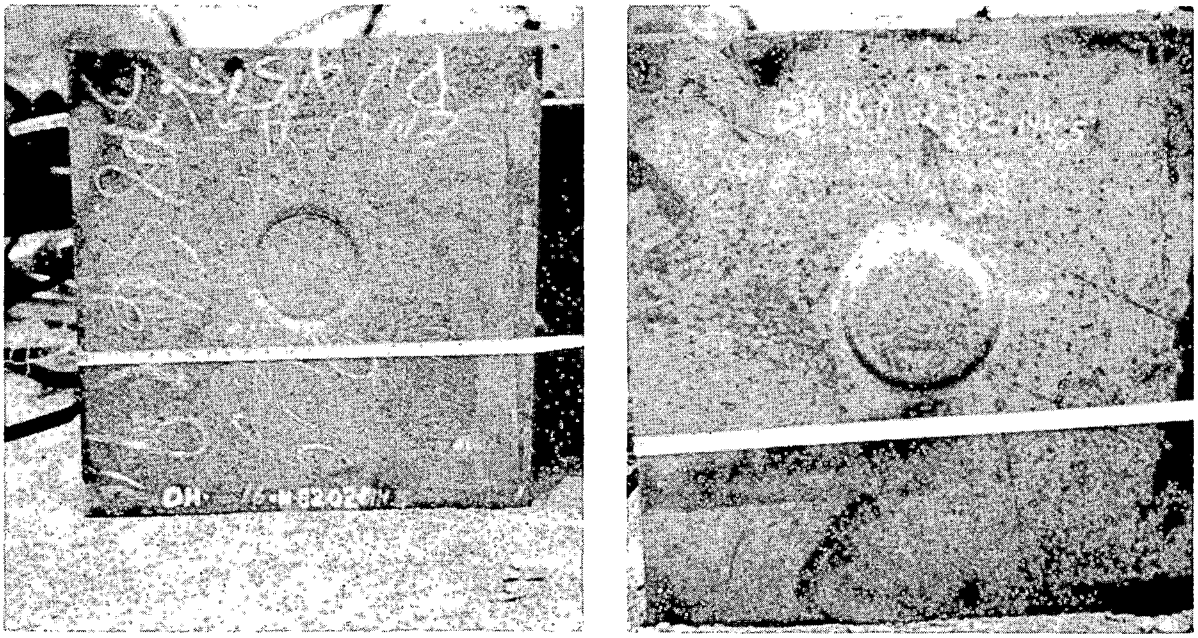
Test No.	Identification Number	Tup Diameter {Inches}	Die Diameter {Inches}	Hammer Height {Inches}	Geometry of Tup
1	DH-16-11-82-02-145	5.5	6.0	32.0	Flat
2	DH-16-11-82-03-136	5.5	6.0	32.5	Flat
3	DH-16-11-82-01-153	5.5	6.0	33.0	Flat
4	DH-16-11-82-04-153	5.5	8.25	34.0	Flat
5	DH-16-11-82-05-134	5.5	8.25	36.0	Flat
6	DH-16-11-82-06-160	5.5	8.25	38.0	Flat
7	DH-16-11-82-07-167	5.5	8.25	40.0	Flat
8	DH-16-11-82-08-175	5.5	11.0	42.0	Flat
9	DH-17-11-82-01-198	5.5	11.0	44.0	Flat
10	DH-26-04-83-03-160	5.5	6.0	10.0	Hemisphere
11	DH-26-04-83-04-160	5.5	6.0	20.0	Hemisphere
12	DH-17-11-82-02-131	5.5	6.0	38.0	Hemisphere
13	DH-17-11-82-03-126	5.5	6.0	42.0	Hemisphere
14	DH-26-04-83-05-160	5.5	6.0	50.0	Hemisphere
15	DH-26-04-83-06-160	5.5	6.0	70.0	Hemisphere
16	DH-26-04-83-01-160	5.5	8.25	10.0	Hemisphere
17	DH-26-04-83-02-160	5.5	8.25	30.0	Hemisphere
18	DH-18-11-82-09-149	5.5	8.25	50.0	Hemisphere
19	DH-18-11-82-10-126	5.5	8.25	60/0	Hemisphere
20	DH-18-11-82-11-149	5.5	8.25	70.0	Hemisphere
21	DH-18-11-82-12-140	5.5	8.25	90.0	Hemisphere
22	DH-25-04-83-20-160	5.5	11.0	10.0	Hemisphere
23	DH-25-04-83-21-160	5.5	11.0	30.0	Hemisphere
24	DH-25-04-83-22-160	5.5	11.0	50.0	Hemisphere
25	DH-25-04-83-23-160	5.5	11.0	70.0	Hemisphere
26	DH-25-04-83-16-160	5.5	13.95	10.0	Hemisphere
27	DH-25-04-83-17-160	5.5	13.95	30.0	Hemisphere
28	DH-25-04-83-18-260	5.5	13.95	50.0	Hemisphere
29	DH-25-04-83-19-160	5.5	13.95	70.0	Hemisphere
30	DH-26-04-83-15-160	5.5	13.95	80.0	Hemisphere
31	DH-26-04-83-16-160	5.5	13.95	80.0	Hemisphere
32	DH-27-04-83-01-160	5.5	13.95	80.0	Hemisphere
33	DH-27-04-83-02-160	5.5	13.95	80.0	Hemisphere
34	DH-25-04-83-01-160	3.75	6.0	10.0	Hemisphere
35	DH-25-04-83-02-160	3.75	6.0	20.0	Hemisphere
36	DH-25-04-83-03-160	3.75	6.0	30.0	Hemisphere
37	DH-25-04-83-04-160	3.75	6.0	40.0	Hemisphere
38	DH-25-04-83-05-160	3.75	8.25	10.0	Hemisphere
39	DH-25-04-83-06-160	3.75	8.25	20.0	Hemisphere
40	DH-25-04-83-07-160	3.75	8.25	30.0	Hemisphere
41	DH-25-04-83-08-160	3.75	8 25	40.0	Hemisphere
42	DH-25-04-83-09-160	3.75	11.0	10.0	Hemisphere
43	DH-25-04-83-10-160	3.75	11.0	20.0	Hemisphere
44	DH-25=04-83-11-160	3.75	11.0	30.0	Hemisphere
45	DH-25-04-83-12-160	3.75	13.75	10.0	Hemisphere
46	DH-25-04-83-13-160	3.75	13.75	20.0	Hemisphere

APPENDIX A

SUMMARY OF INITIAL CONDITIONS OF IMPACT TESTS {Continuation}

Test No.	Identification Number	Tup Diameter {Inches}	Die Diameter {Inches}	Hammer Height {Inches}	Geometry of Tup
47	DH-25-04-83-14-160	3.75	13.75	30.0	Hemisphere
48	DH-25-04-83-15-160	3.75	13.75	40.0	Hemisphere
49	DH-26-04-83-07-160	2.0	6.0	4.0	Hemisphere
50	DH-26-04-83-08-160	2.0	6.0	8.0	Hemisphere
51	DH-17-11-82-04-140	2.0	6.0	12.0	Hemisphere
52	DH-17-11-82-05-167	2.0	6.0	13.0	Hemisphere
53	DH-17-11-82-06-167	2.0	6.0	14.0	Hemisphere
54	DH-17-11-82-09-147	2.0	6.0	15.0	Hemisphere
55	DH-17-11-82-07-167	2.0	6.0	16.0	Hemisphere
56	DH-17-11-82-08-136	2.0	6.0	17.0	Hemisphere
57	DH-26-04-83-09-160	2.0	8.25	4.0	Hemisphere
58	DH-26-04-83-10-160	2.0	8.25	8.0	Hemisphere
59	DH-18-11-82-01-179	2.0	8.25	12.0	Hemisphere
60	DH-17-11-82-12-171	2.0	8.25	13.0	Hemisphere
61	DH-17-11-82-11-157	2.0	8.25	16.0	Hemisphere
62	DH-17-11-82-19-167	2.0	8.25	18.0	Hemisphere
63	DH-26-04-83-11-160	2.0	11.0	4.0	Hemisphere
64	DH-26-04-83-12-160	2.0	11.0	8.0	Hemisphere
65	DH-18-11-82-04-160	2.0	11.0	12.0	Hemisphere
66	DH-18-11-82-03-179	2.0	11.0	13.0	Hemisphere
67	DH-18-11-82-02-171	2.0	11.0	14.0	Hemisphere
68	DH-26-04-83-13-160	2.0	13.75	4.0	Hemisphere
69	DH-26-04-83-14-160	2.0	13.75	8.0	Hemisphere
70	DH-18-11-82-08-167	2.0	13.75	13.0	Hemisphere
71	DH-18-11-82-05-171	2.0	13.75	14.0	Hemisphere
72	DH-18-11-82-07-163	2.0	13.75	14.0	Hemisphere
73	DH-18-11-82-06-160	2.0	13.75	15.0	Hemisphere

APPENDIX B
PHOTOGRAPHS OF STEEL PLATES FOLLOWING IMPACT TESTS



IMPACT SIDE BOTTOM SIDE

Figure B1: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 1

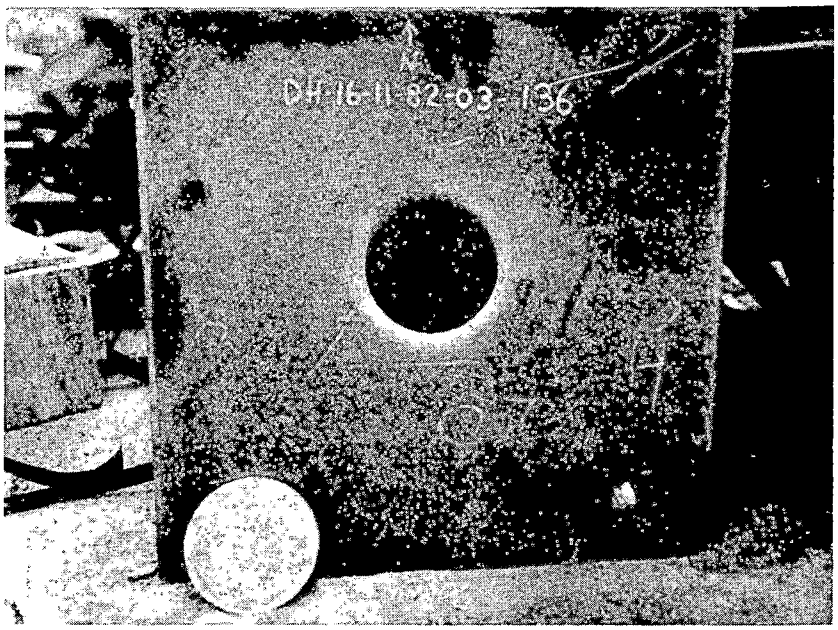


Figure B2: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 2

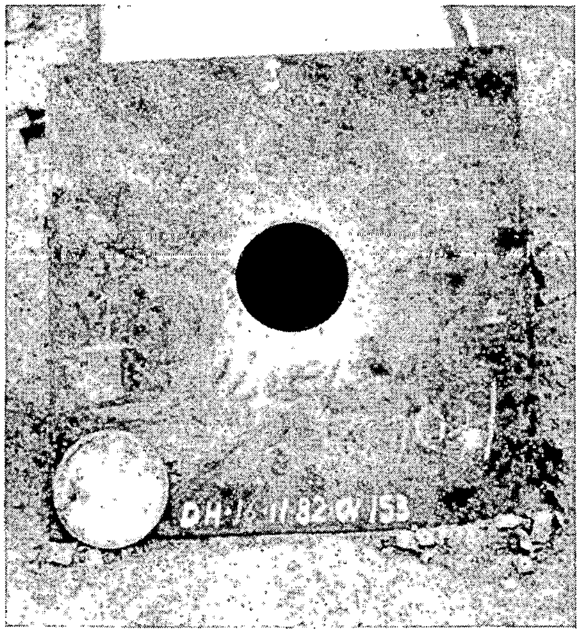
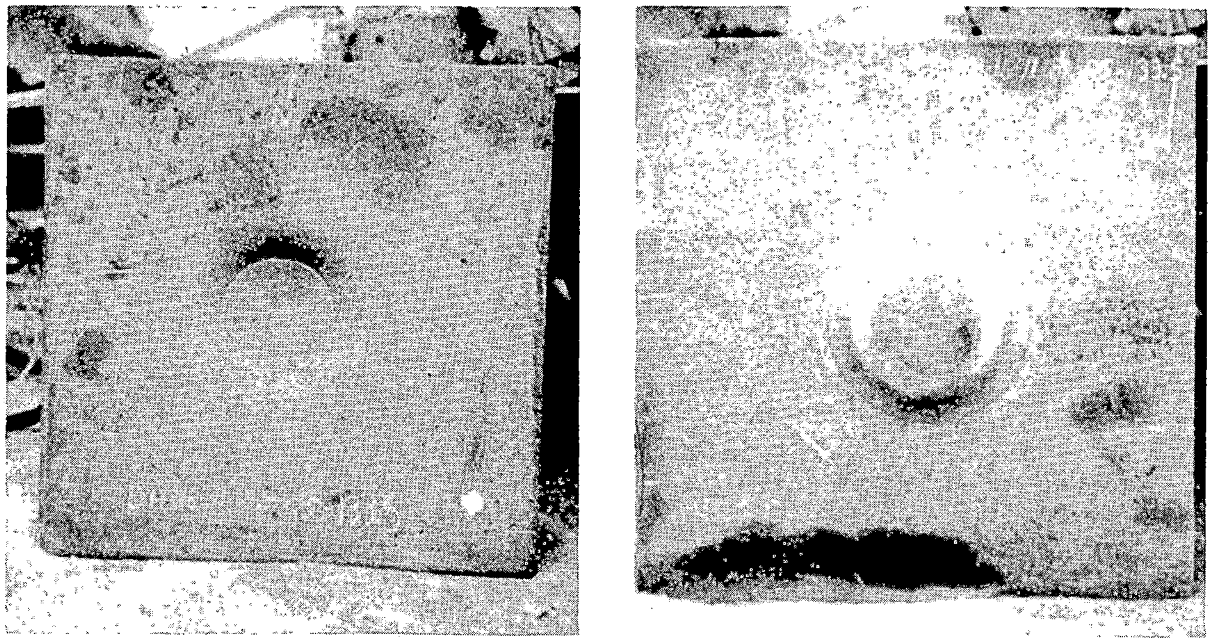


Figure B3: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 3

IMPACT SIDE

BOTTOM SIDE

Figure B4: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 4



IMPACT SIDE BOTTOM SIDE

Figure B5: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 5

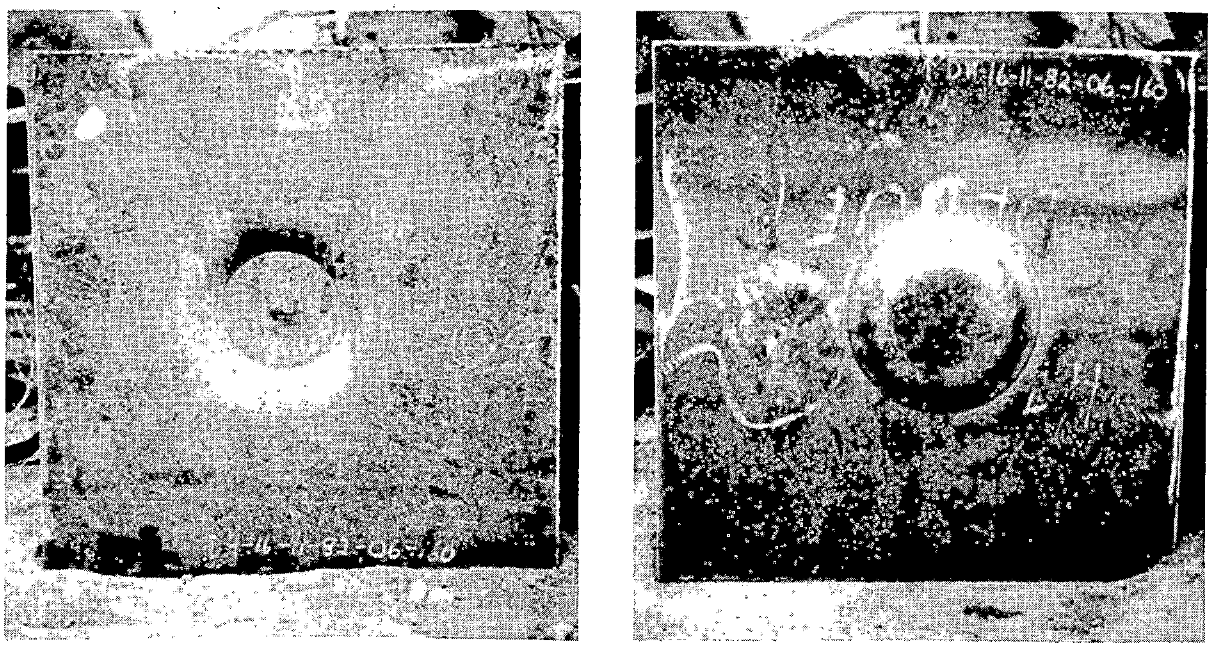


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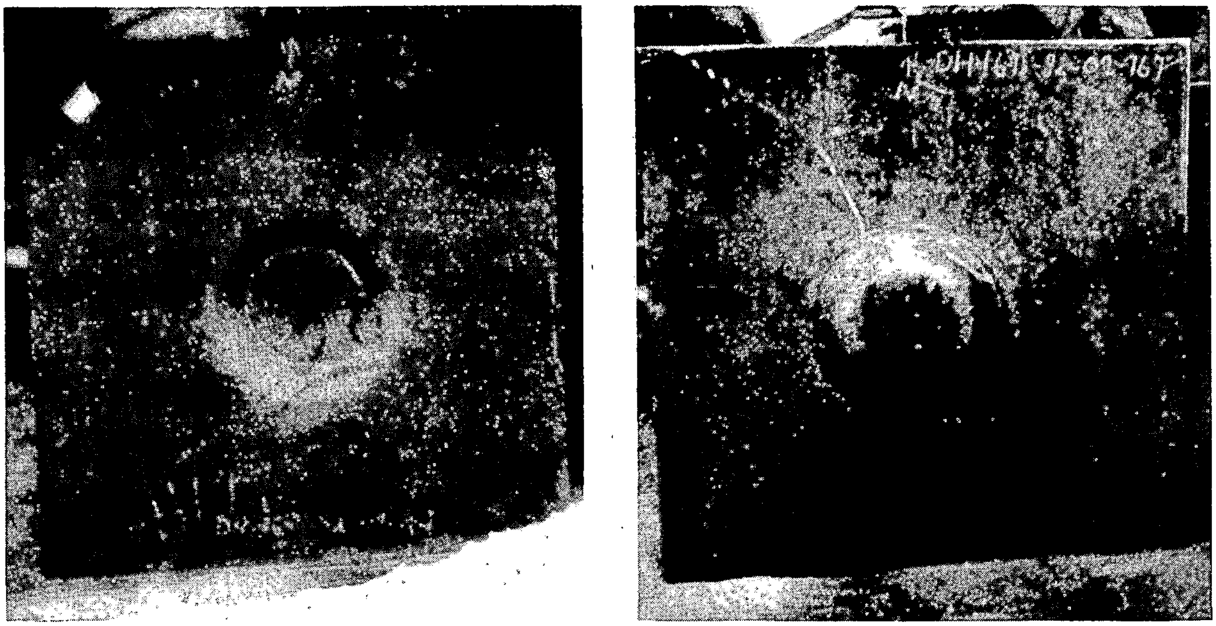
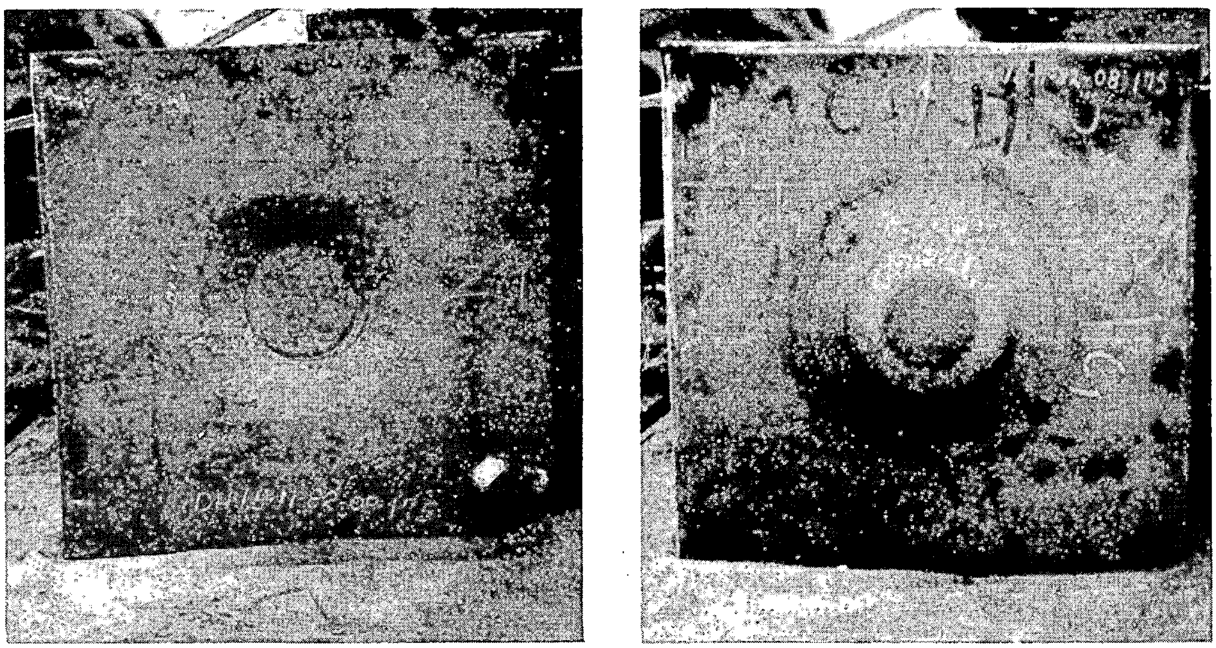
Figure B6: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 6



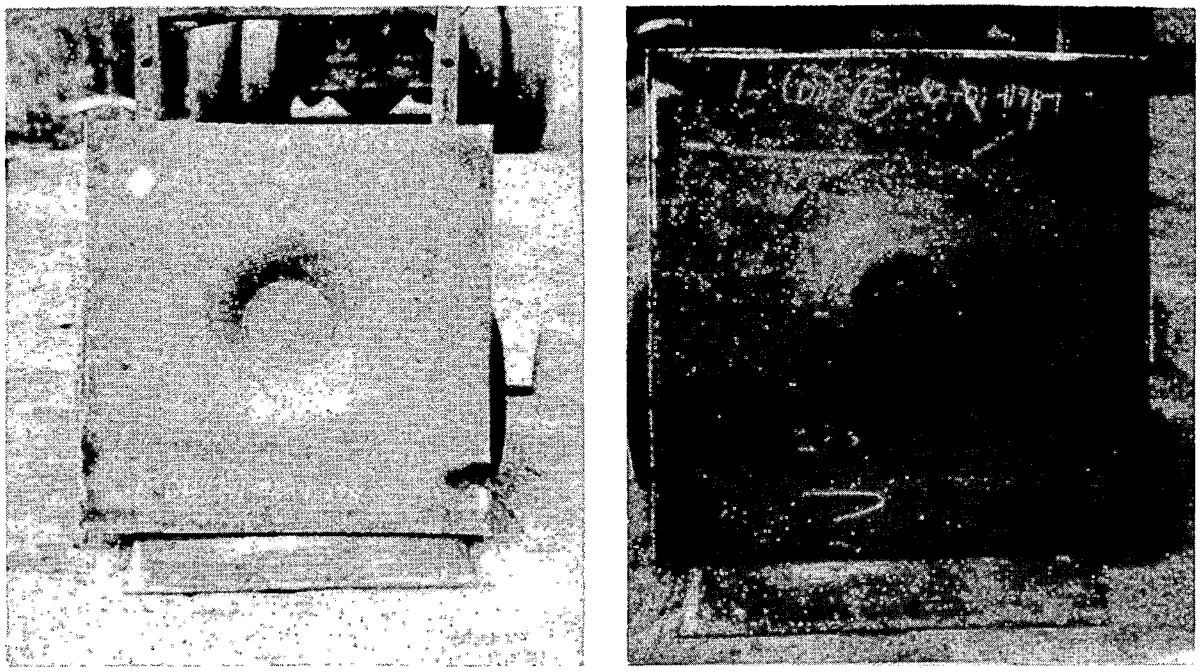
IMPACT SIDE BOTTOM SIDE

Figure B7: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 7



IMPACT SIDE BOTTOM SIDE

Figure B8: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 8



IMPACT SIDE — BOTTOM SIDE

Figure B9: Steel Plate Response to 5.5 Inch Flat Tup in Test Number 9

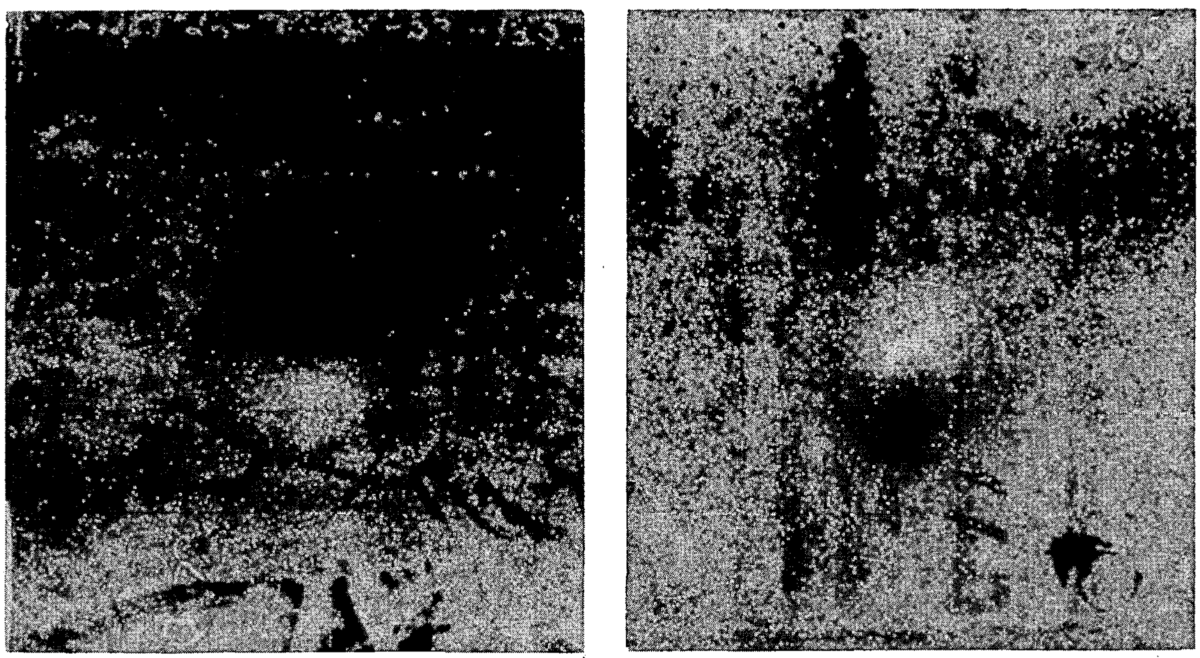


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Figure B10: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 10

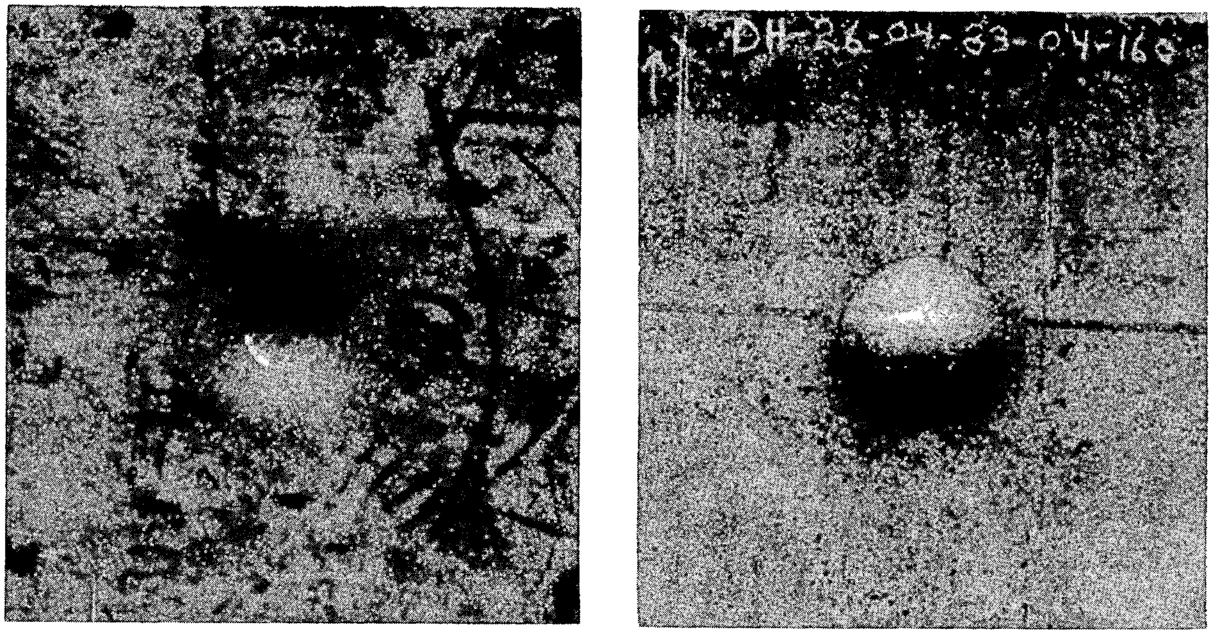

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Figure B11: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 11

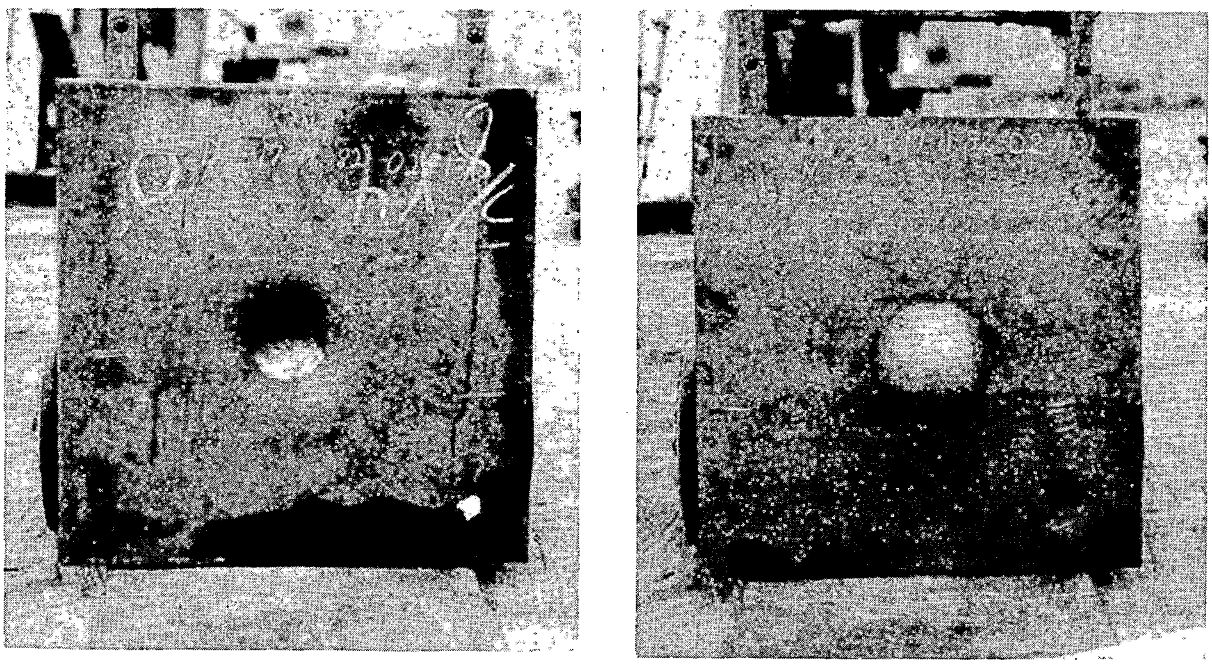

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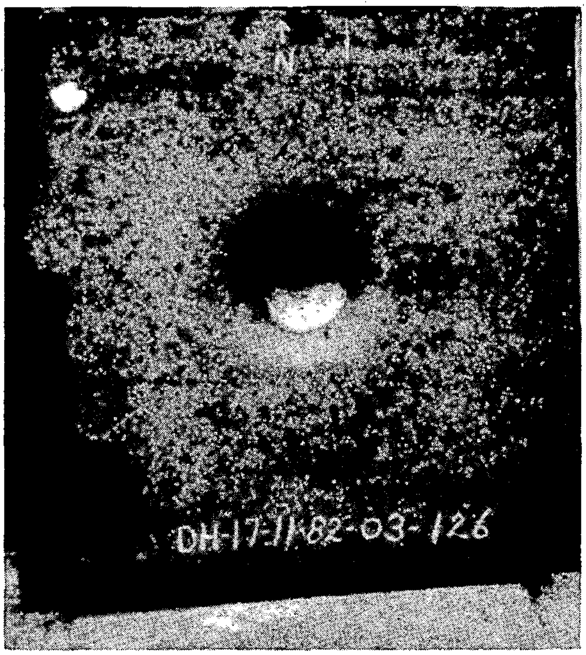
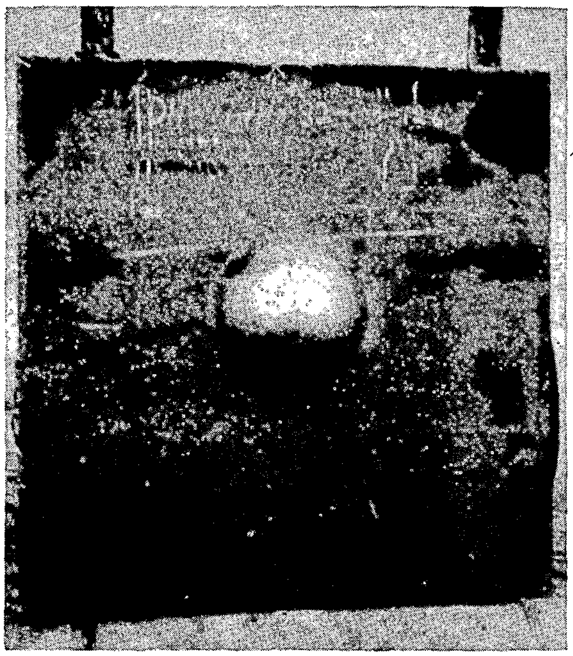
Figure B12: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 12





IMPACT SIDE BOTTOM SIDE

Figure B13: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 13

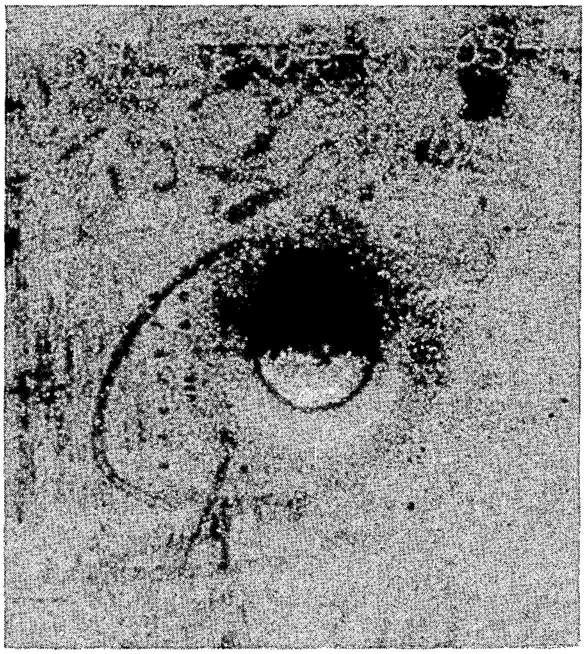


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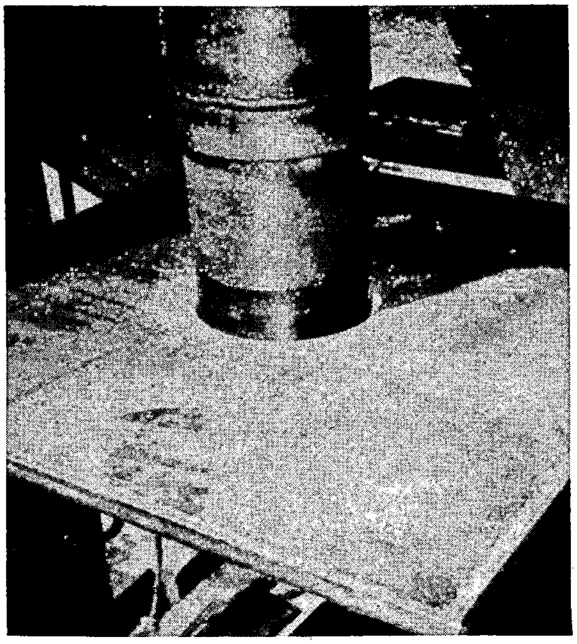
Figure B14: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 14



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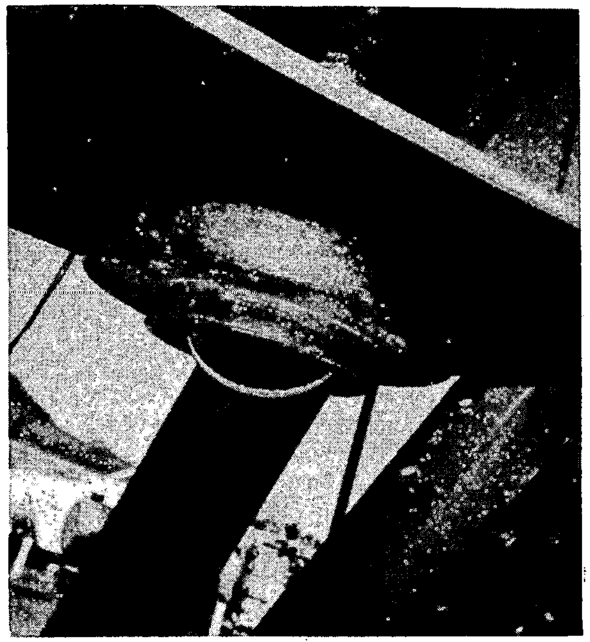

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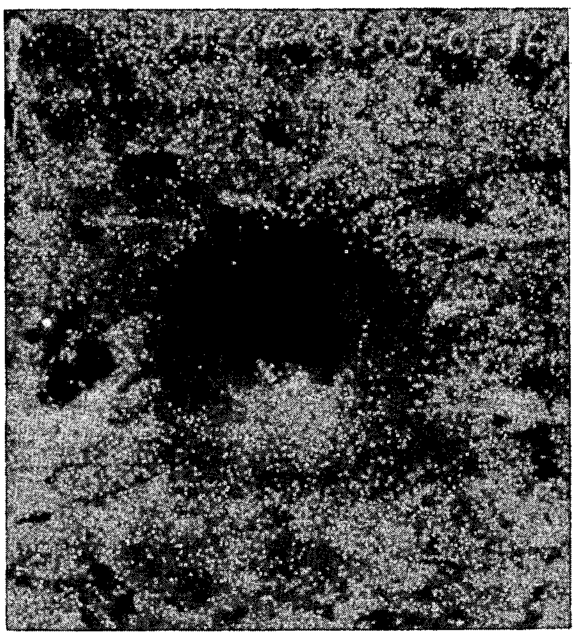
Figure B15: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 15



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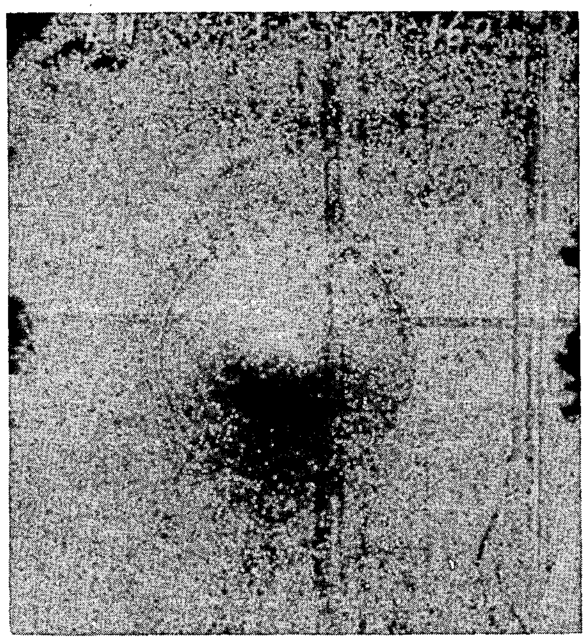

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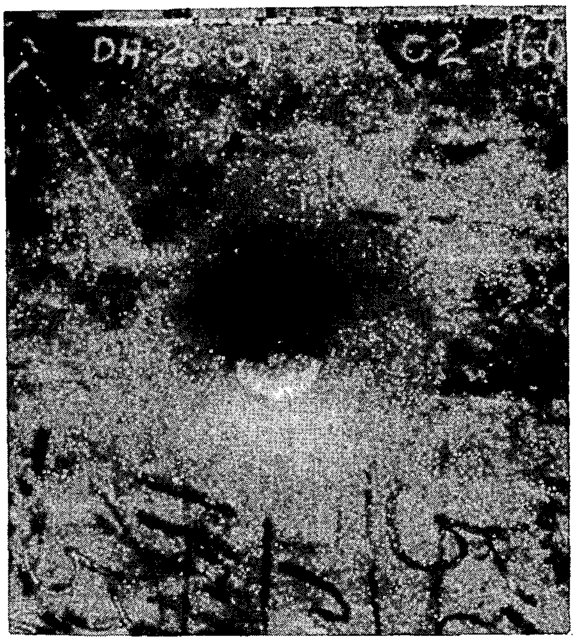
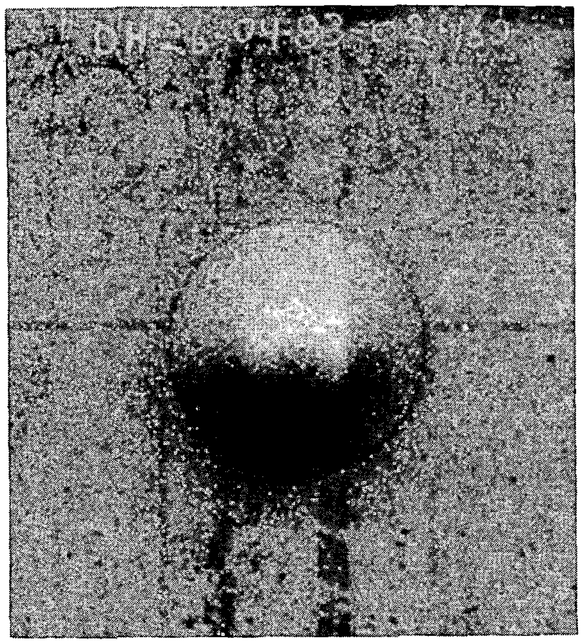
Figure B16: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 16





IMPACT SIDE

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Figure B17: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 17

IMPACT SIDE

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Figure B18: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 18

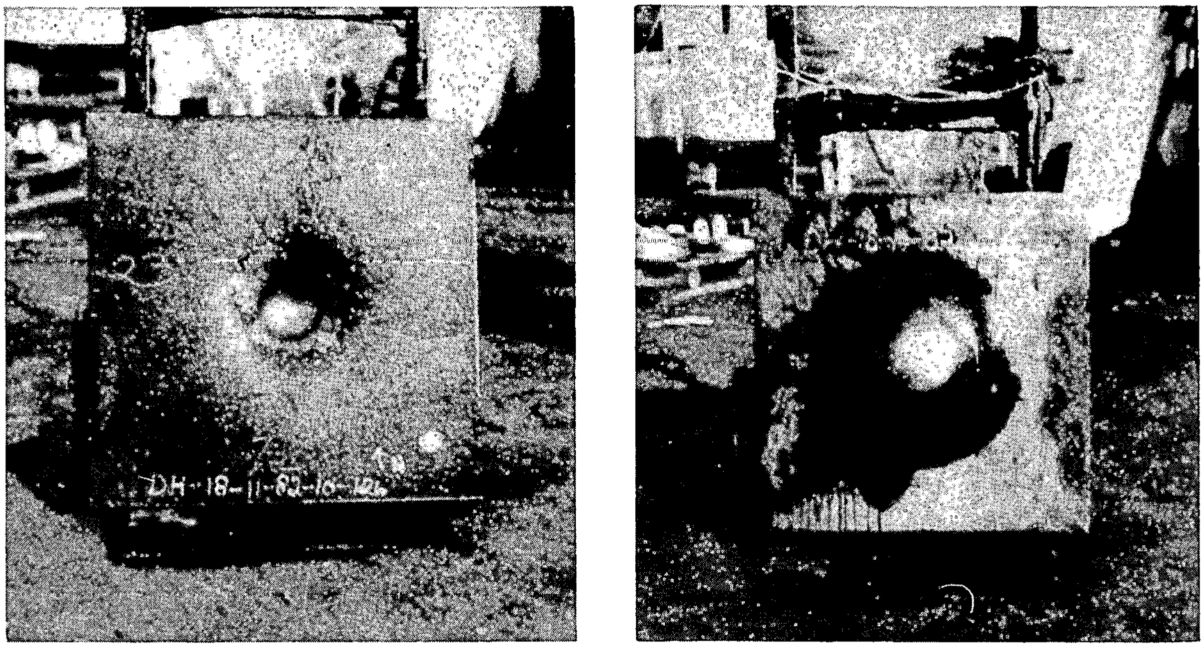

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Figure B19: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 19

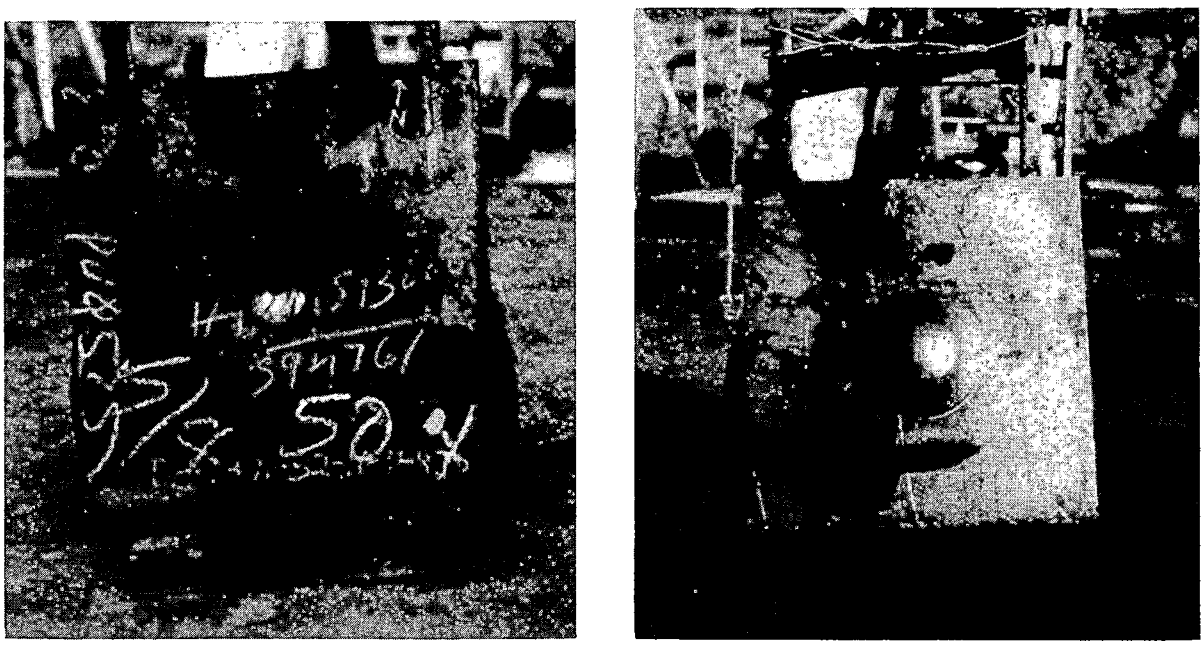

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Figure B20: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 20

NO DATA

NO DATA

IMPACT SIDE

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Figure B21: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 21

PHOTO MISSING

PHOTO MISSING

IMPACT SIDE

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Figure B22: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 22

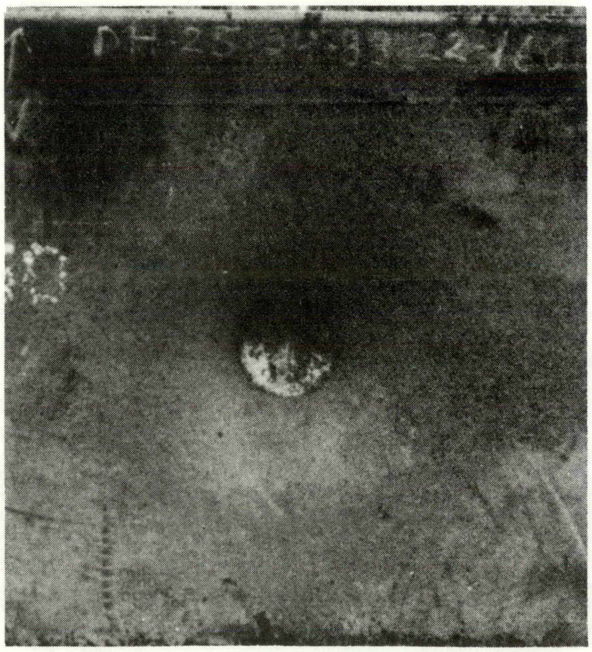
PHOTO MISSING

PHOTO MISSING

IMPACT SIDE

BOTTOM SIDE

Figure B23: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 23



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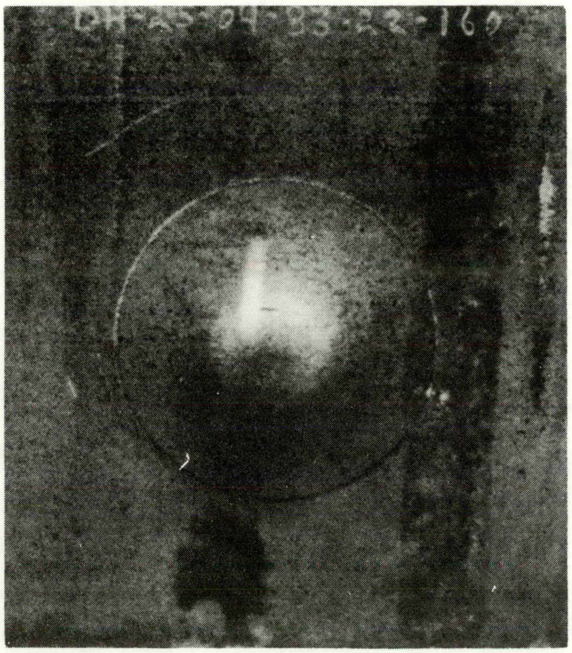

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Figure B24: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 24

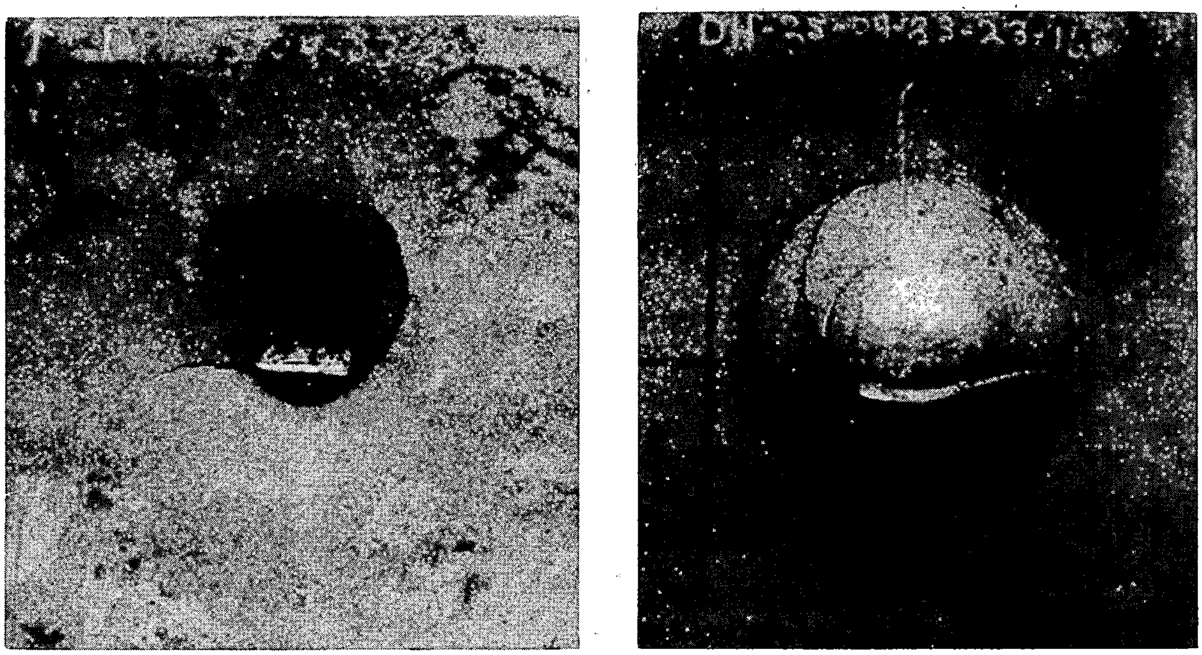

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Figure B25: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 25

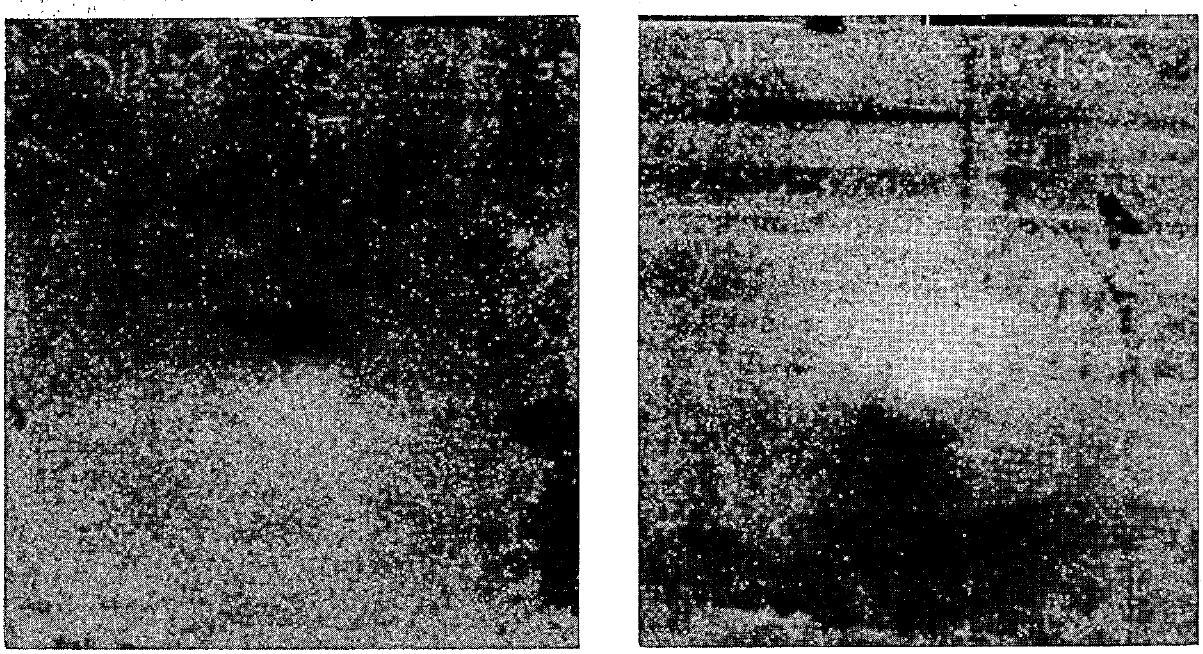

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Figure B26: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 26

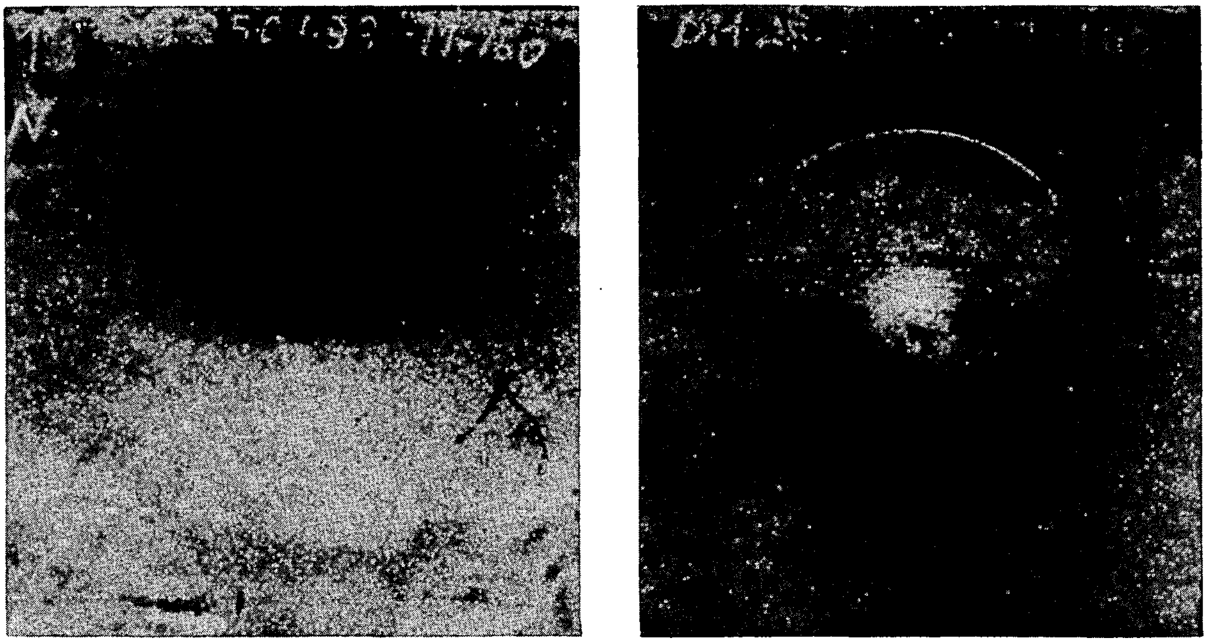

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Figure B27: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 27

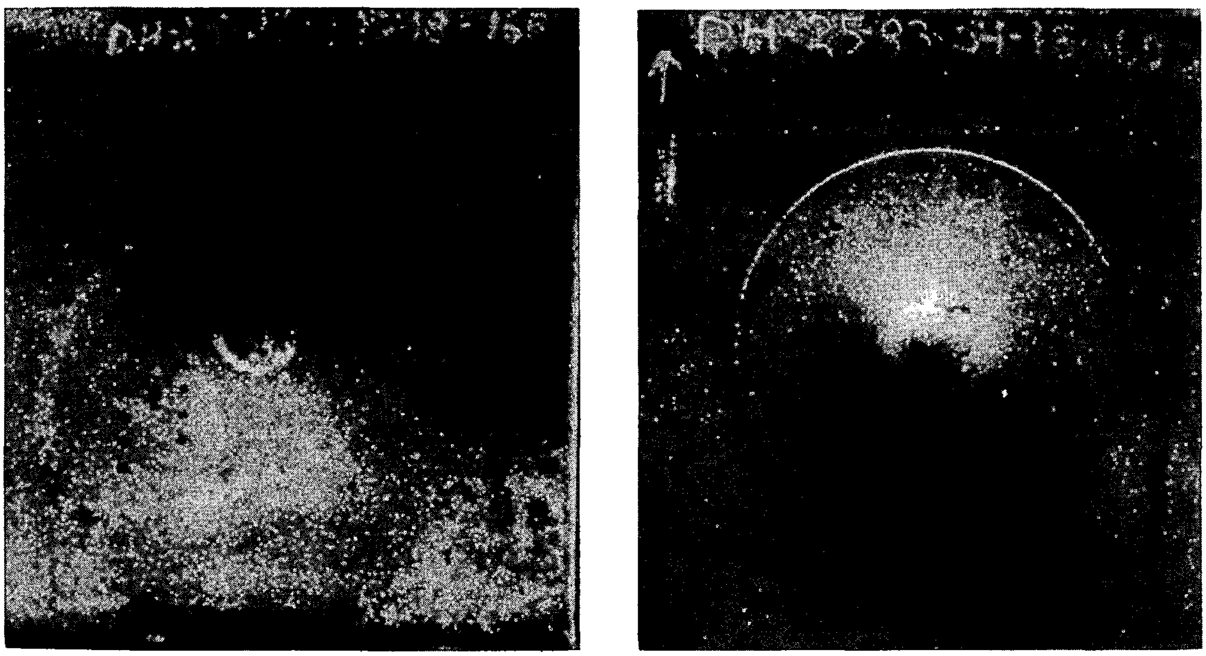

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Figure B28: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 28

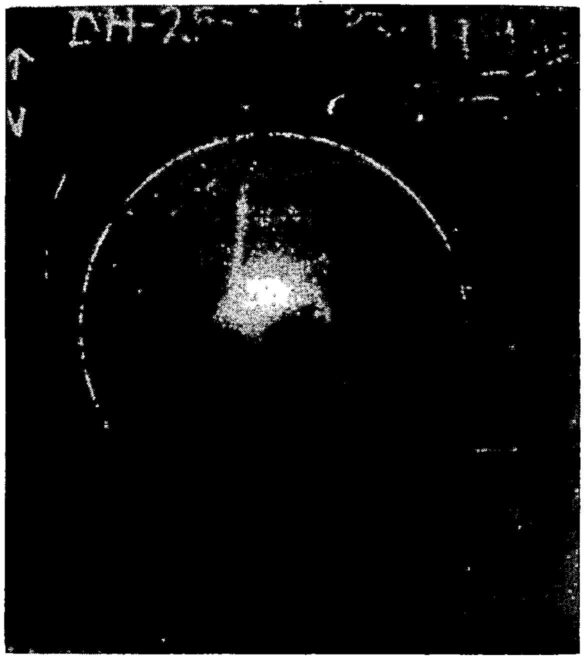

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Figure B29: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 29

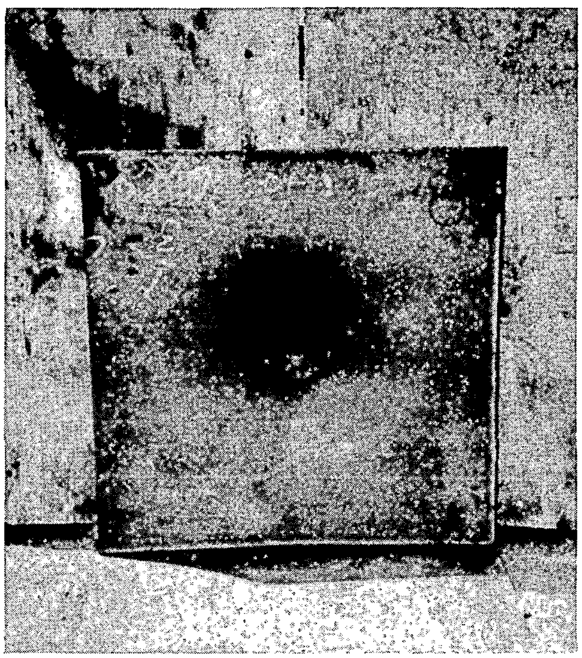

PHOTO MISSING

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Figure B30: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 30

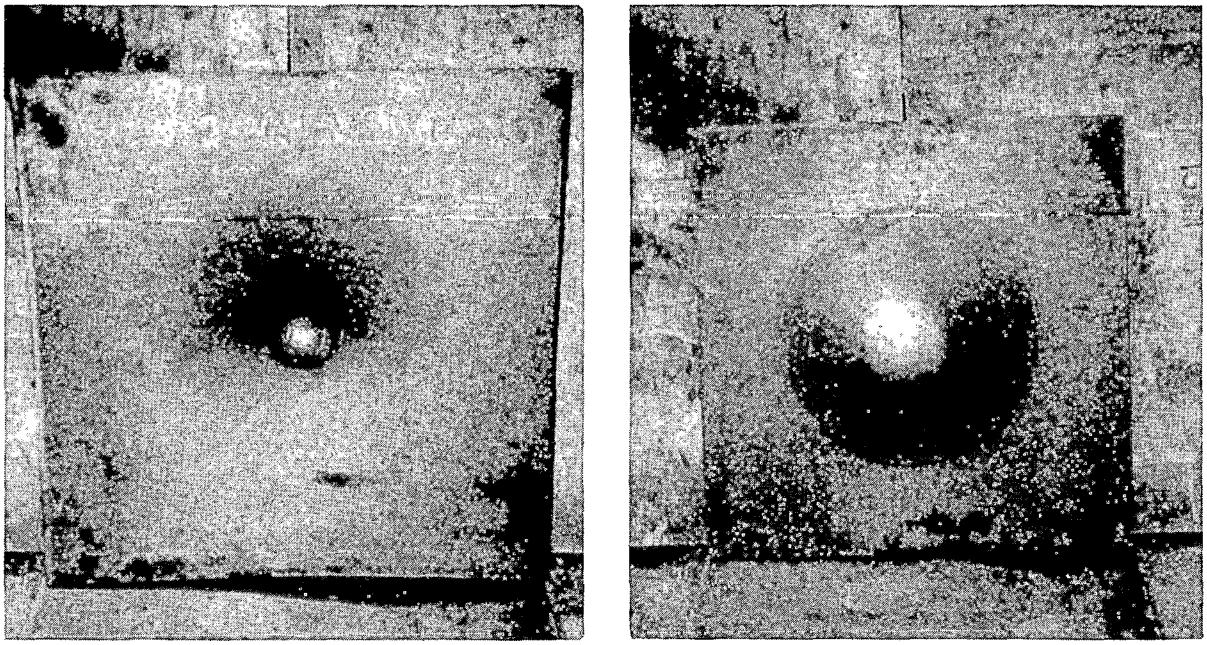

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Figure B31: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 31

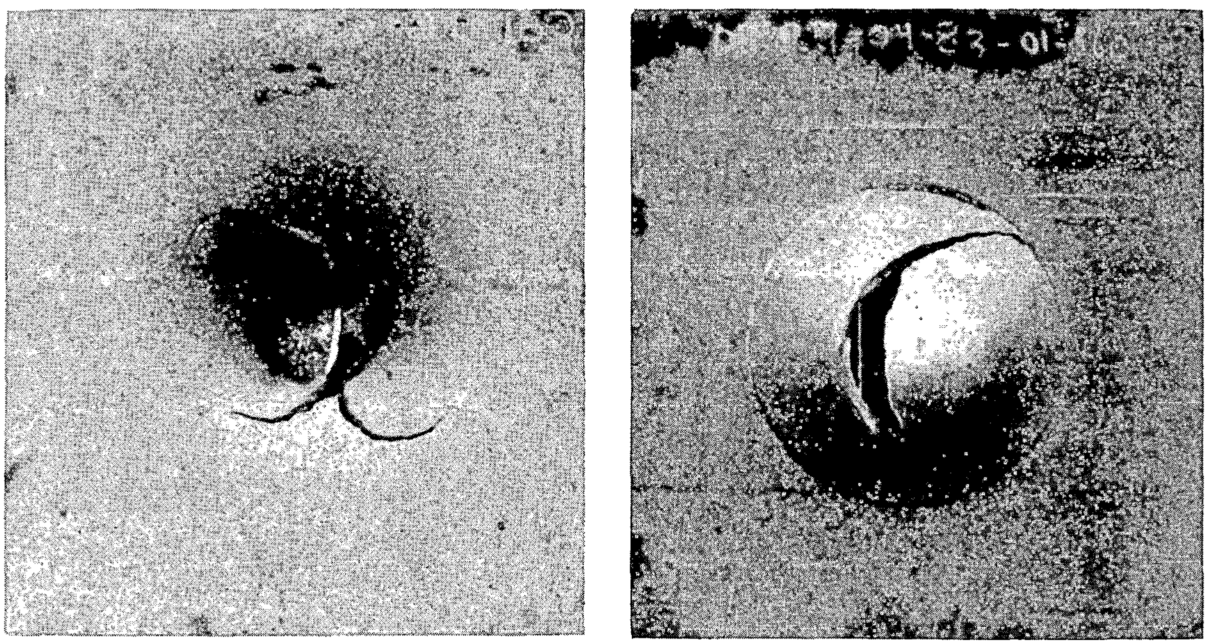

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Figure B32: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 32

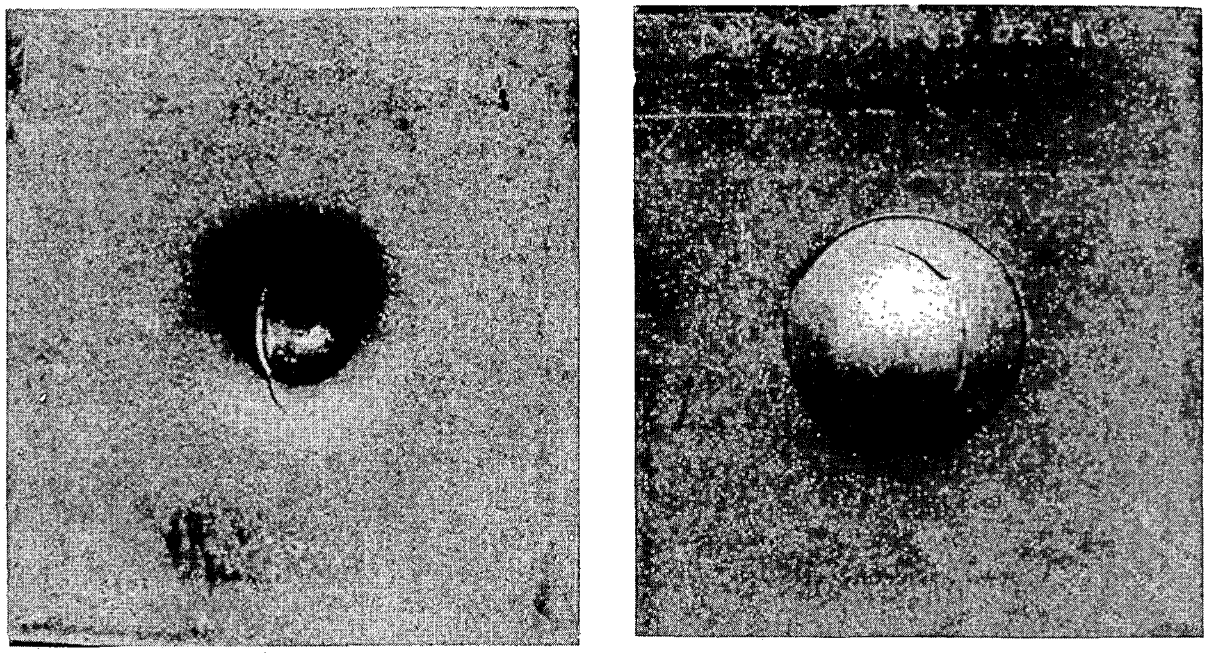

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Figure B33: Steel Plate Response to 5.5 Inch Hemispherical Tup in Test Number 33

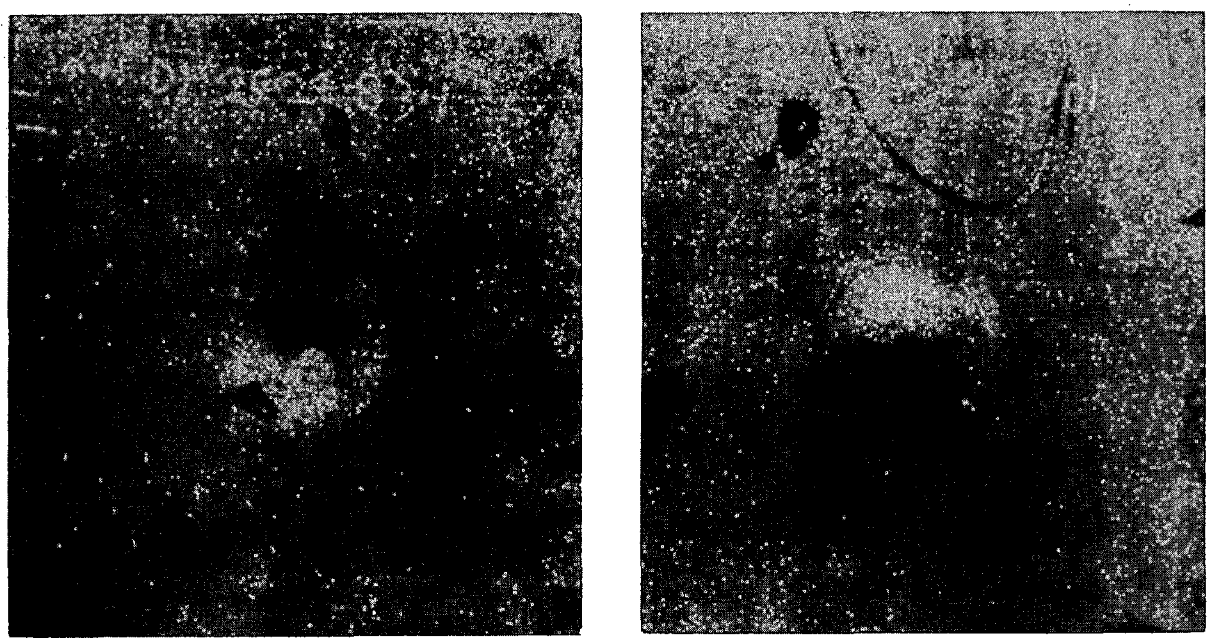

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Figure B34: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 34

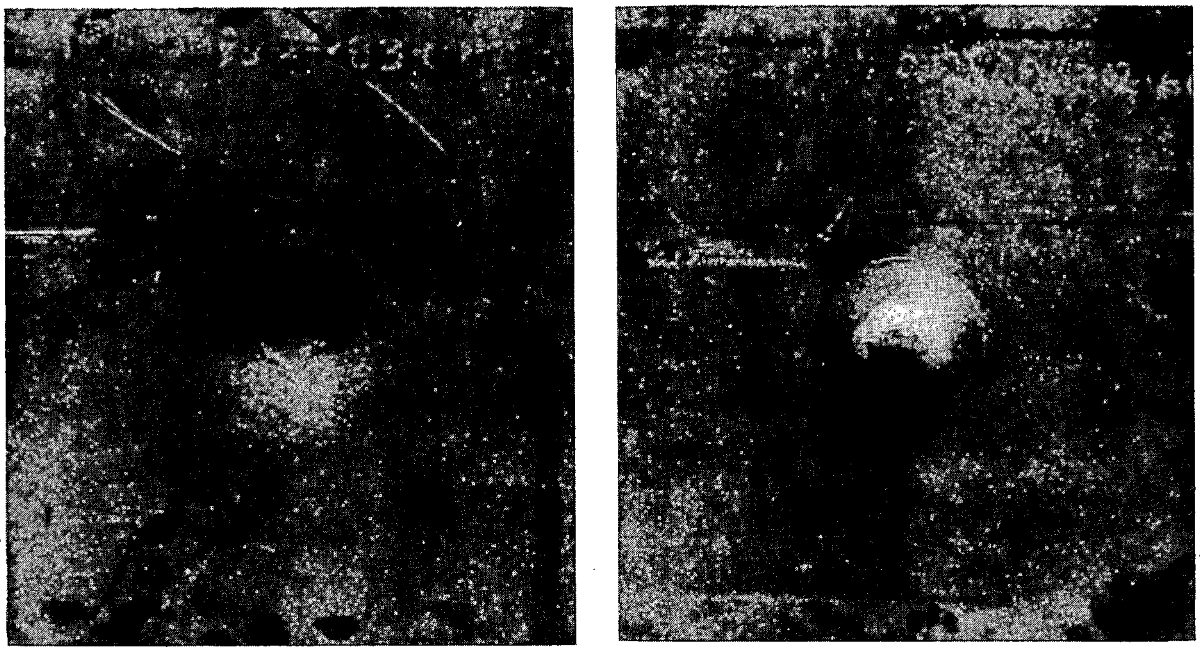

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Figure B35: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 35

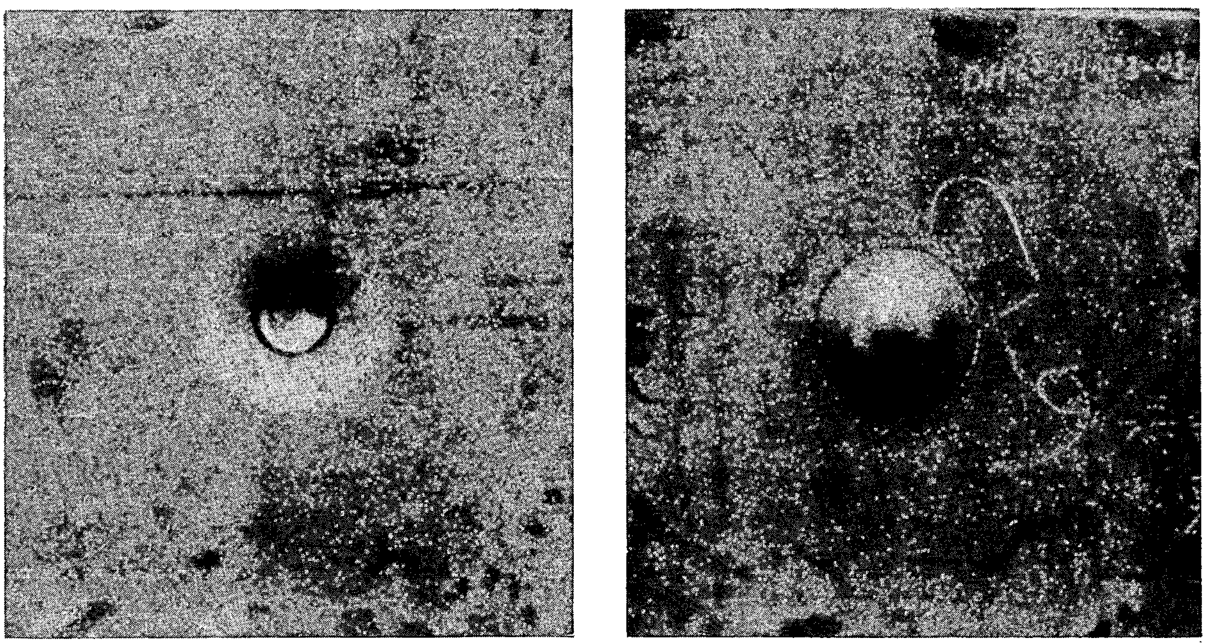

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Figure B36: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 36

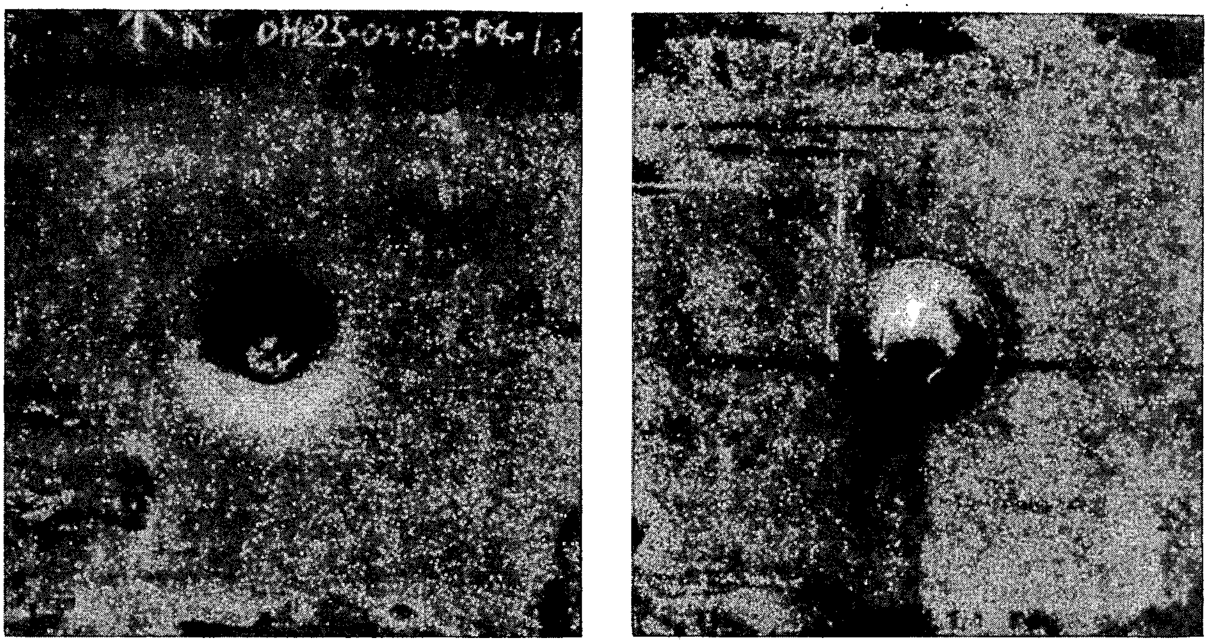

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Figure B37: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 37

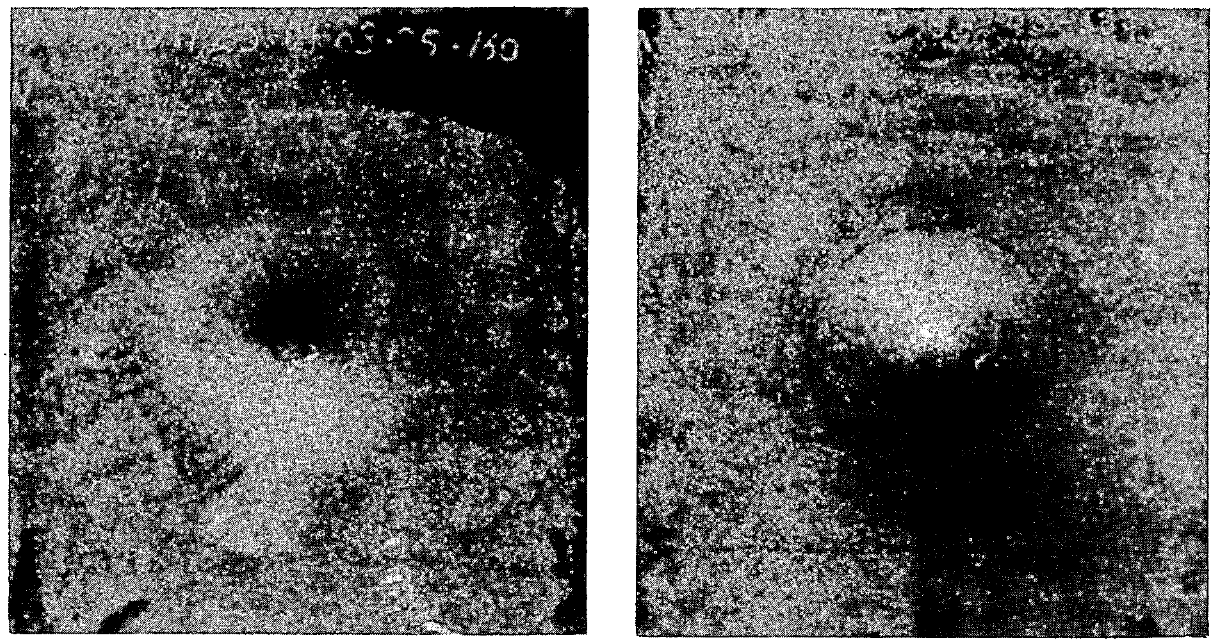

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Figure B38: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 38

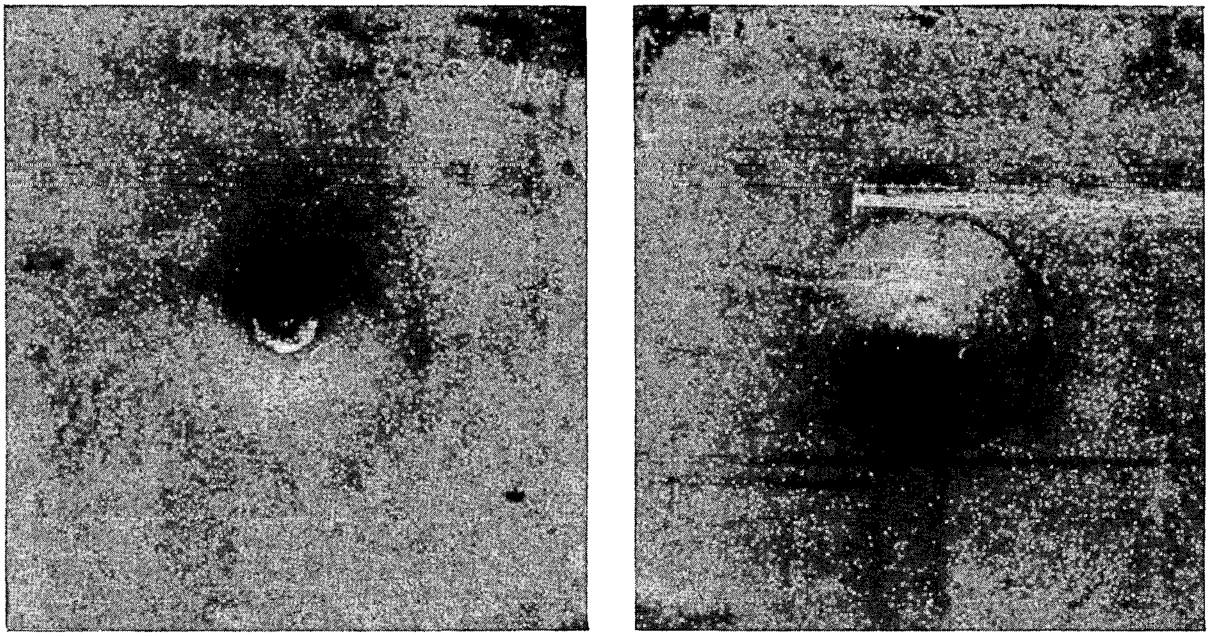

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Figure B39: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 39

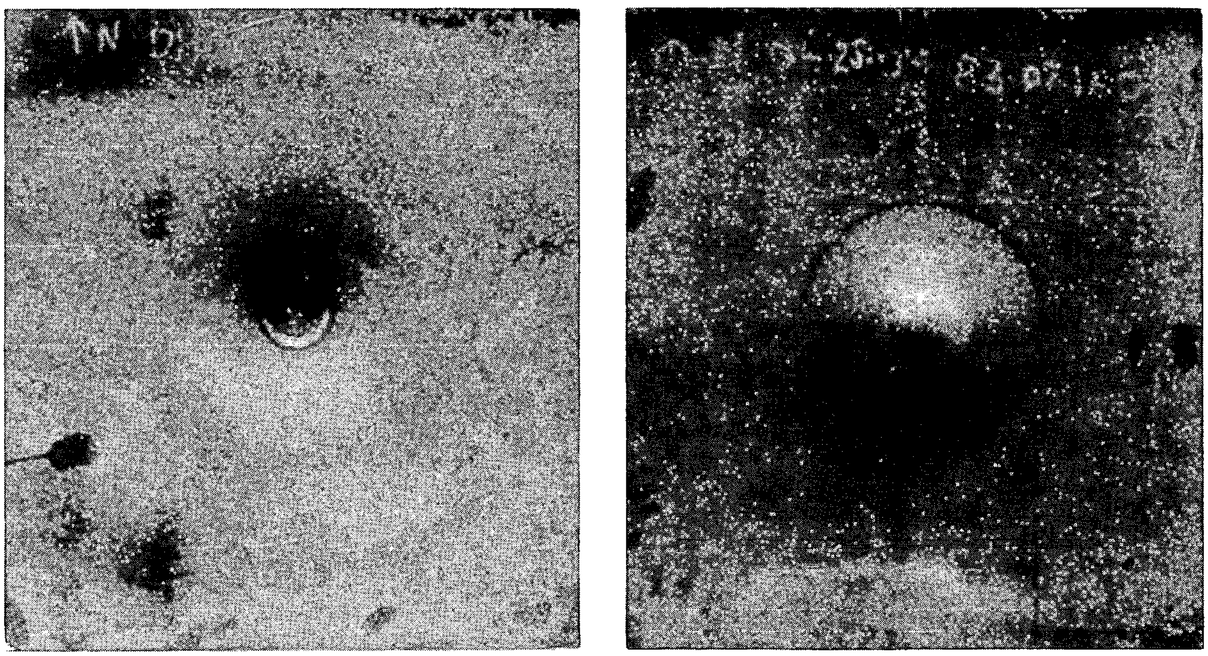

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Figure B40: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 40

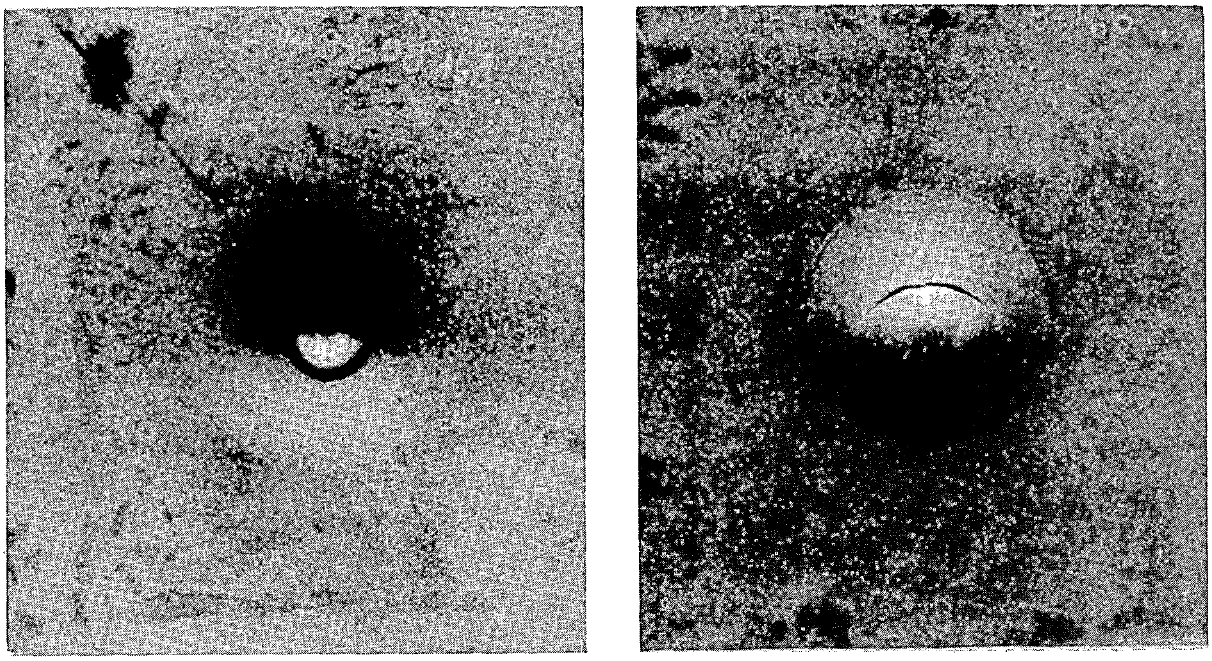

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Figure B41: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 41

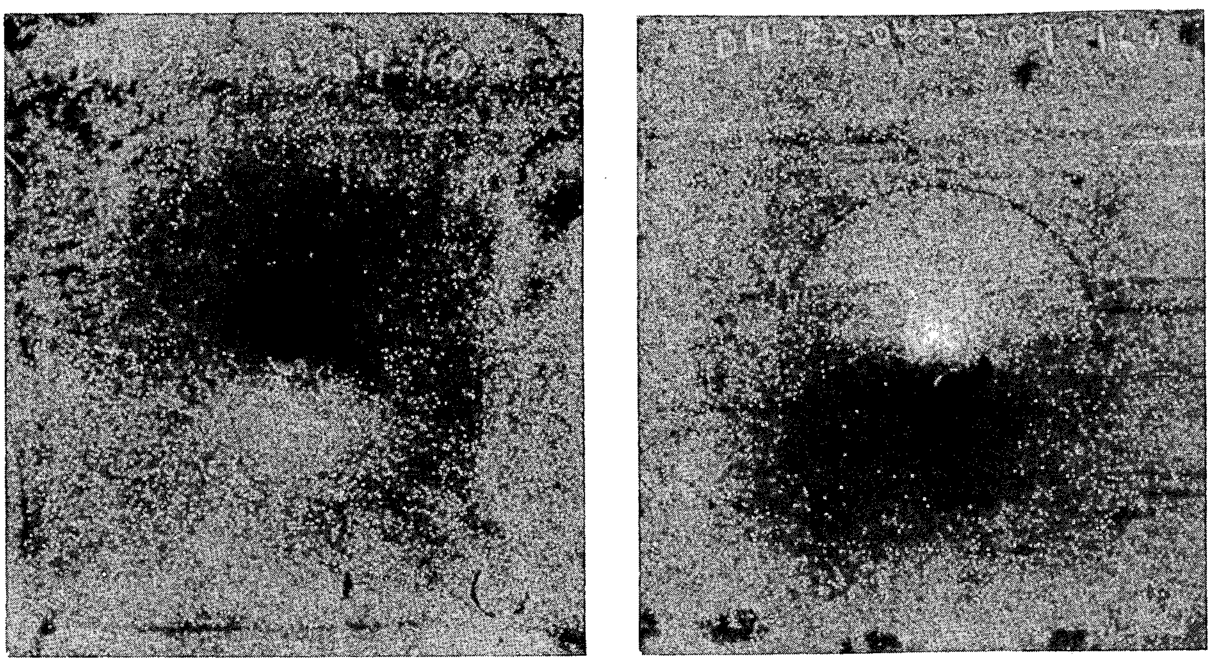

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Figure B42: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 42

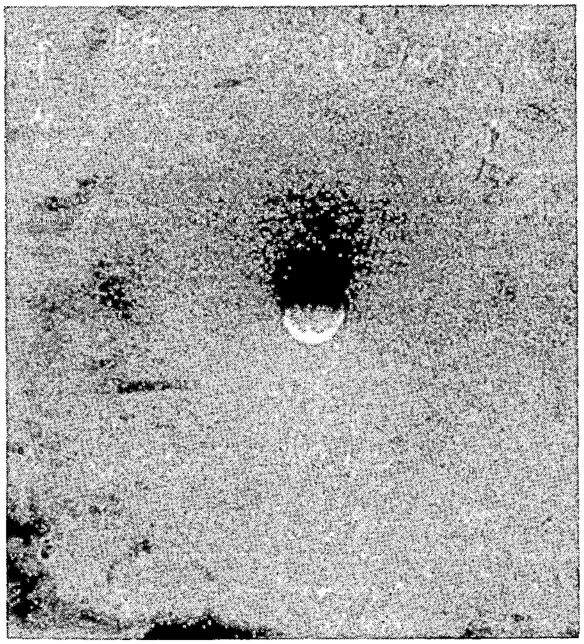

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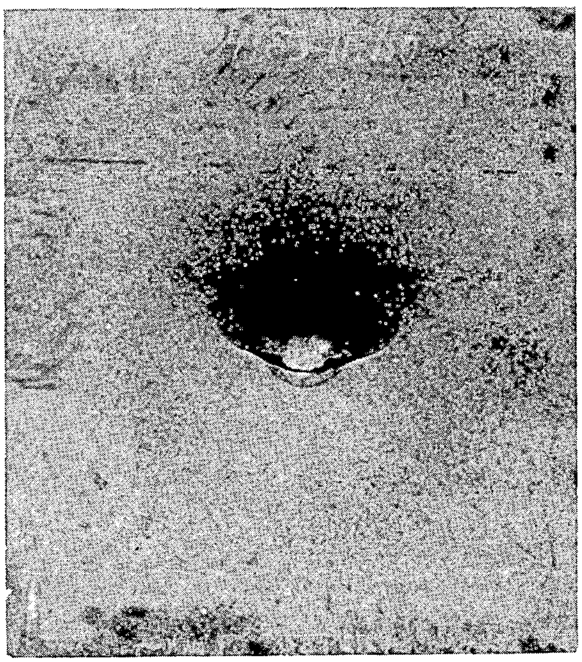
Figure B43: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 43



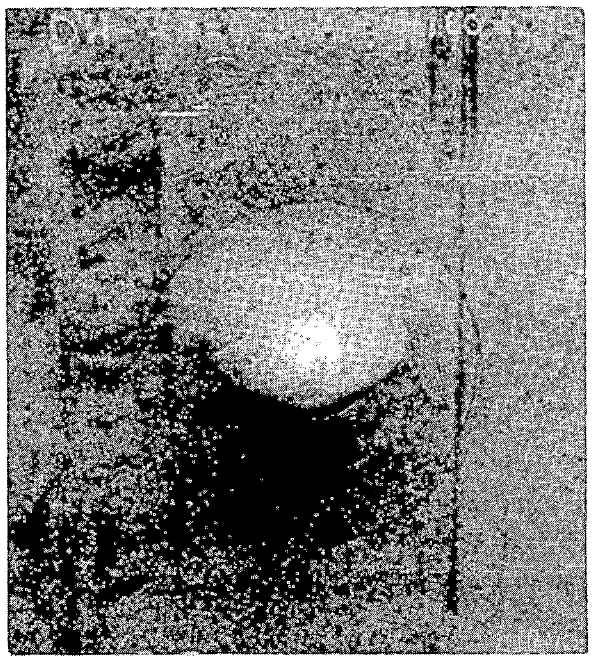


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Figure B44: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 44

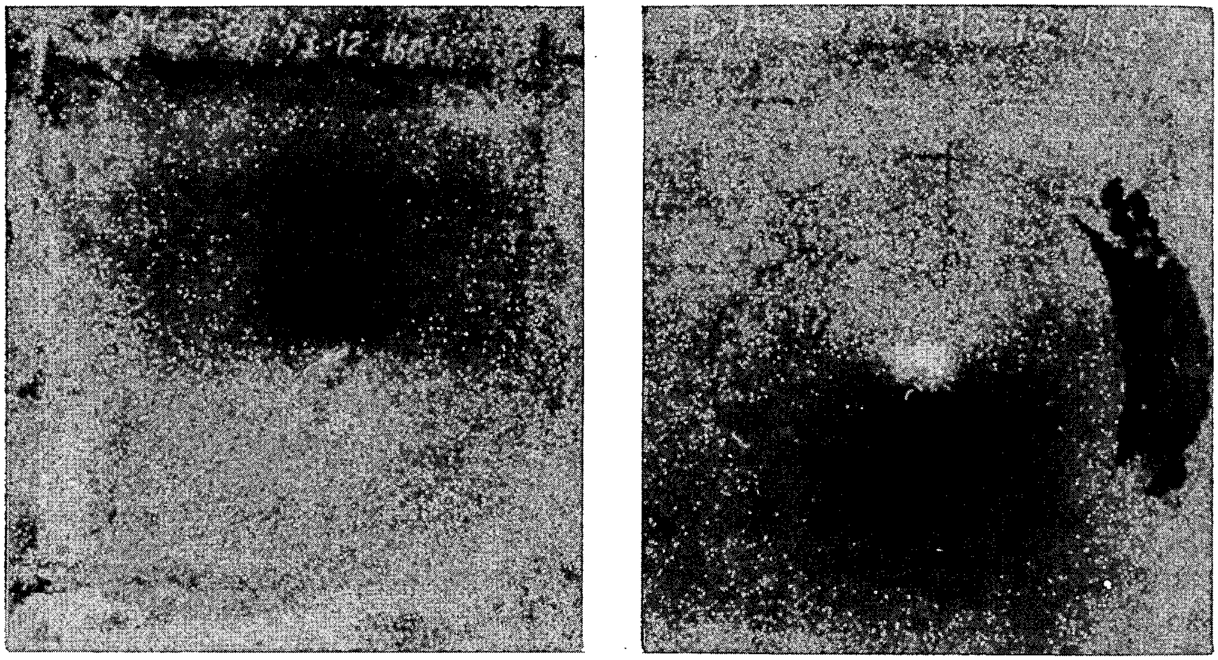

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Figure B45: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 45

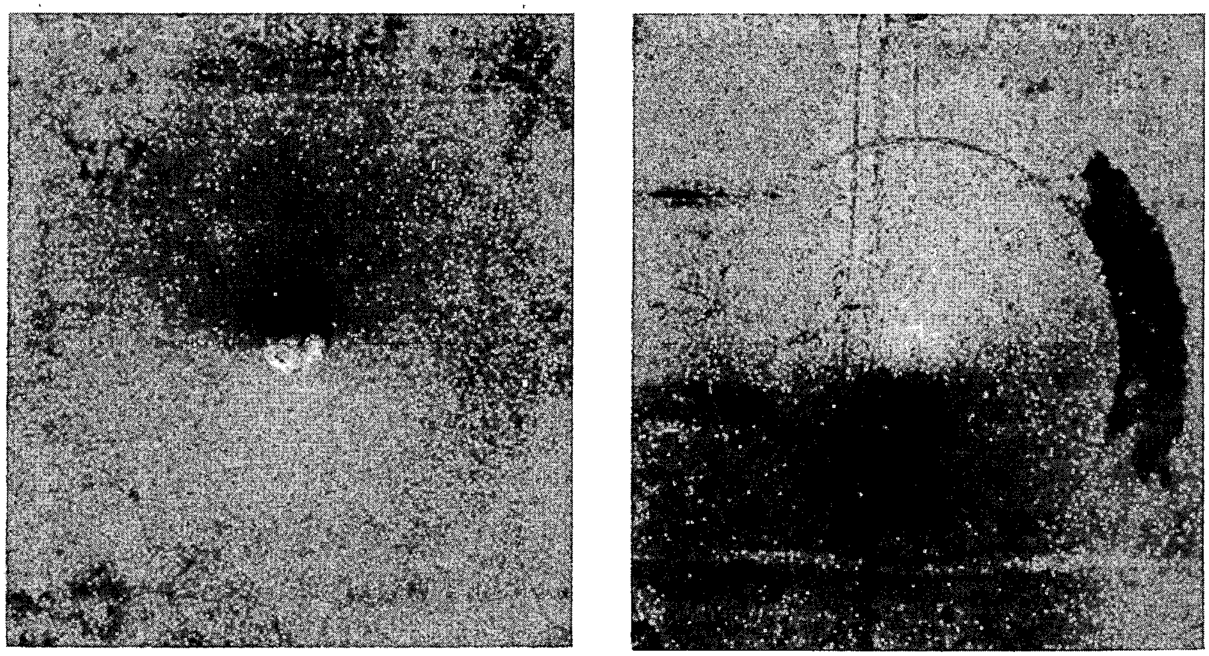

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Figure B46: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 46

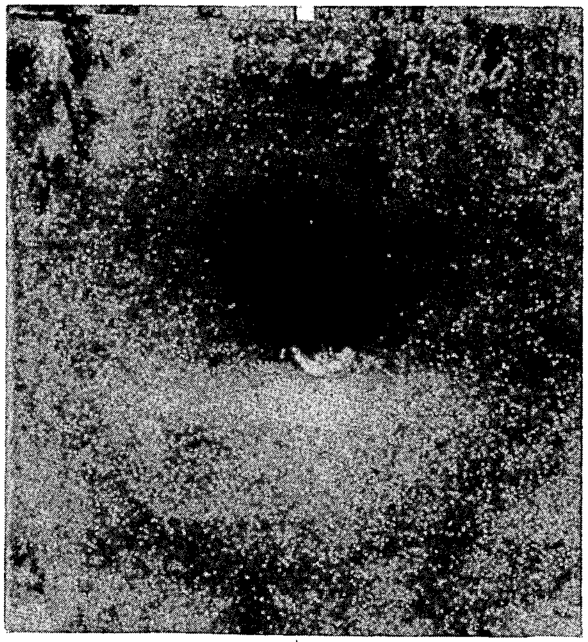

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Figure B47: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 47

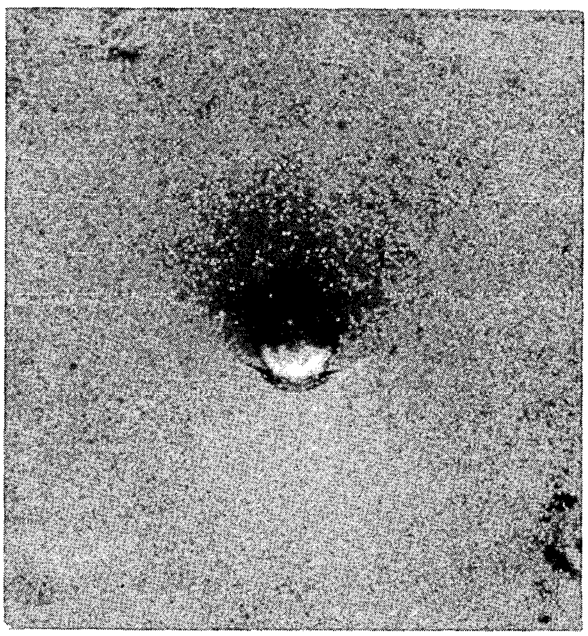

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Figure B48: Steel Plate Response to 3.75 Inch Hemispherical Tup in Test Number 48

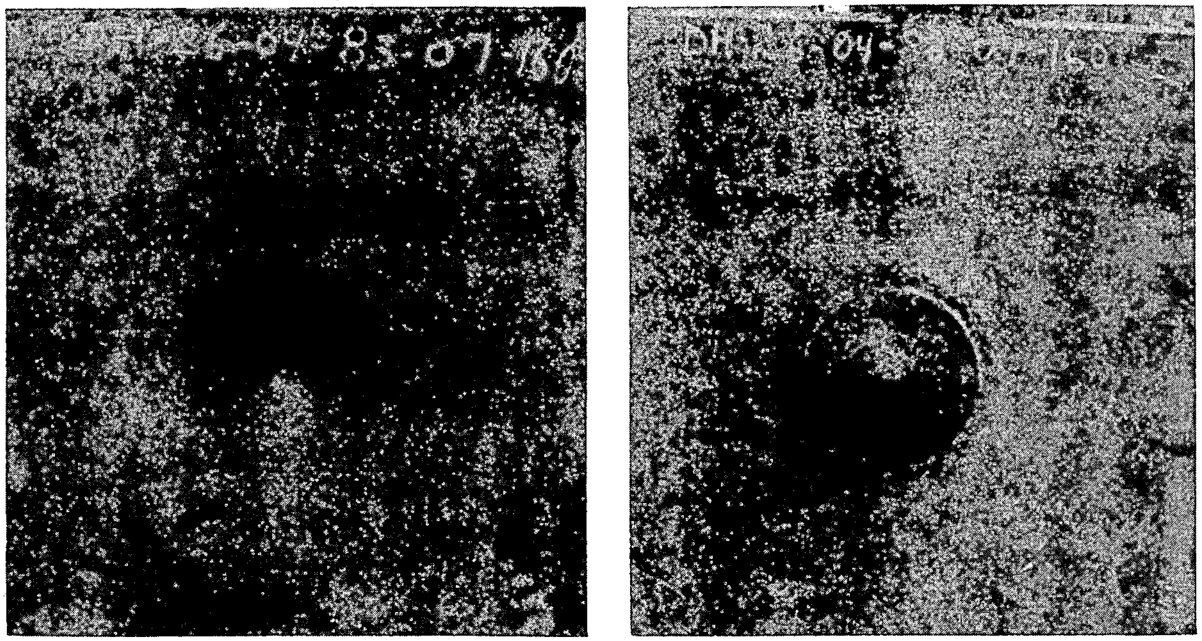

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Figure B49: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 49

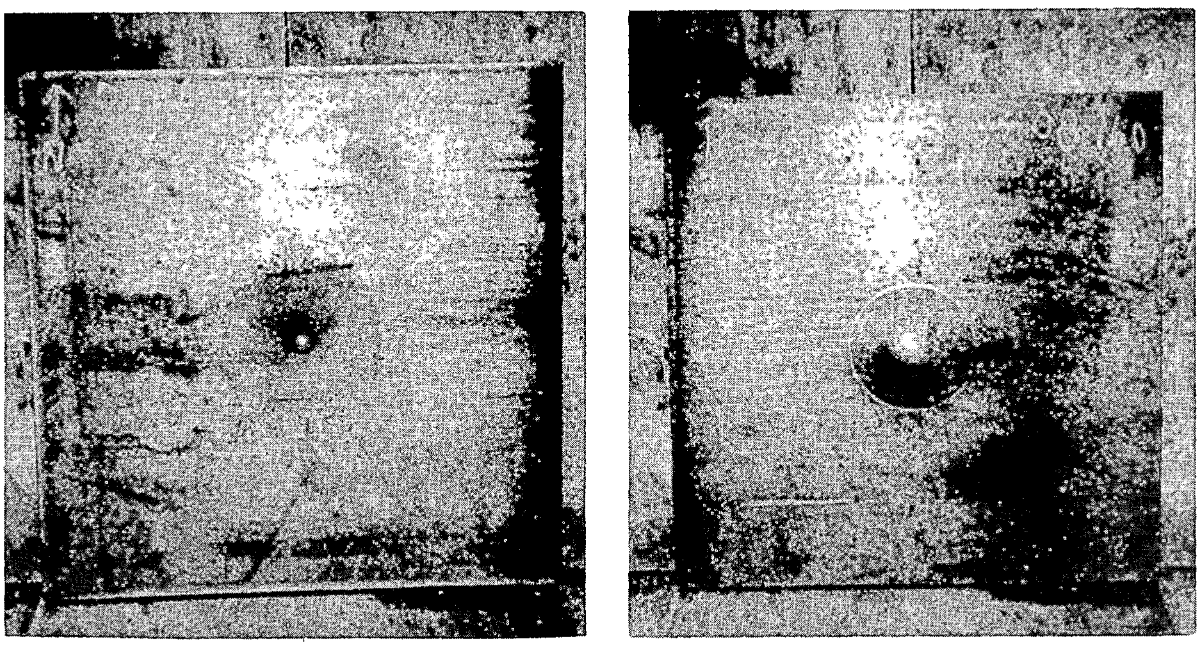

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Figure B50: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 50

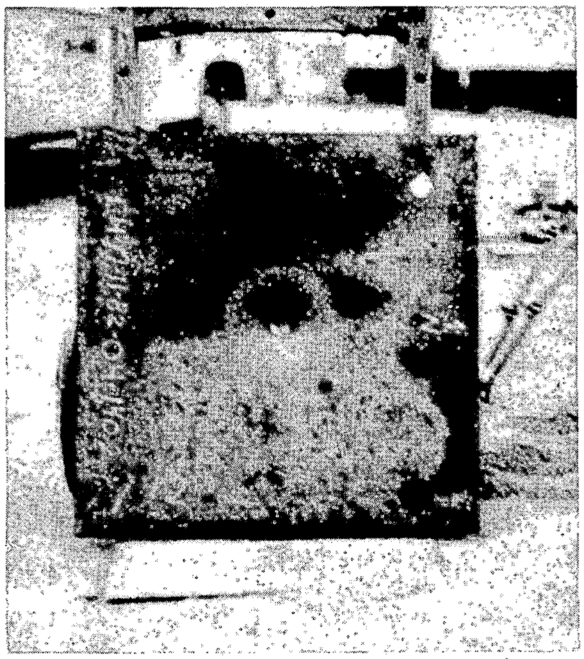

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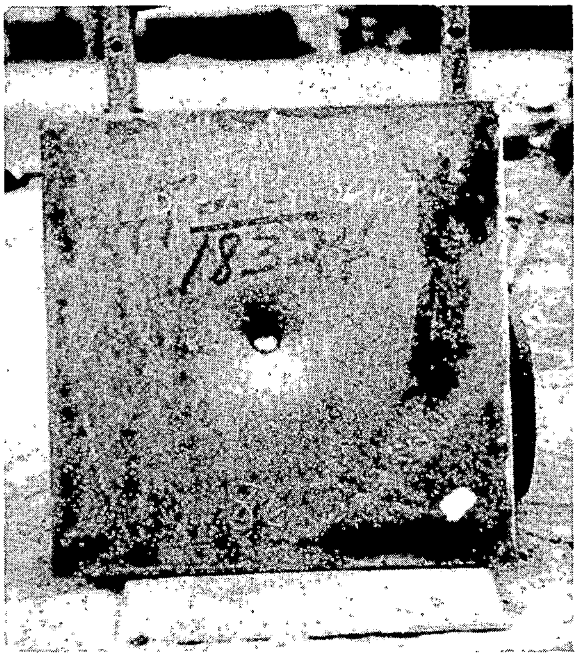
Figure B51: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 51

IMPACT SIDE

BOTTOM SIDE

Figure B52: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 52



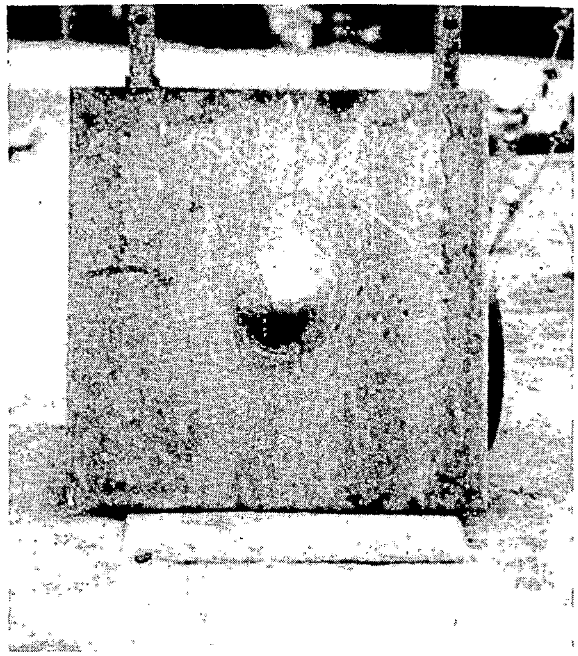


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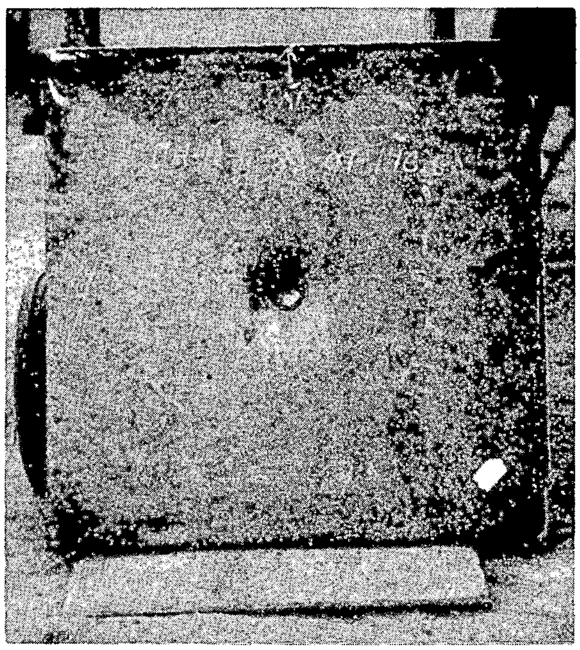
Figure B53: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 53



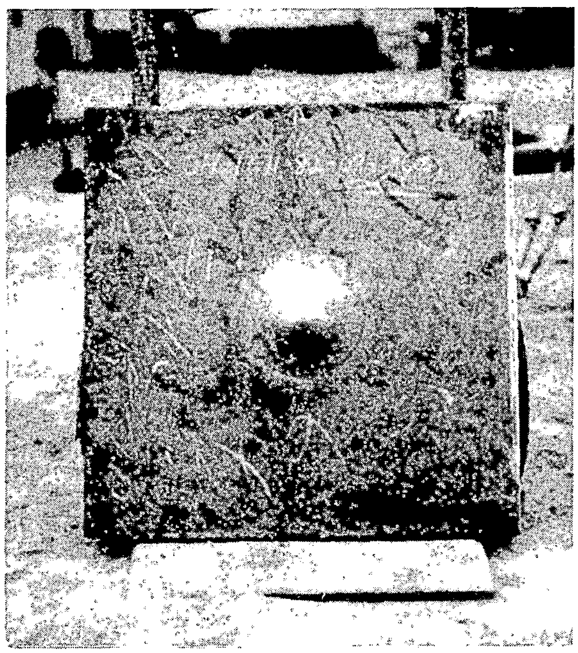


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Figure B54:: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 54

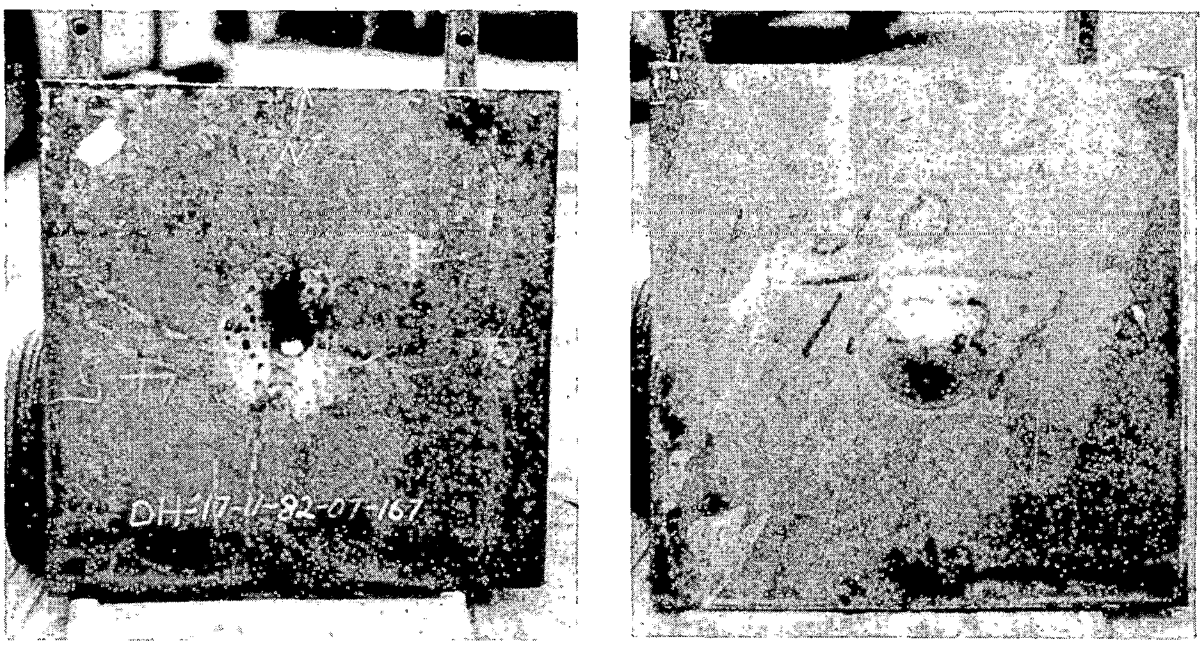

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Figure B55: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 55

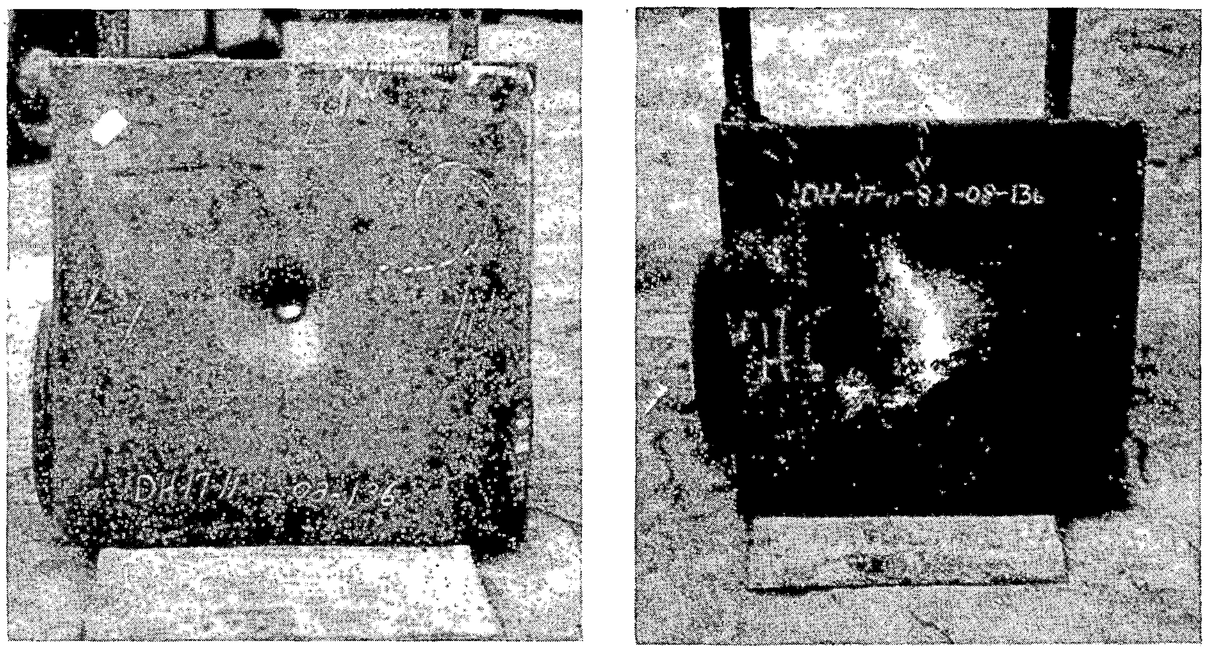

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Figure B56: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 56

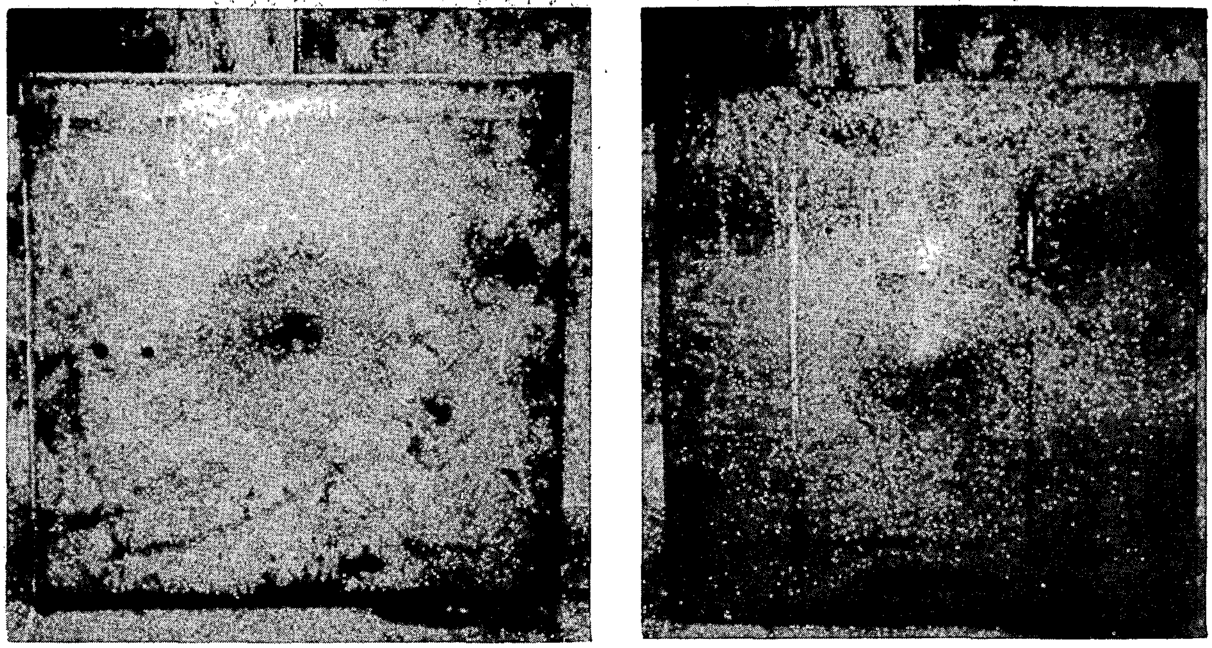

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Figure B57: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 57

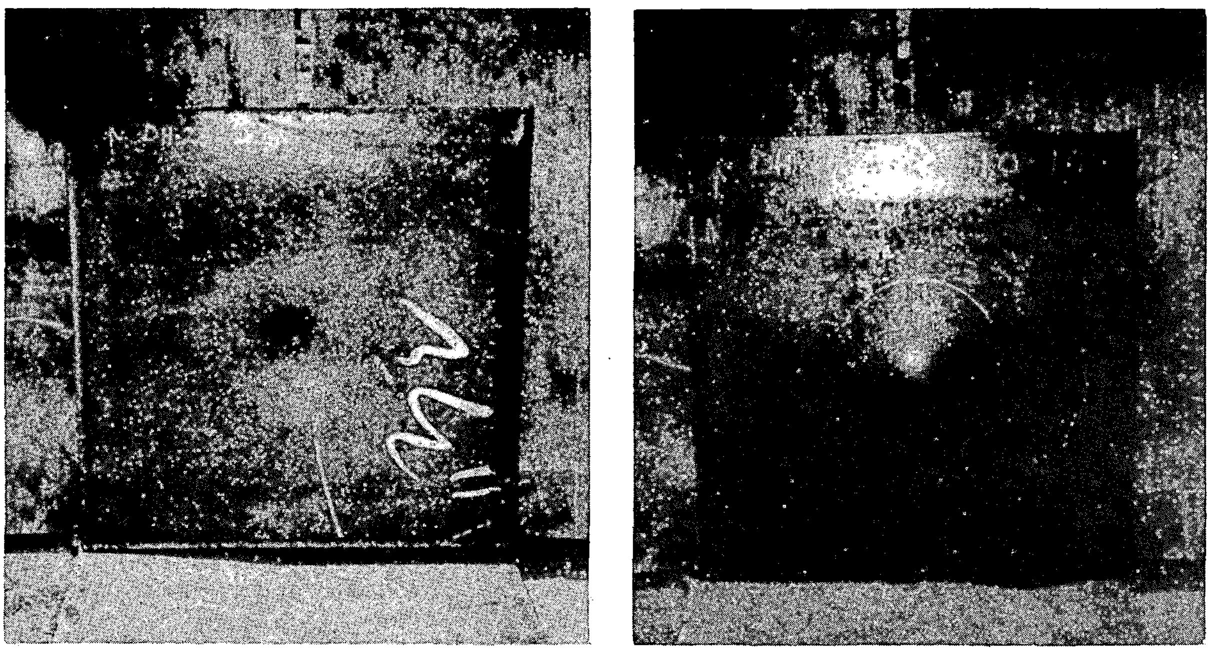

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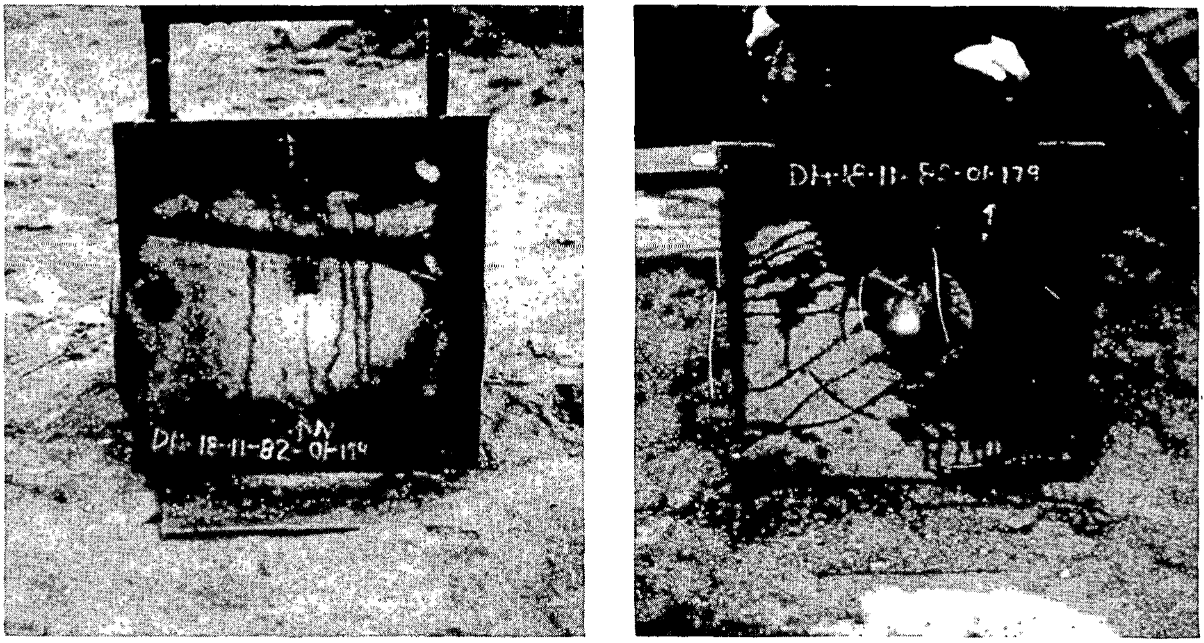
Figure B58: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 58

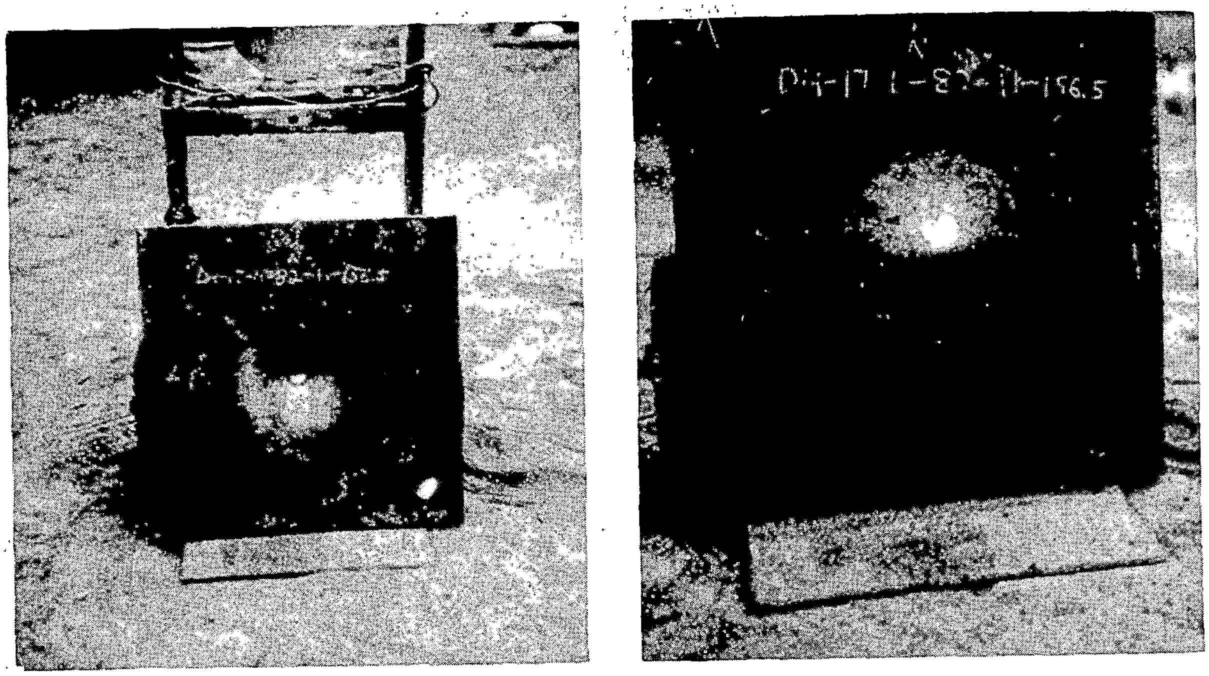


IMPACT SIDE BOTTOM SIDE

Figure B59: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 59

IMPACT SIDE BOTTOM SIDE

Figure B60: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 60



IMPACT SIDE HEMISPHERICAL

Figure B61: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 61

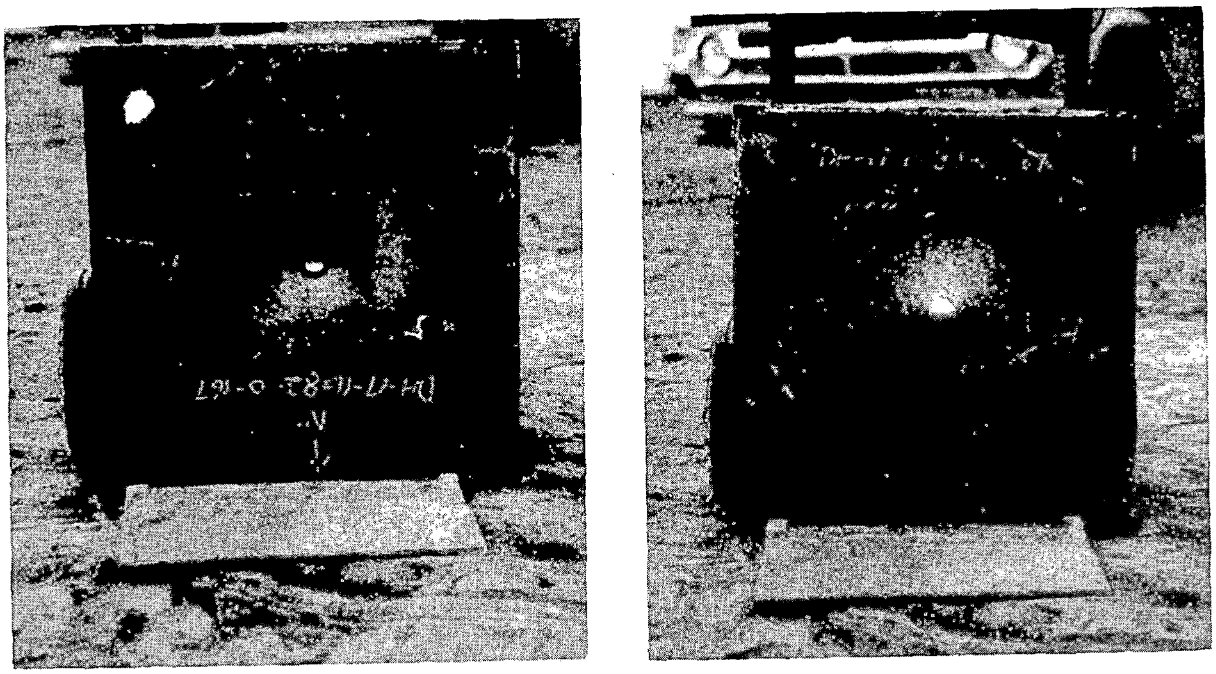


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Figure B62: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 62

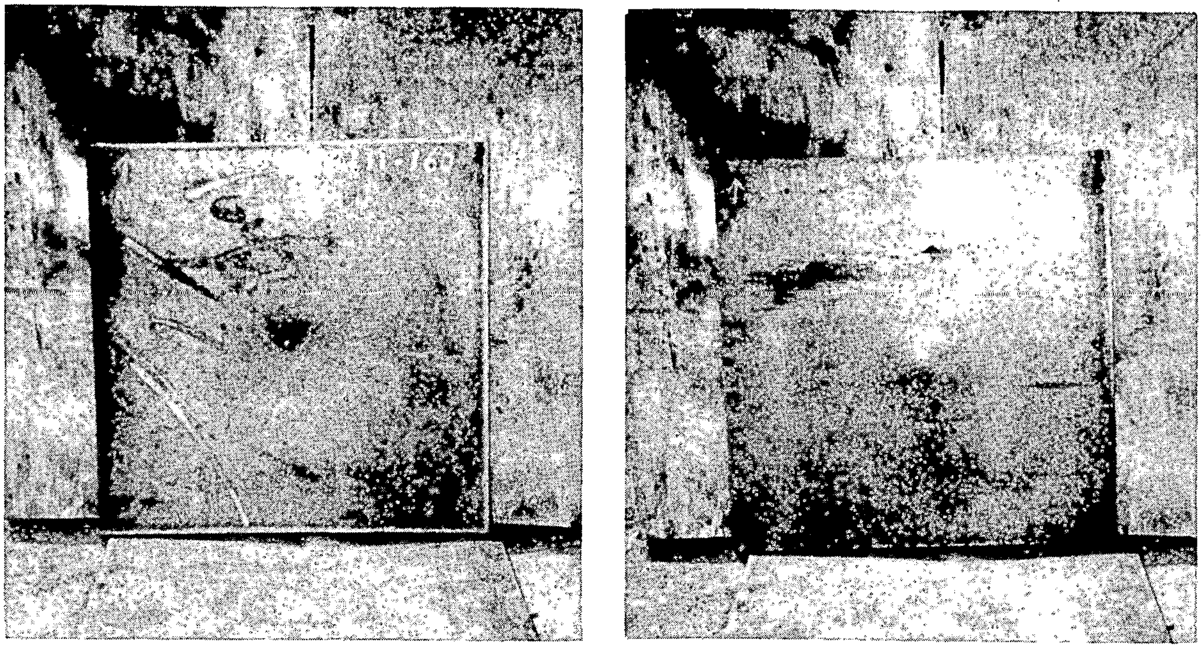

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Figure B63: Steel Plate Response to 2 Inch Hemisphereical Tup in Test Number 63

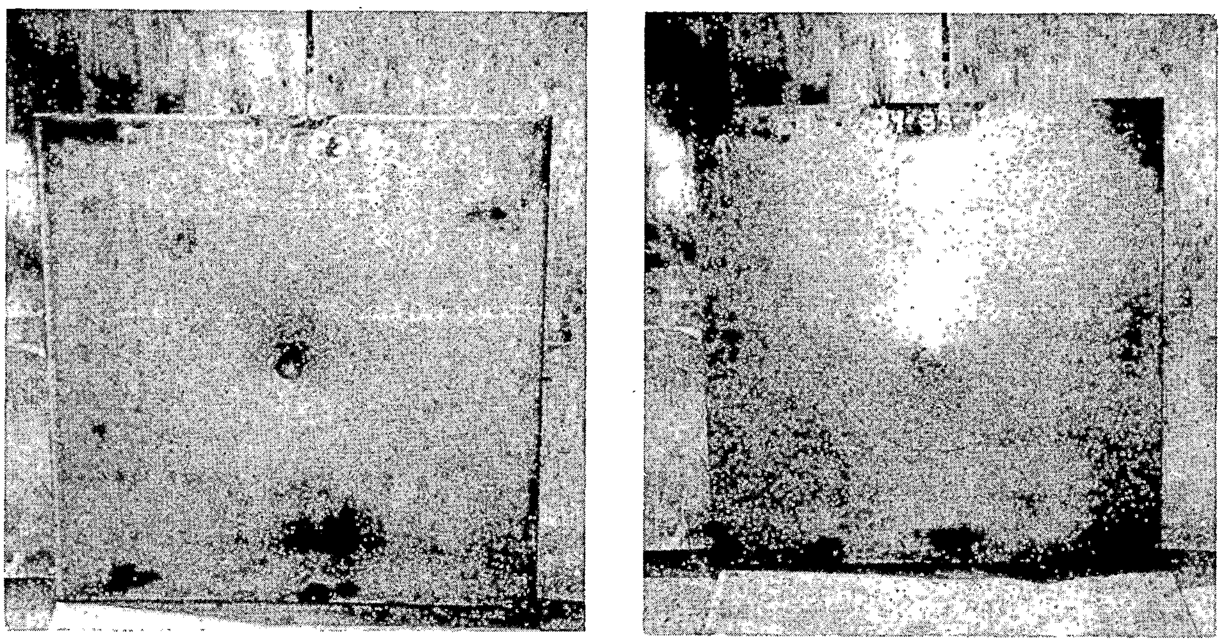

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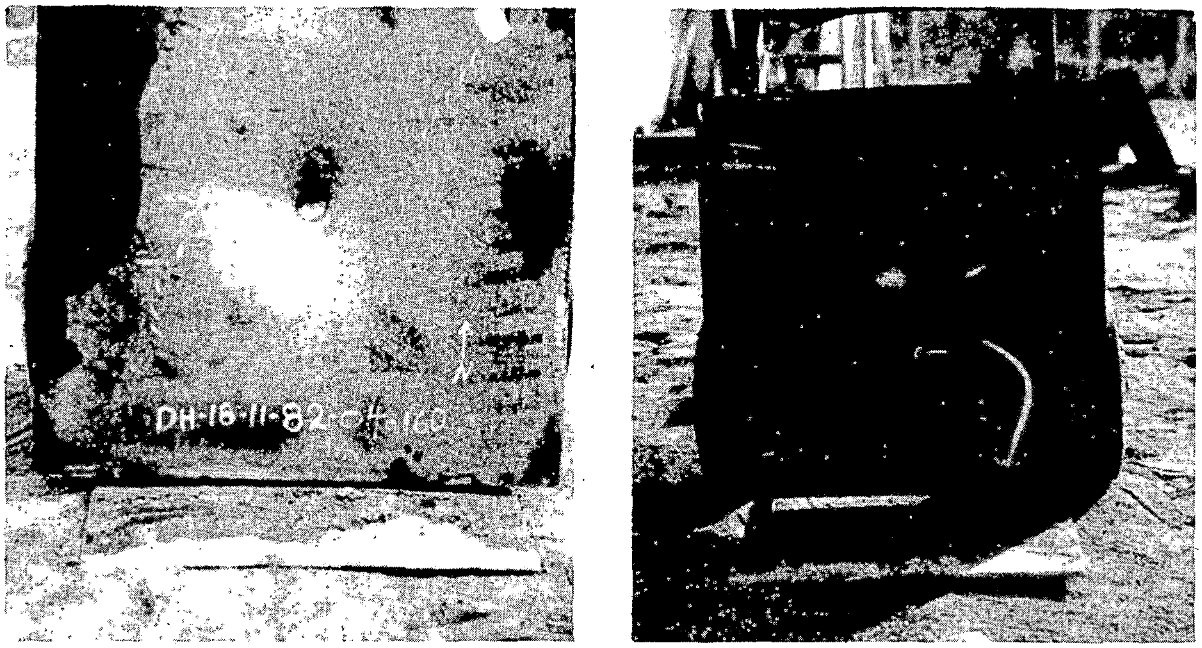
Figure B64: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 64



IMPACT SIDE BOTTOM SIDE

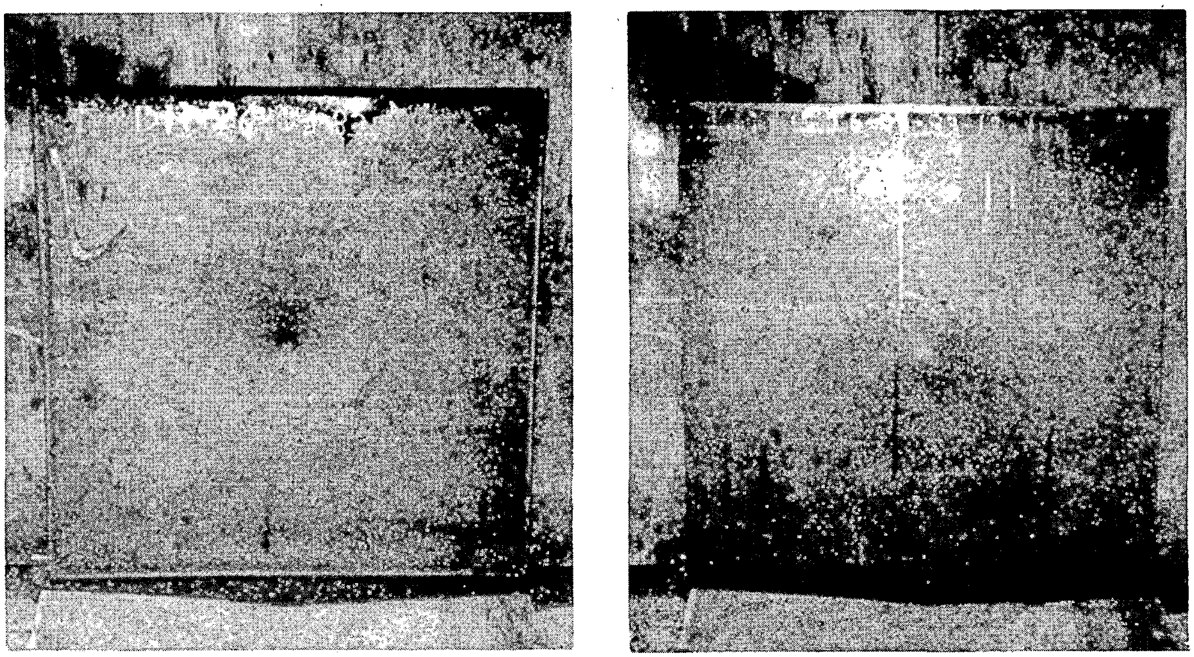
Figure B65: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 65

IMPACT SIDE BOTTOM SIDE

Figure B66: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 66

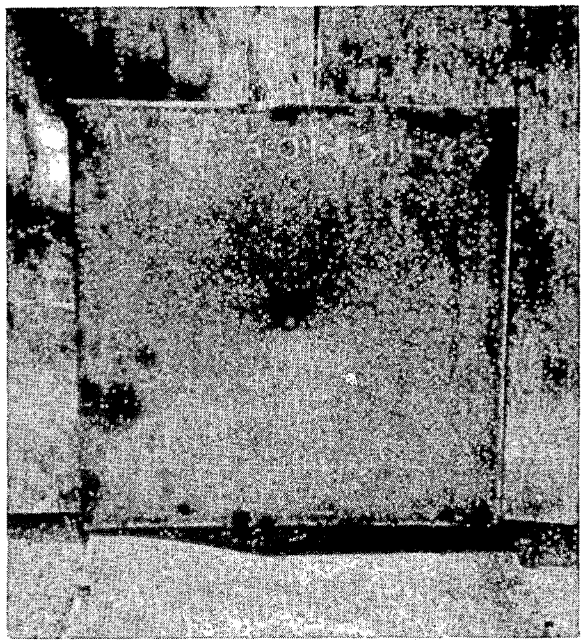
IMPACT SIDE BOTTOM SIDE

Figure B67: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 67



IMPACT SIDE BOTTOM SIDE

Figure B68: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 68

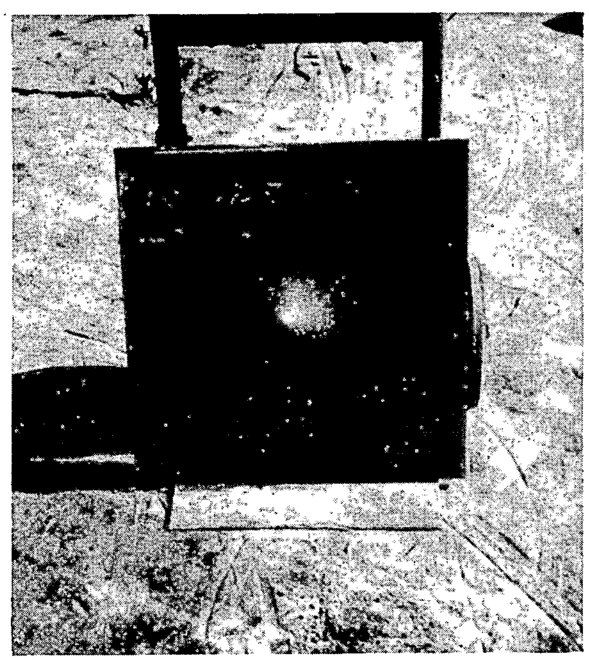


IMPACT SIDE

BOTTOM SIDE

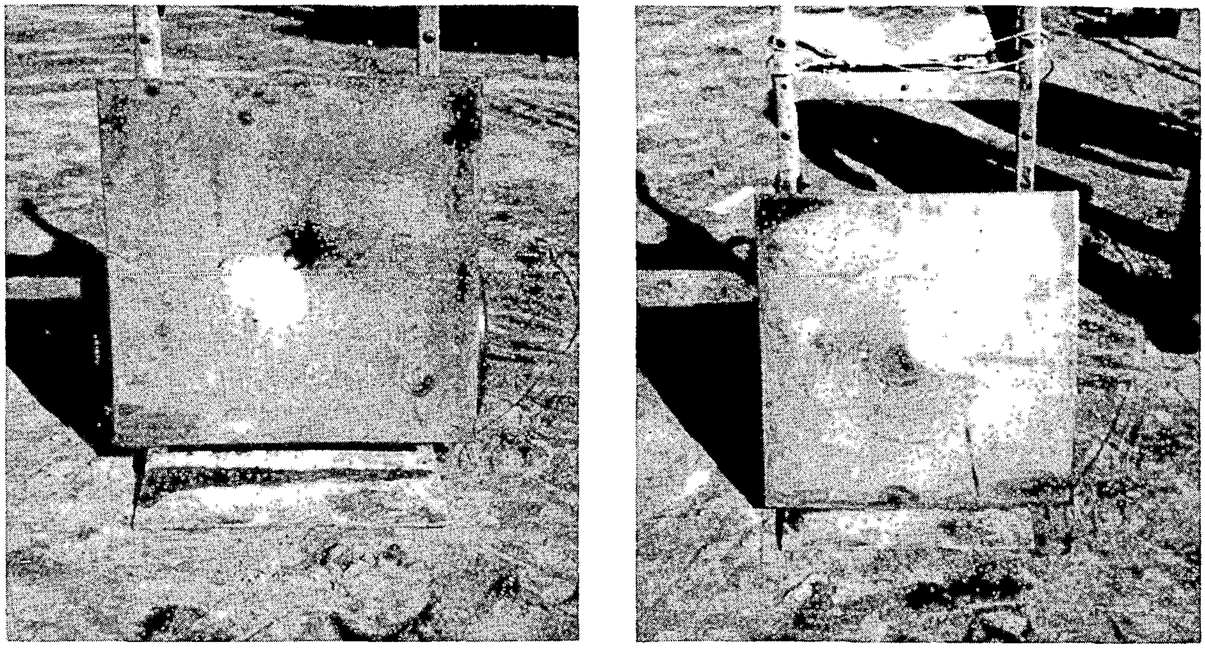
Figure B69: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 69

IMPACT SIDE



BOTTOM SIDE

Figure B70: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 70

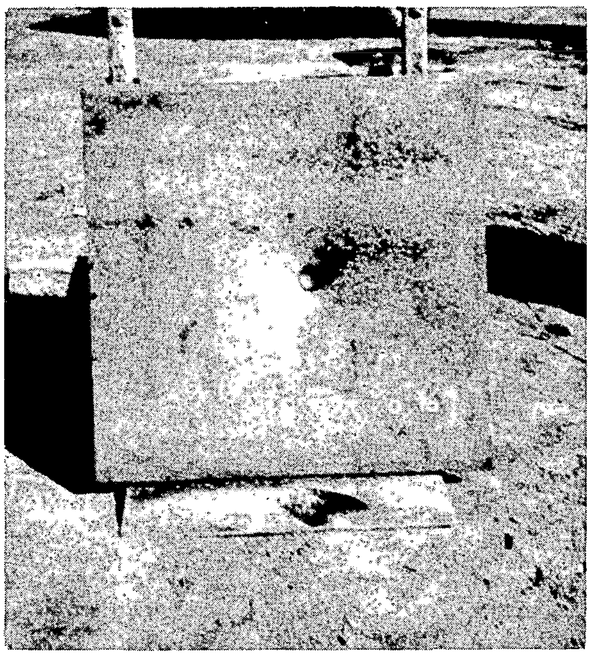


IMPACT SIDE BOTTOM SIDE

Figure B71: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 71

IMPACT SIDE BOTTOM SIDE

Figure B72: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 72



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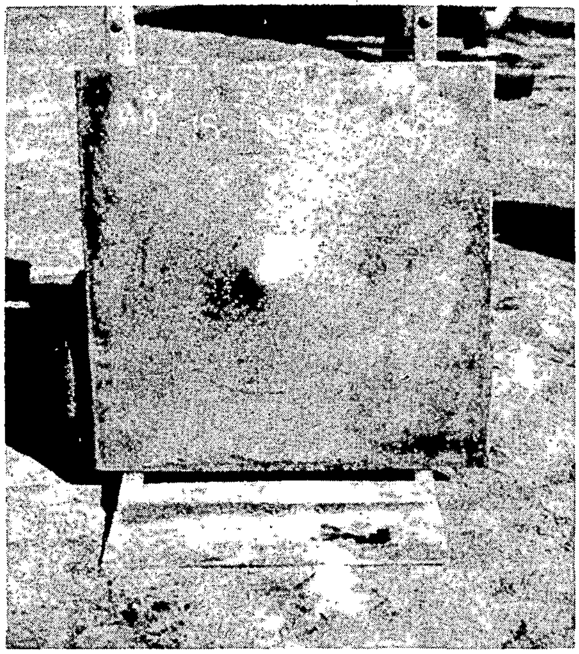


BOTTOM SIDE

Figure B73: Steel Plate Response to 2 Inch Hemispherical Tup in Test Number 73

APPENDIX C
DIAL MICROMETER MEASUREMENTS OF DENT DEPTHS

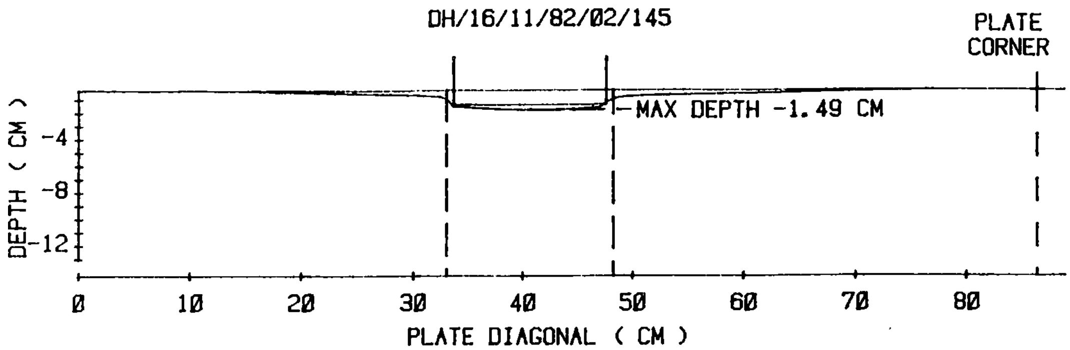


Figure C1: Dial Micrometer Measurements of Dent Depths for Test Number 1

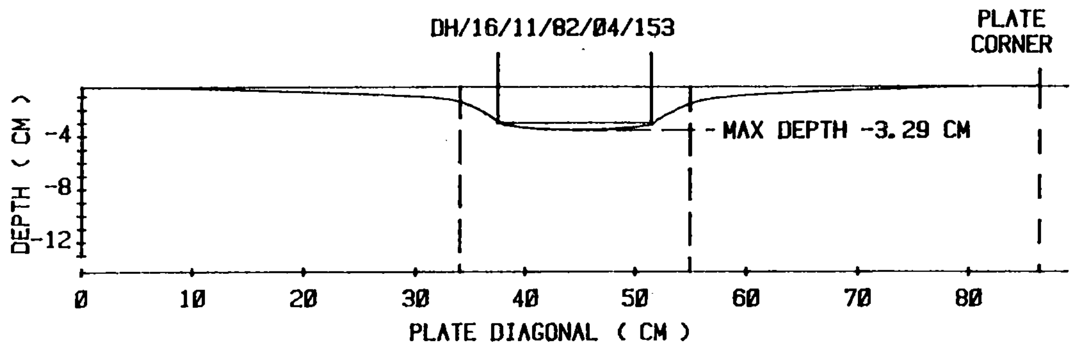


Figure C2: Dial Micrometer Measurements of Dent Depths for Test Number 4

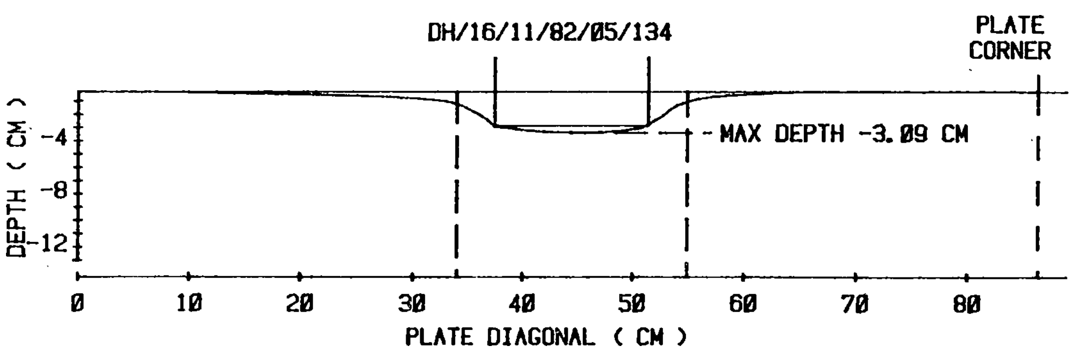


Figure C3: Dial Micrometer Measurements of Dent Depths for Test Number 5

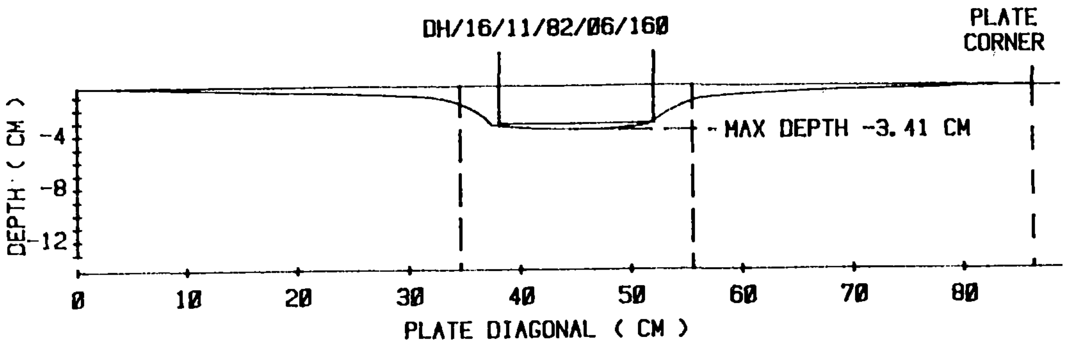


Figure C4: Dial Micrometer Measurements of Dent Depths for Test Number 6

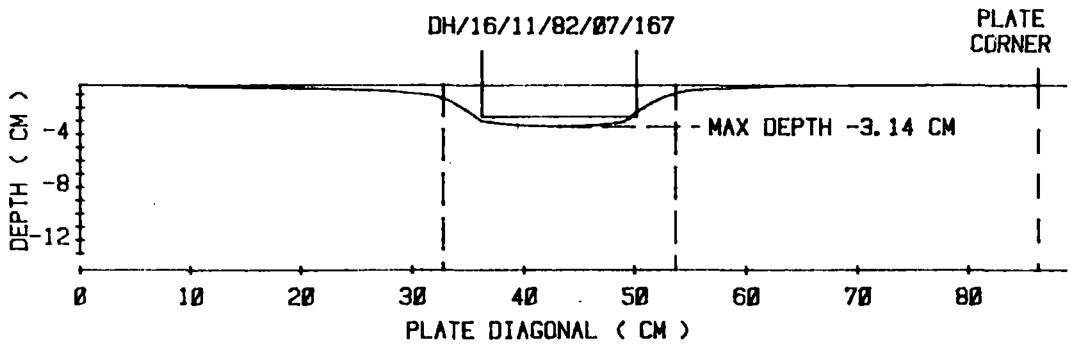


Figure C5: Dial Micrometer Measurements of Dent Depths for Test Number 7

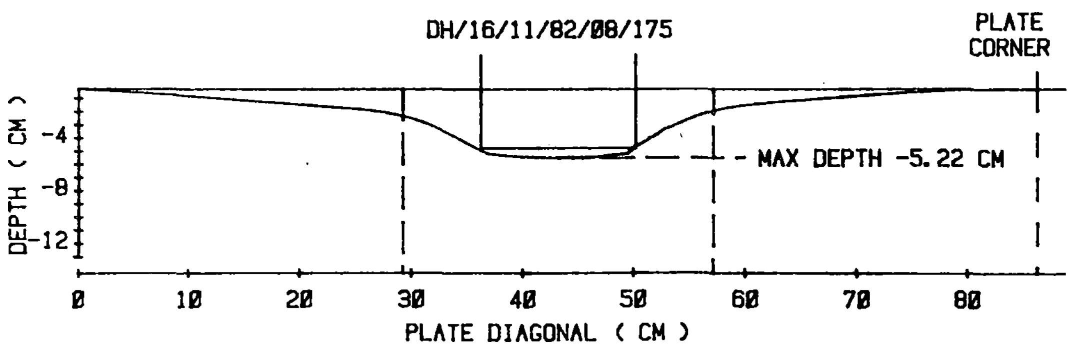


Figure C6: Dial Micrometer Measurements of Dent Depths for Test Number 8

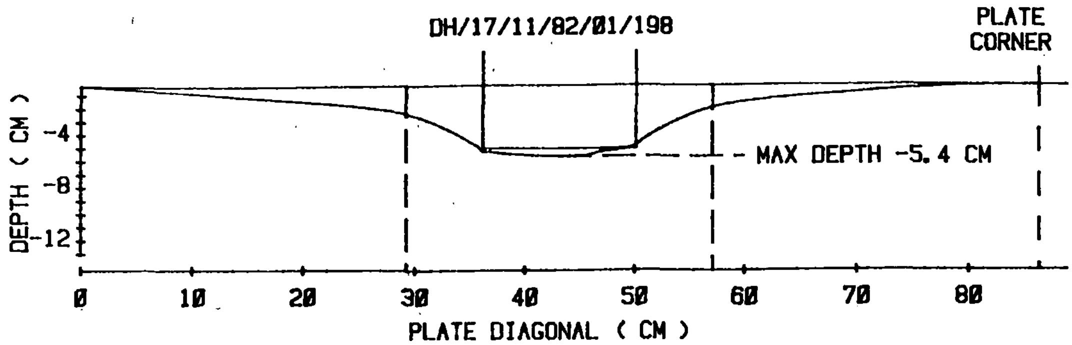


Figure C7: Dial Micrometer Measurements of Dent Depths for Test Number 9

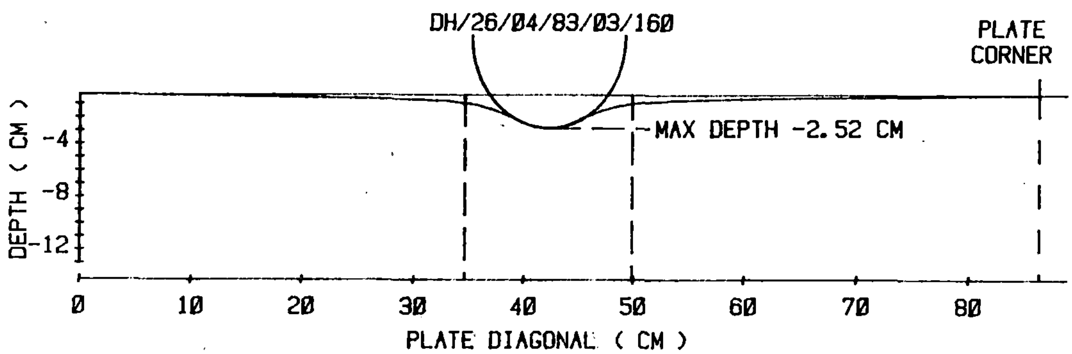


Figure C8: Dial Micrometer Measurements of Dent Depths for Test Number 10

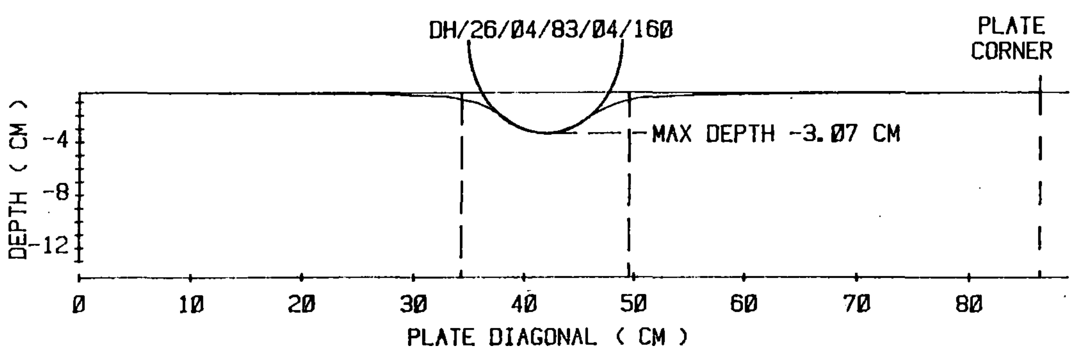


Figure C9: Dial Micrometer Measurements of Dent Depths for Test Number 11

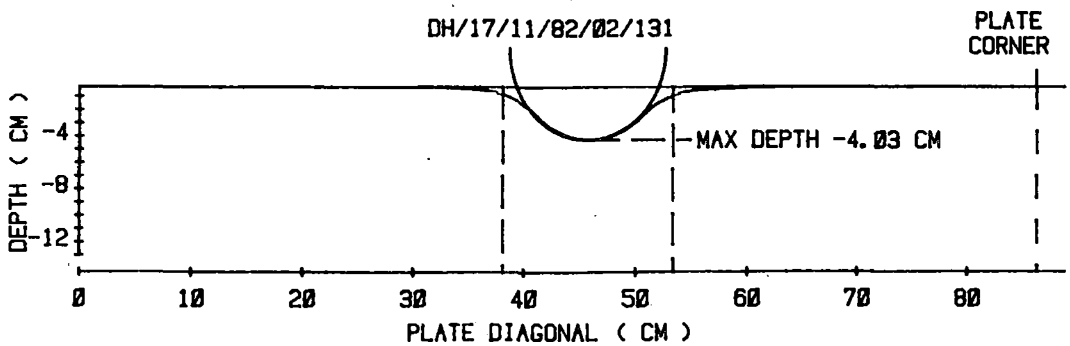


Figure C10: Dial Micrometer Measurements of Dent Depths for Test Number 12

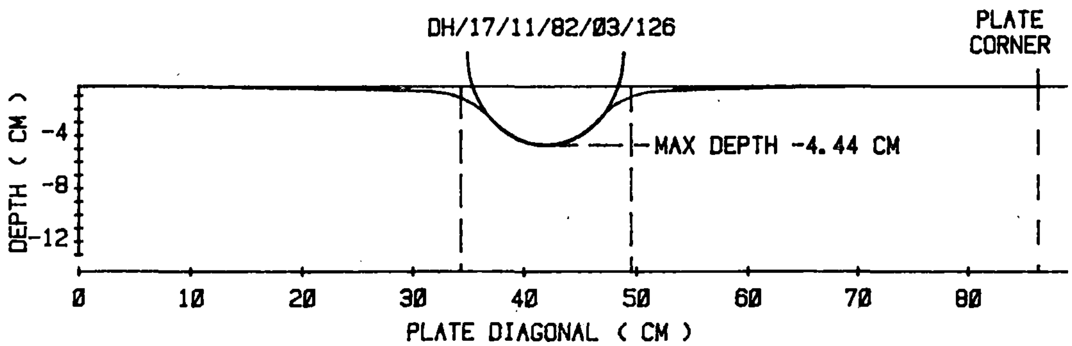


Figure C11: Dial Micrometer Measurements of Dent Depths for Test Number 13

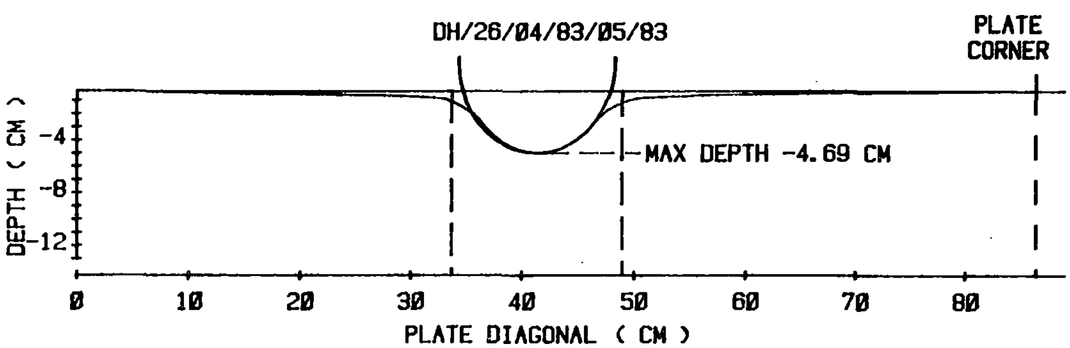


Figure C12: Dial Micrometer Measurements of Dent Depths for Test Number 14

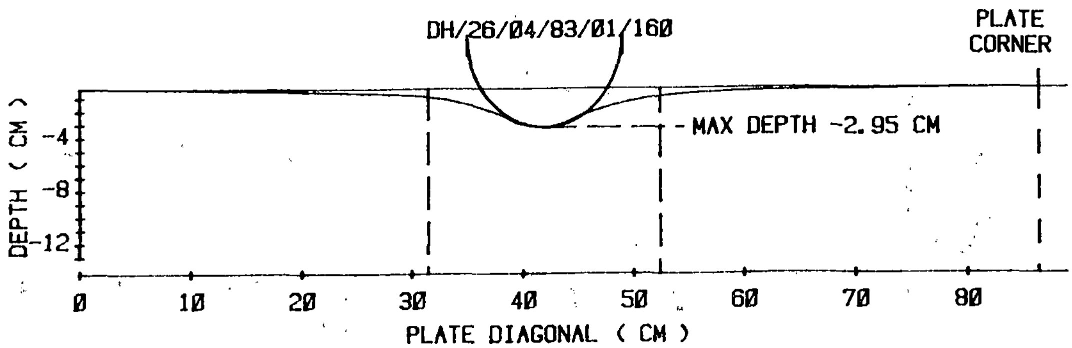


Figure C13: Dial Micrometer Measurements of Dent Depths for Test Number 16

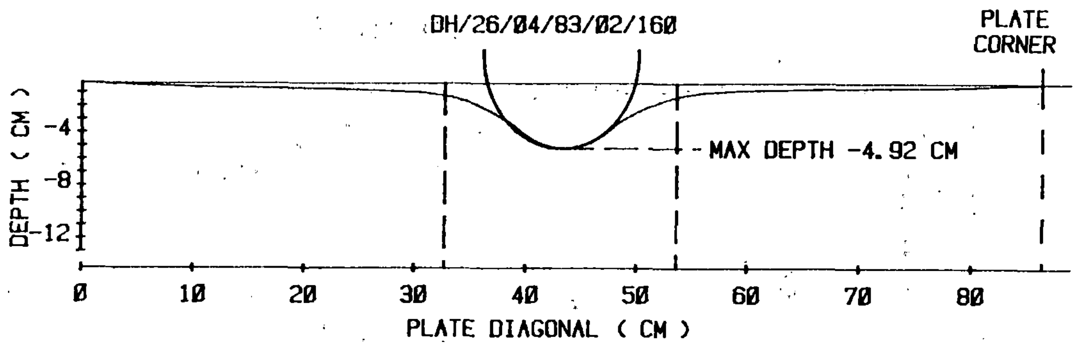


Figure C14: Dial Micrometer Measurements of Dent Depths for Test Number 17

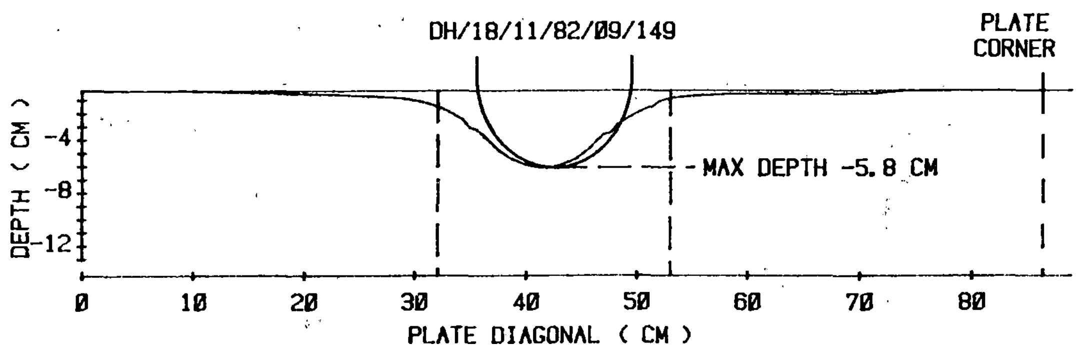


Figure C15: Dial Micrometer Measurements of Dent Depths for Test Number 18

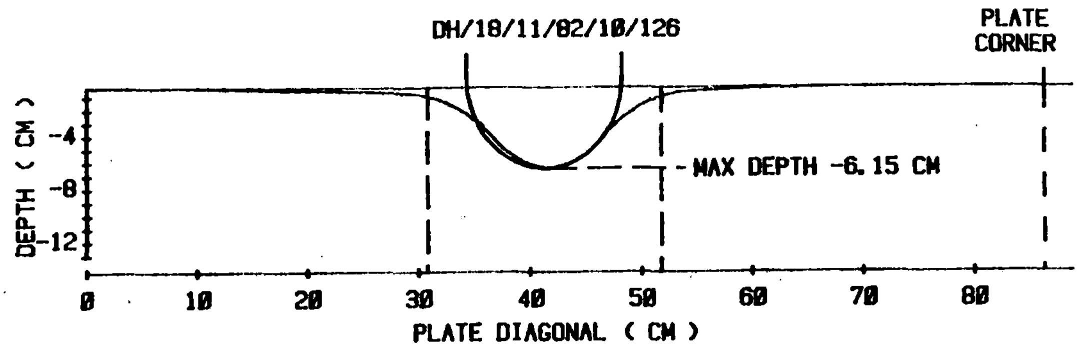


Figure C16: Dial Micrometer Measurements of Dent Depths for Test Number 19

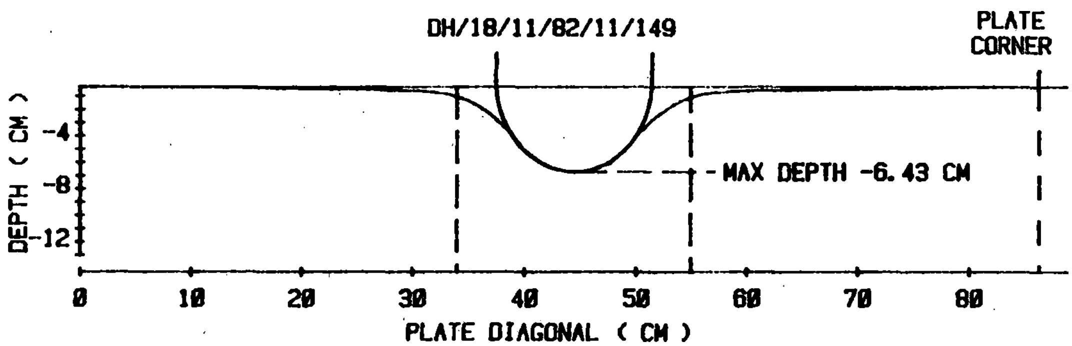


Figure C17: Dial Micrometer Measurements of Dent Depths for Test Number 20

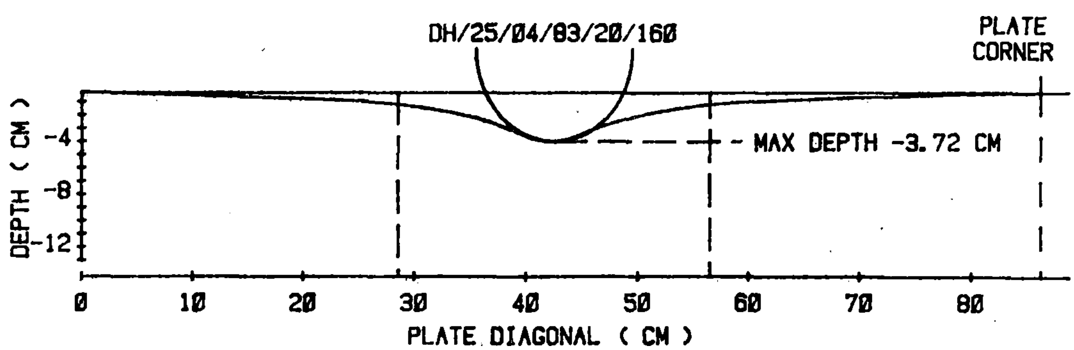


Figure C18: Dial Micrometer Measurements of Dent Depths for Test Number 22

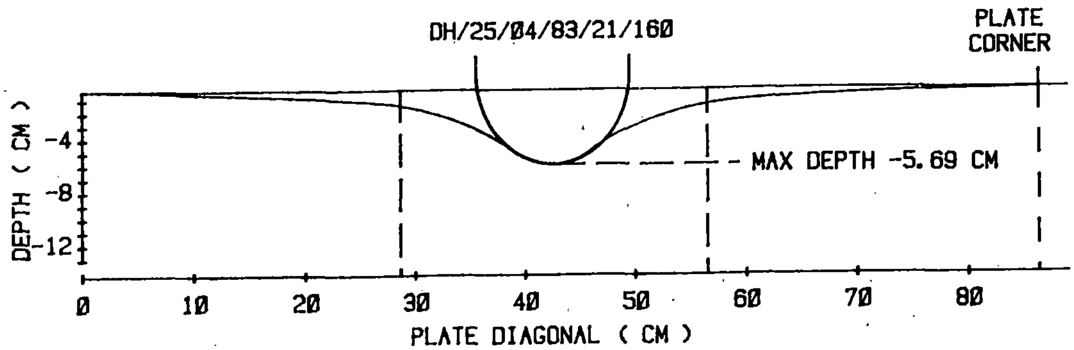


Figure C19: Dial Micrometer Measurements of Dent Depths for Test Number 23

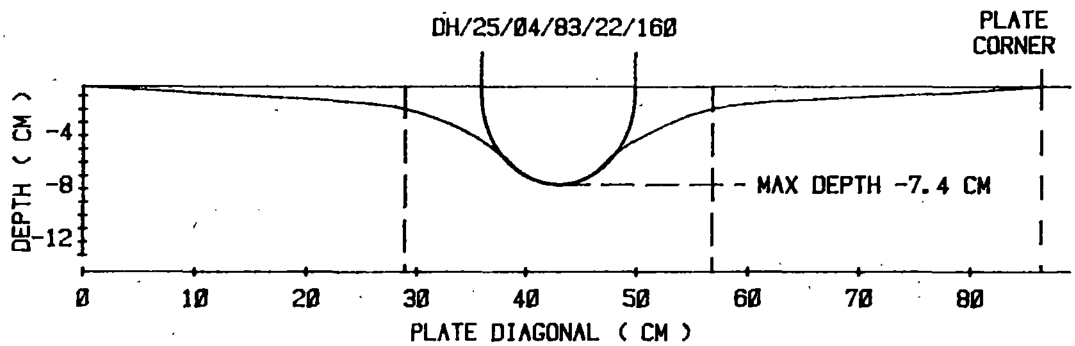


Figure C20: Dial Micrometer Measurements of Dent Depths for Test Number 24

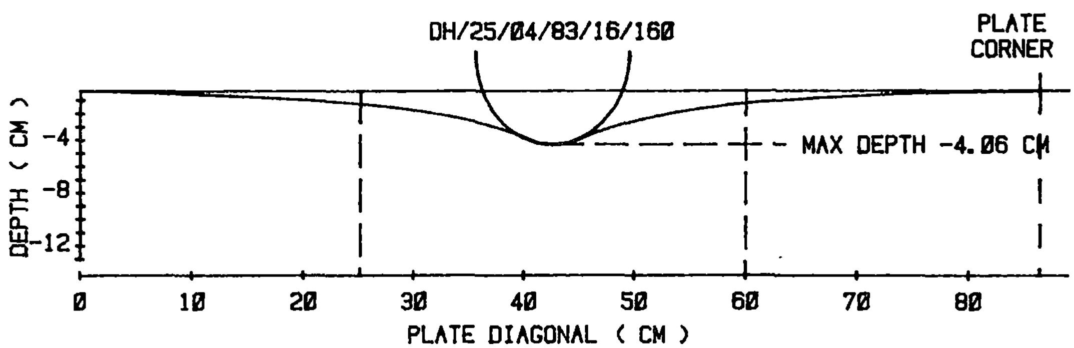


Figure C21: Dial Micrometer Measurements of Dent Depths for Test Number 26

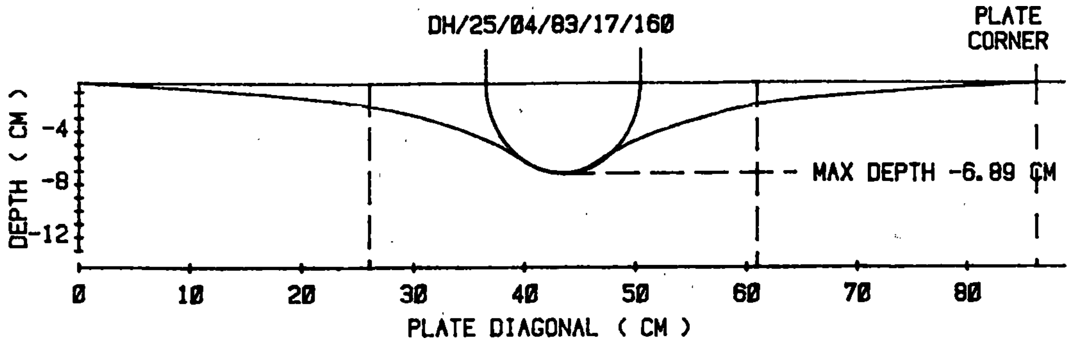


Figure C22: Dial Micrometer Measurements of Dent Depths for Test Number 27

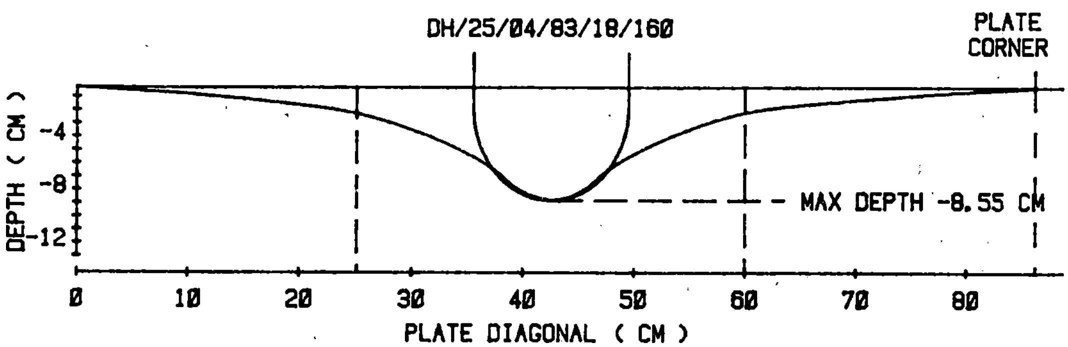


Figure C23: Dial Micrometer Measurements of Dent Depths for Test Number 28

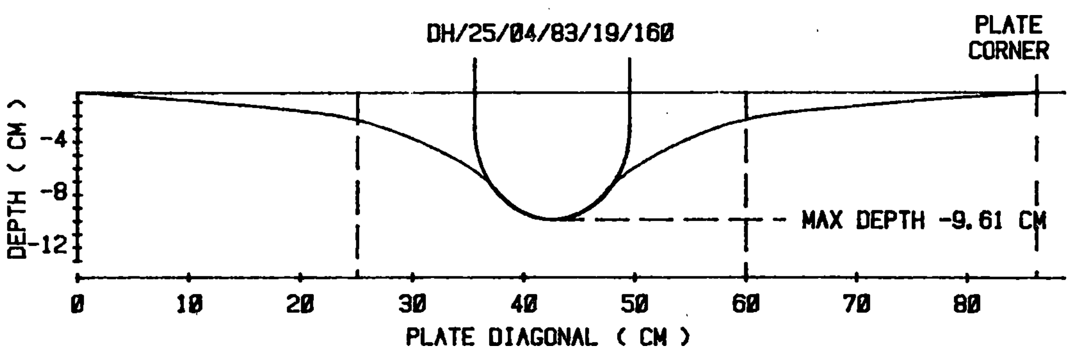


Figure C24: Dial Micrometer Measurements of Dent Depths for Test Number 29

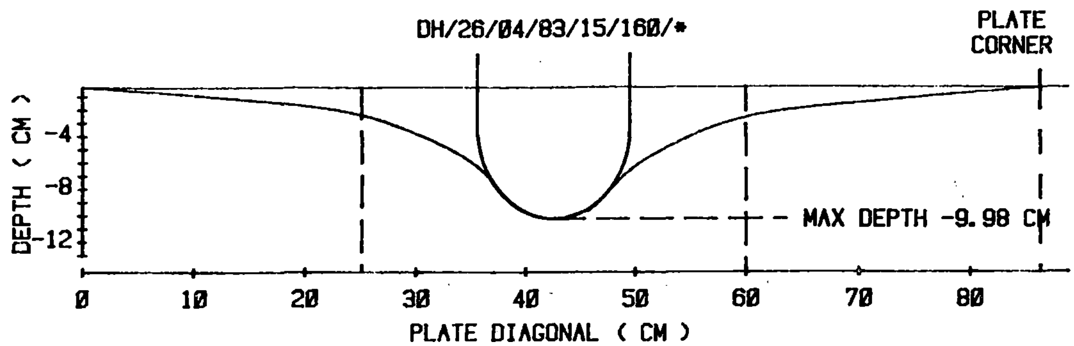


Figure C25: Dial Micrometer Measurements of Dent Depths for Test Number 30

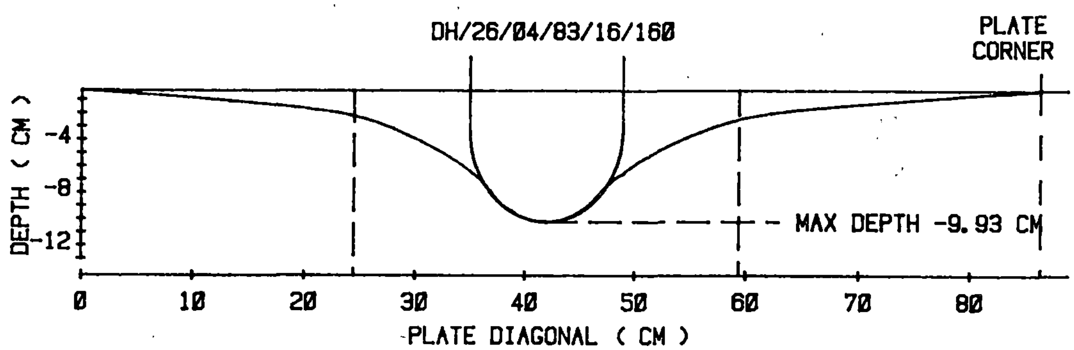


Figure C26: Dial Micrometer Measurements of Dent Depths for Test Number 31

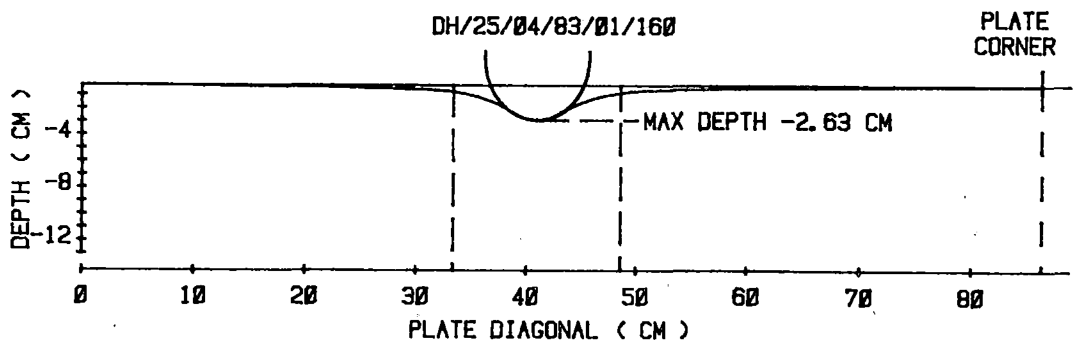
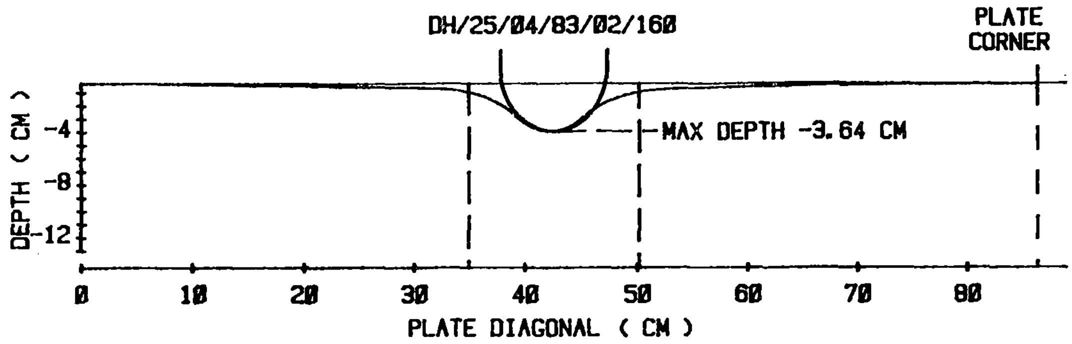


Figure C27: Dial Micrometer Measurements of Dent Depths for Test Number 34



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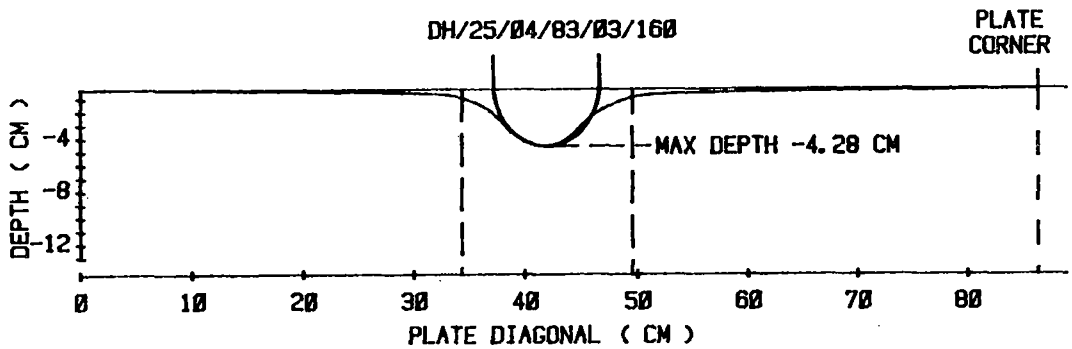

Figure C29: Dial Micrometer Measurements of Dent Depths for Test Number 36

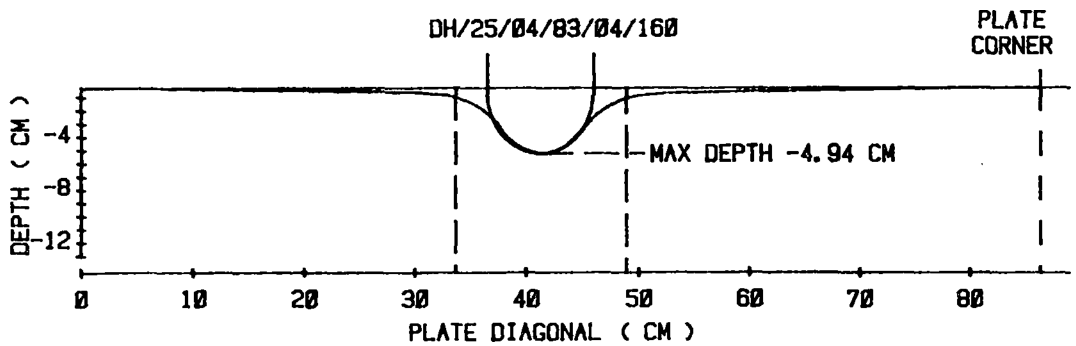

Figure C30: Dial Micrometer Measurements of Dent Depths for Test Number 37

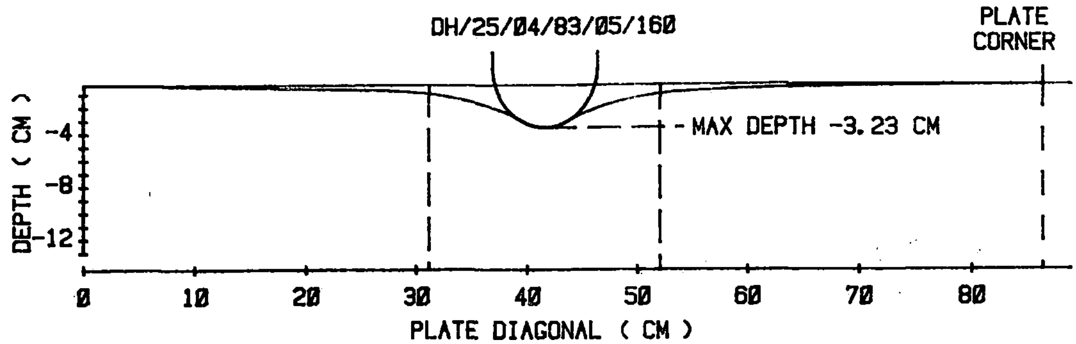

Figure C31: Dial Micrometer Measurements of Dent Depths for Test Number 38

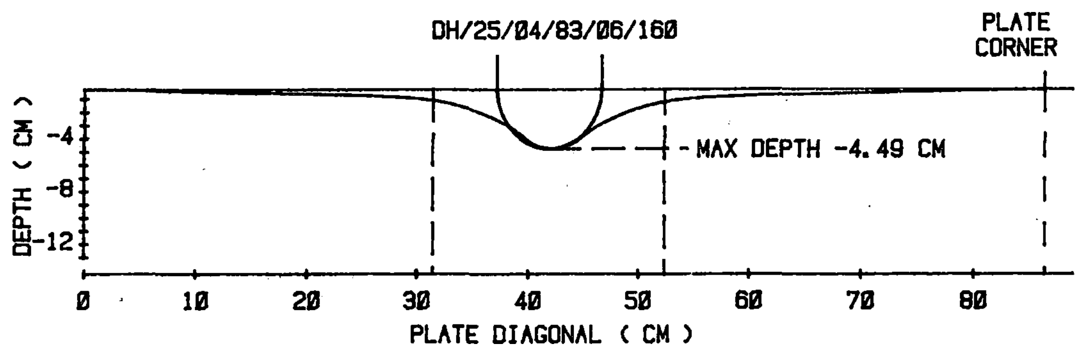

Figure C32: Dial Micrometer Measurements of Dent Depths for Test Number 39

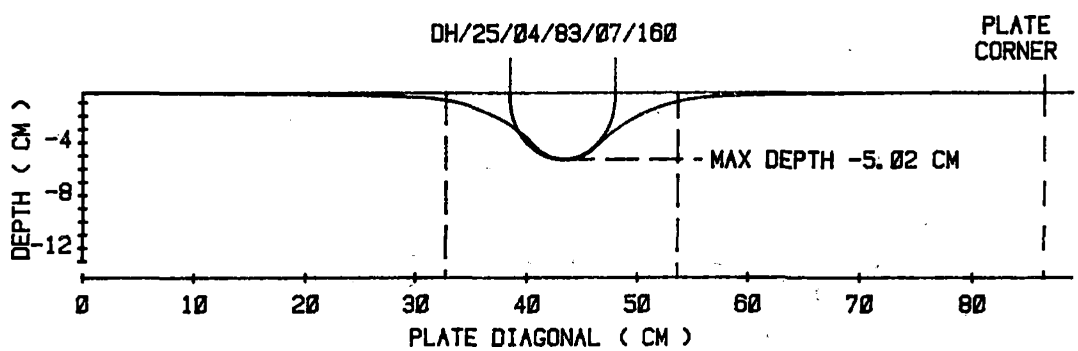

Figure C33: Dial Micrometer Measurements of Dent Depths for Test Number 40

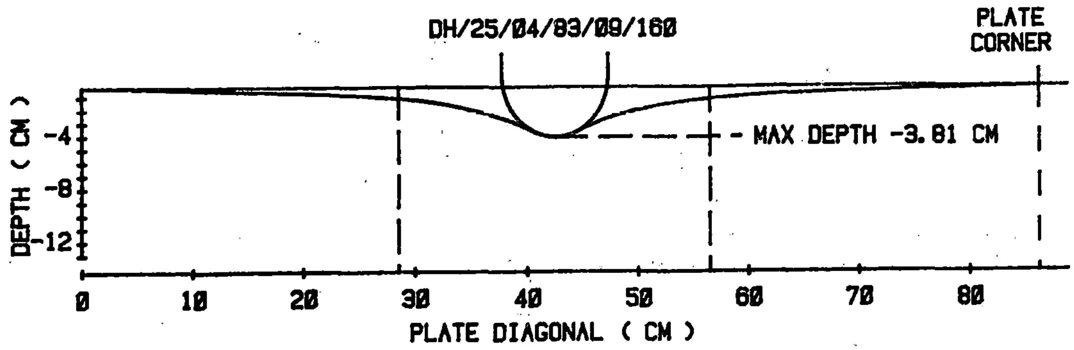

Figure C34: Dial Micrometer Measurements of Dent Depths for Test Number 42

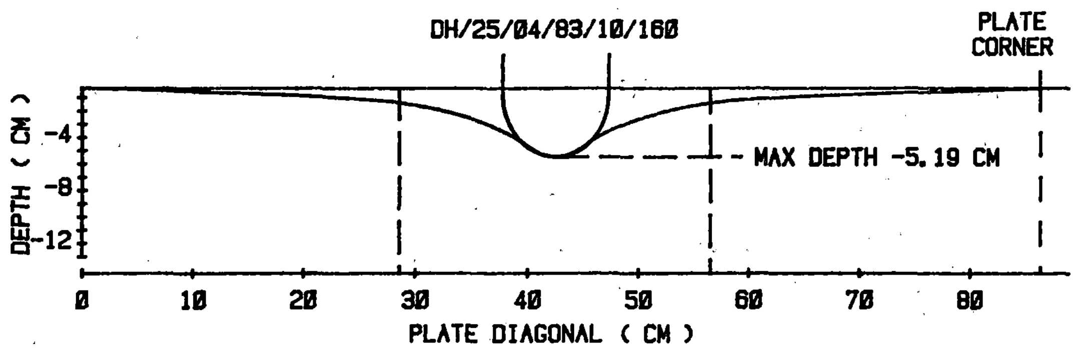

Figure C35: Dial Micrometer Measurements of Dent Depths for Test Number 43

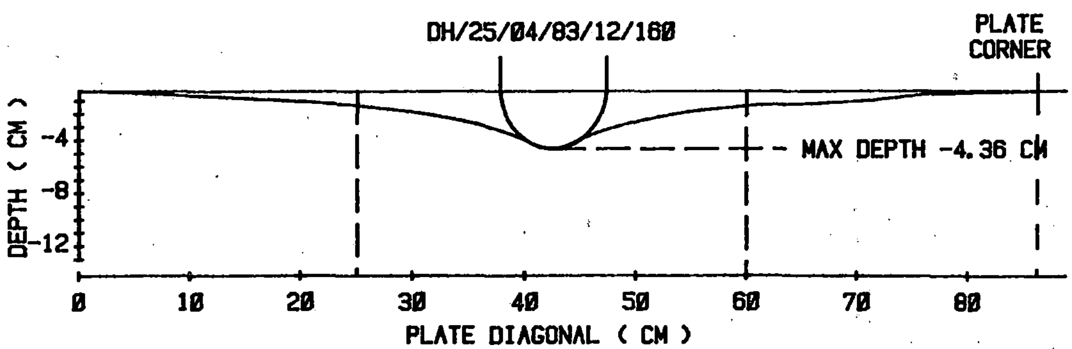

Figure C36: Dial Micrometer Measurements of Dent Depths for Test Number 45

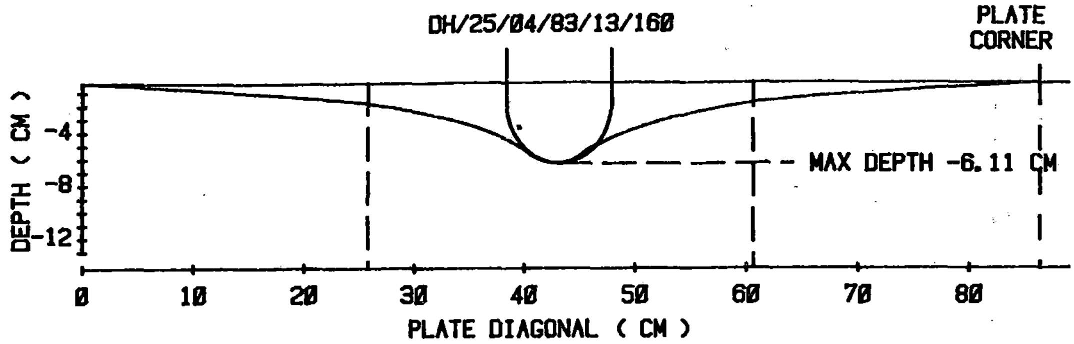

Figure C37: Dial Micrometer Measurements of Dent Depths for Test Number 46

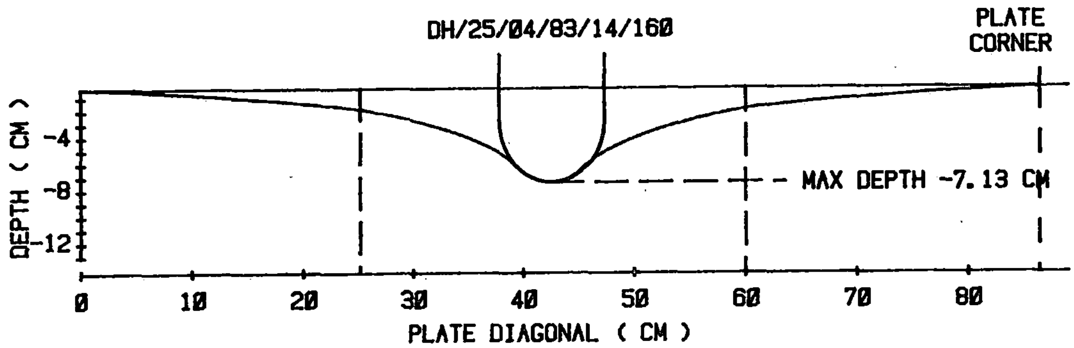

Figure C38: Dial Micrometer Measurements of Dent Depths for Test Number 47

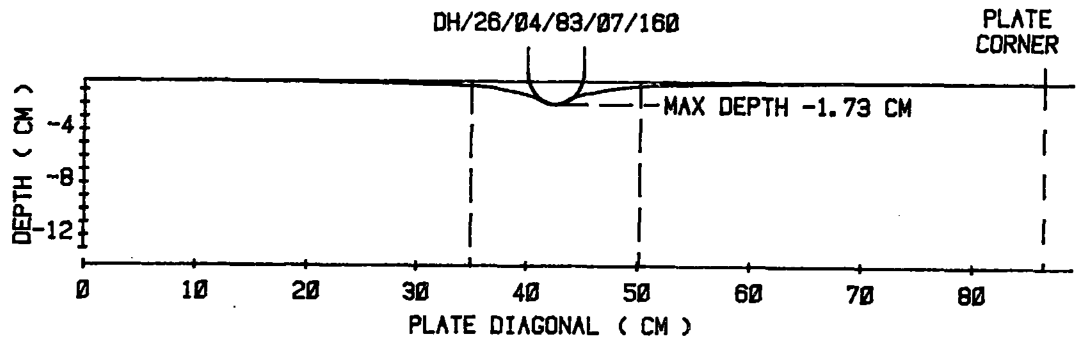

Figure C39: Dial Micrometer Measurements of Dent Depths for Test Number 49

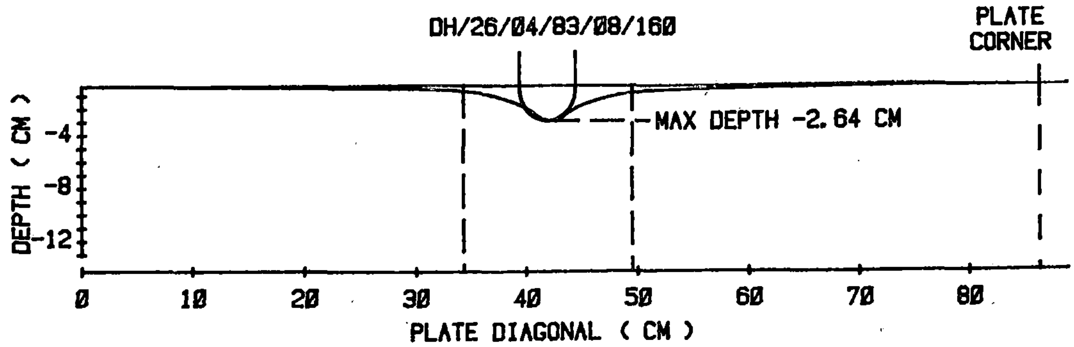

Figure C40: Dial Micrometer Measurements of Dent Depths for Test Number 50

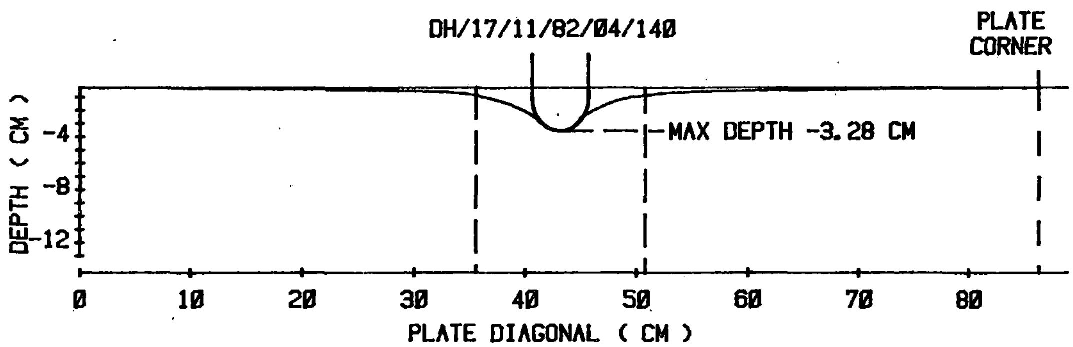

Figure C41: Dial Micrometer Measurements of Dent Depths for Test Number 51

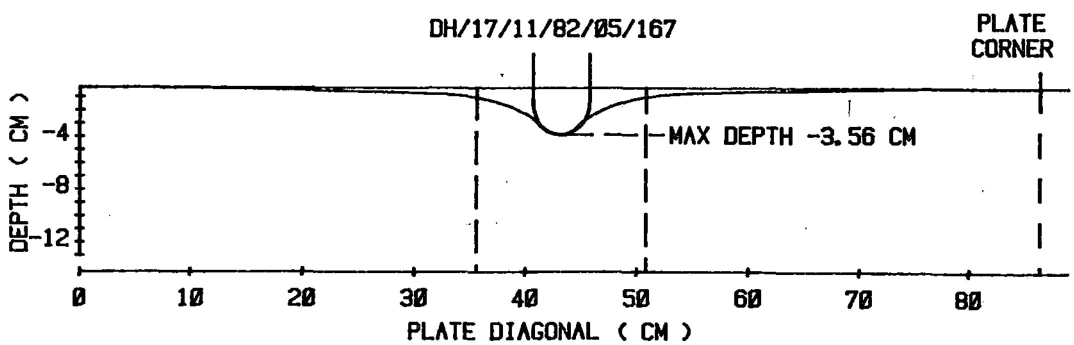

Figure C42: Dial Micrometer Measurements of Dent Depths for Test Number 52

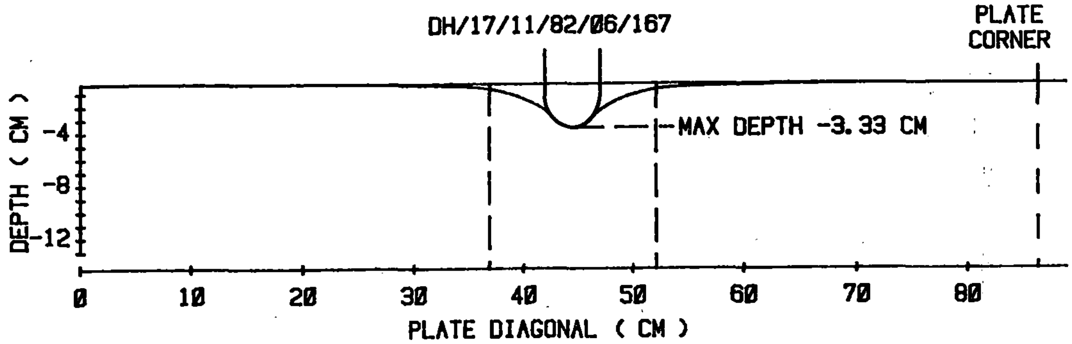

Figure C43: Dial Micrometer Measurements of Dent Depths for Test Number 53

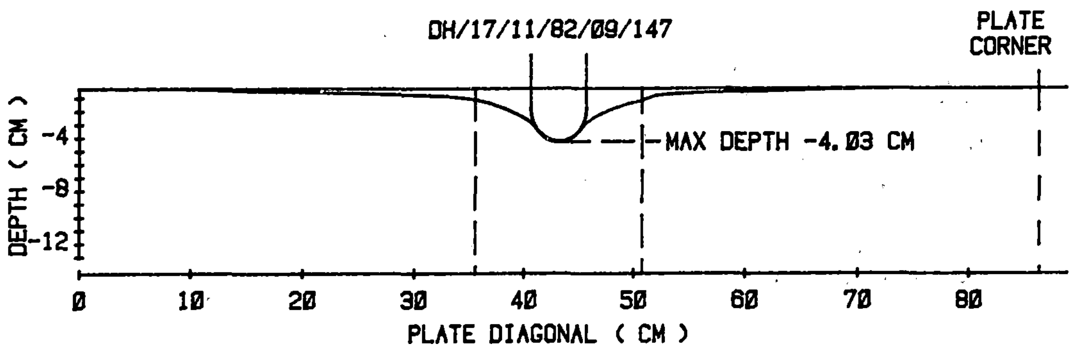

Figure C44: Dial Micrometer Measurements of Dent Depths for Test Number 54

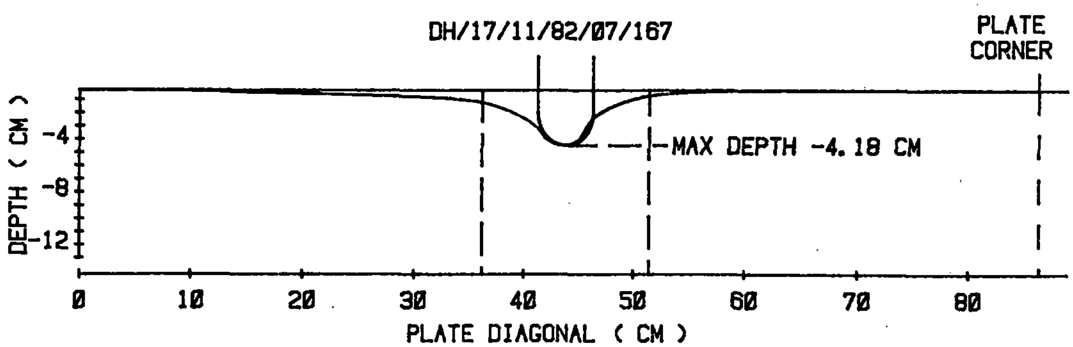

Figure C45: Dial Micrometer Measurements of Dent Depths for Test Number 55

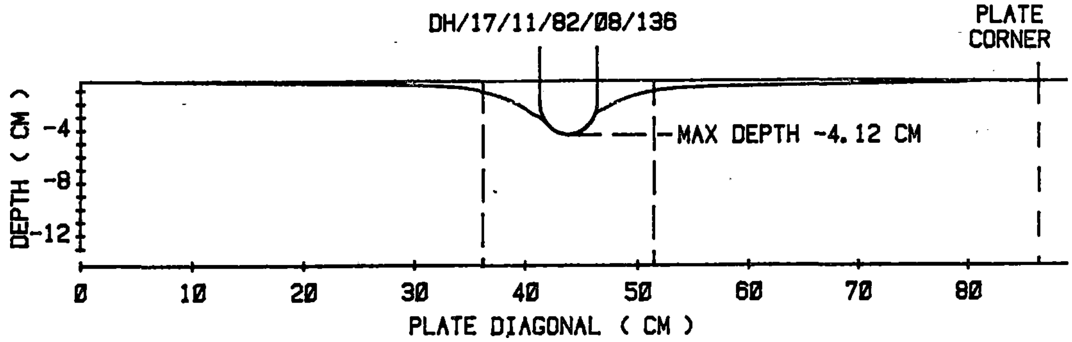

Figure C46: Dial Micrometer Measurements of Dent Depths for Test Number 56

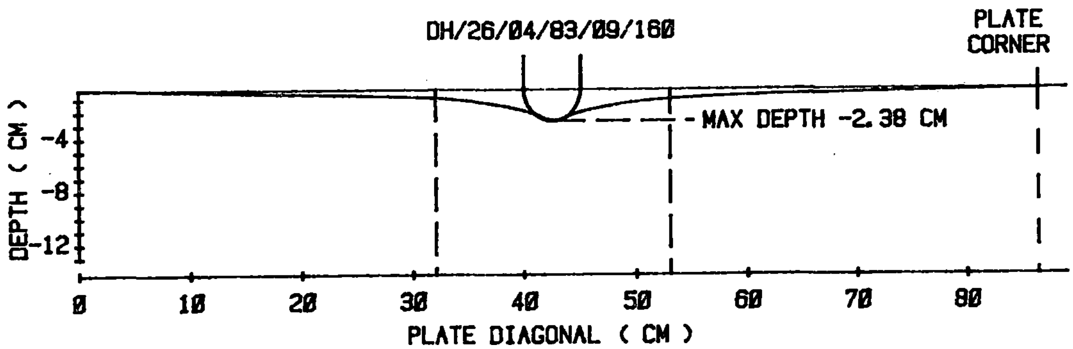

Figure C47: Dial Micrometer Measurements of Dent Depths for Test Number 57

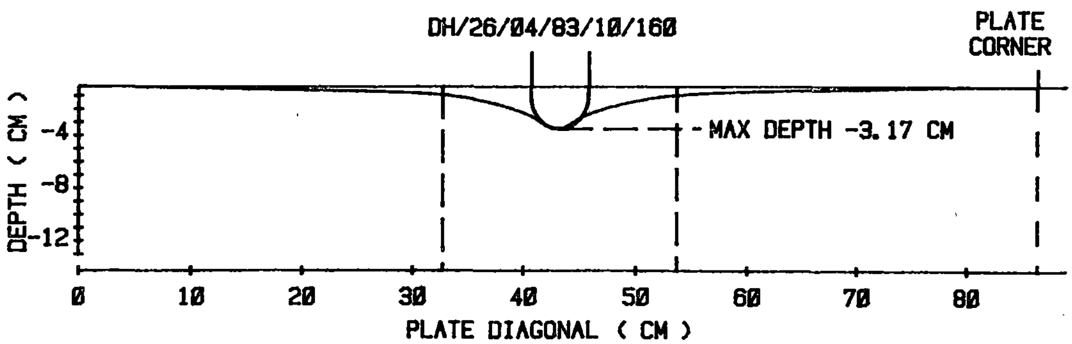

Figure C48: Dial Micrometer Measurements of Dent Depths for Test Number 58

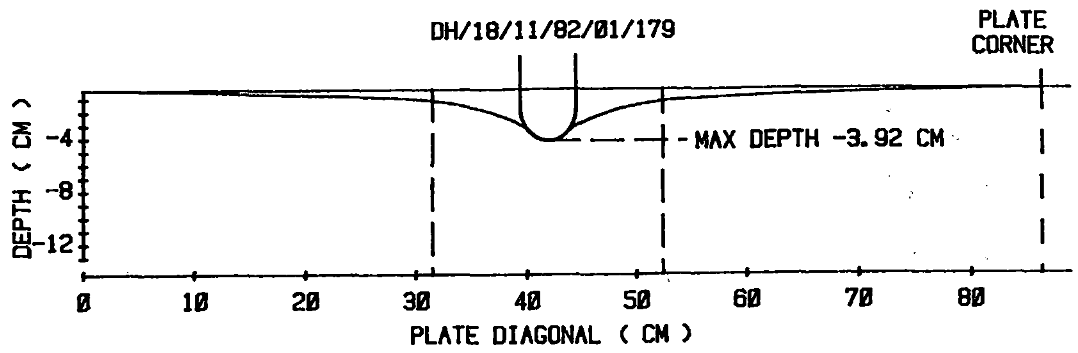

Figure C49: Dial Micrometer Measurements of Dent Depths for Test Number 59

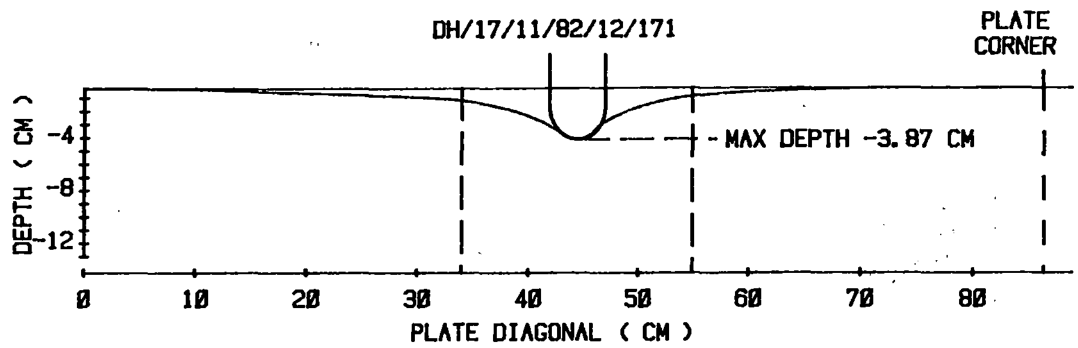

Figure C50: Dial Micrometer Measurements of Dent Depths for Test Number 60

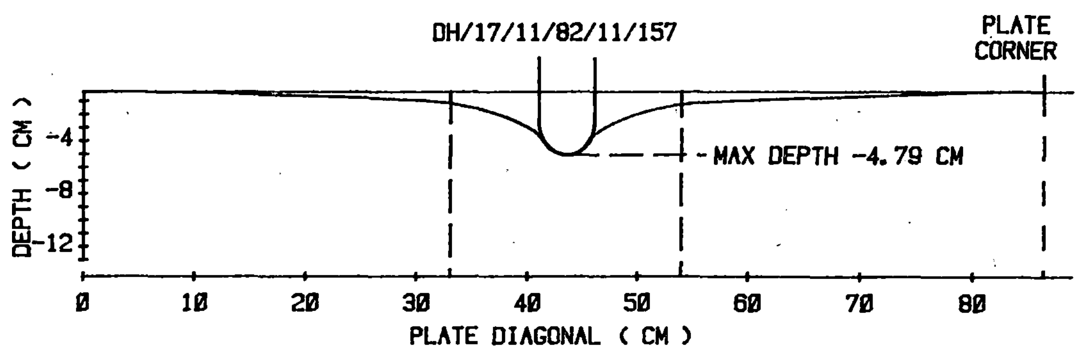

Figure C51: Dial Micrometer Measurements of Dent Depths for Test Number 61

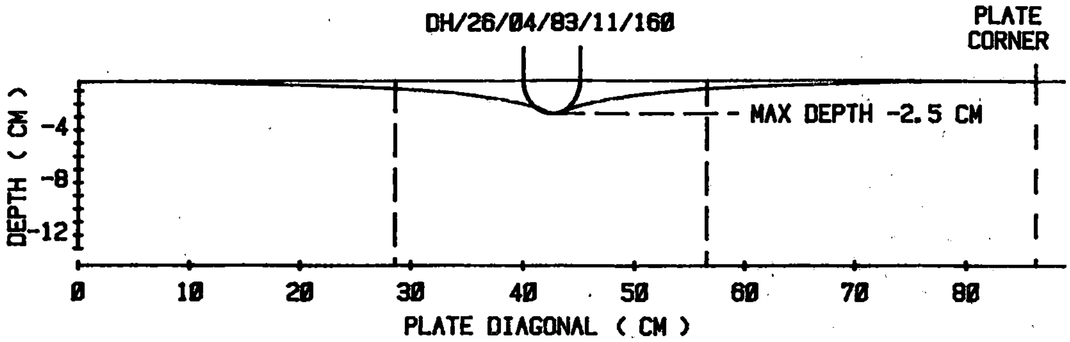

Figure C52: Dial Micrometer Measurements of Dent Depths for Test Number 63

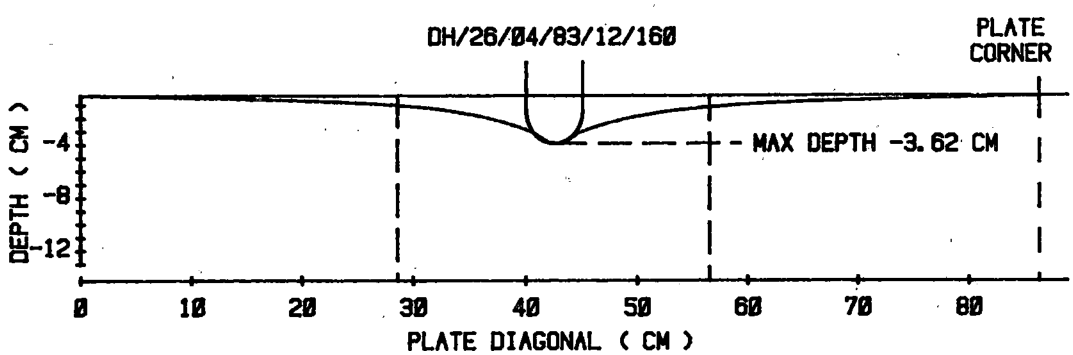

Figure C53: Dial Micrometer Measurements of Dent Depths for Test Number 64

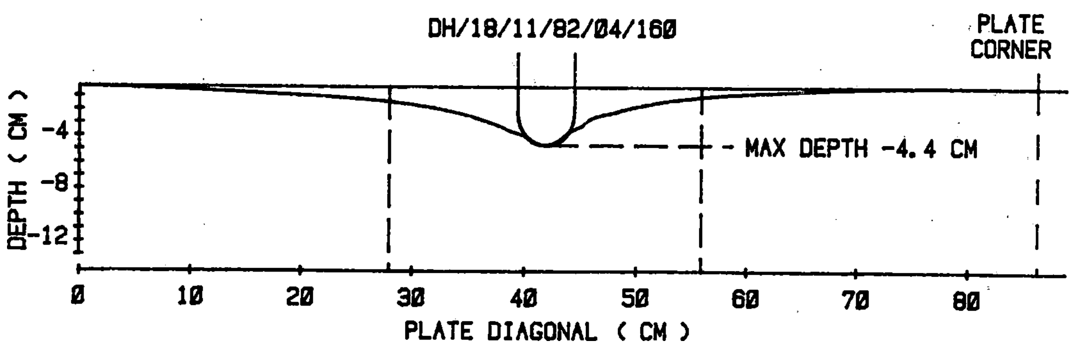

Figure C54: Dial Micrometer Measurements of Dent Depths for Test Number 65

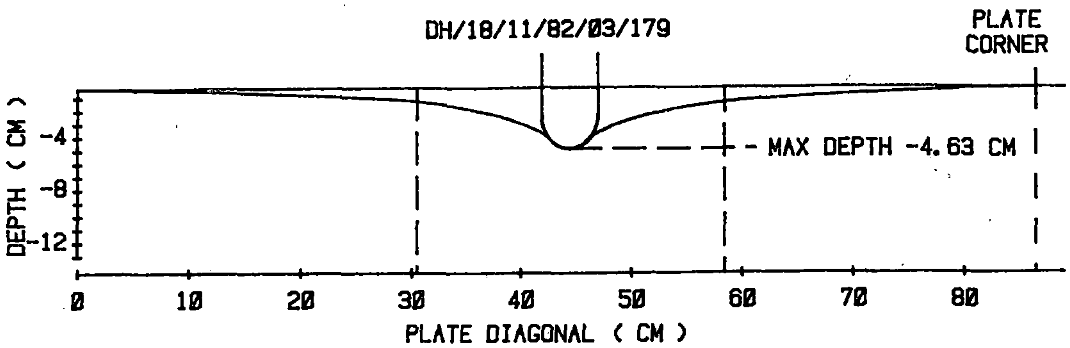

Figure C55: Dial Micrometer Measurements of Dent Depths for Test Number 66

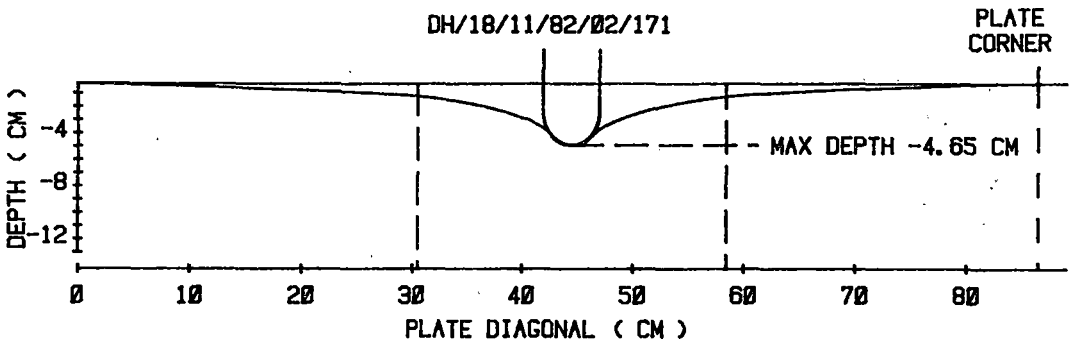

Figure C56: Dial Micrometer Measurements of Dent Depths for Test Number 67

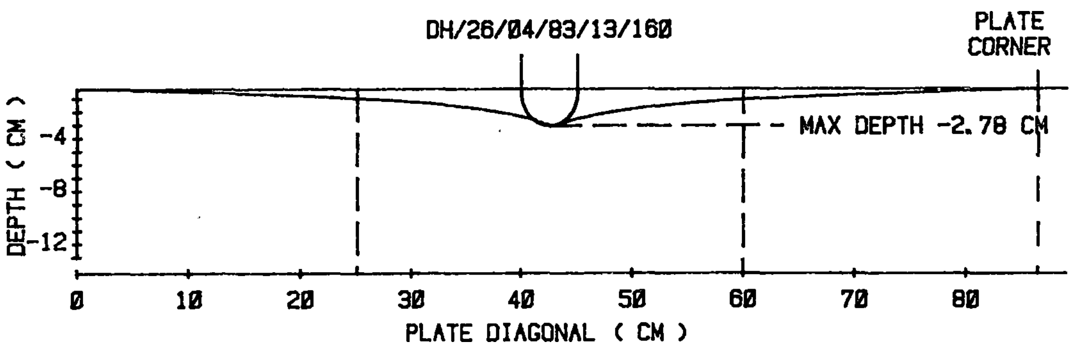

Figure C57: Dial Micrometer Measurements of Dent Depths for Test Number 68

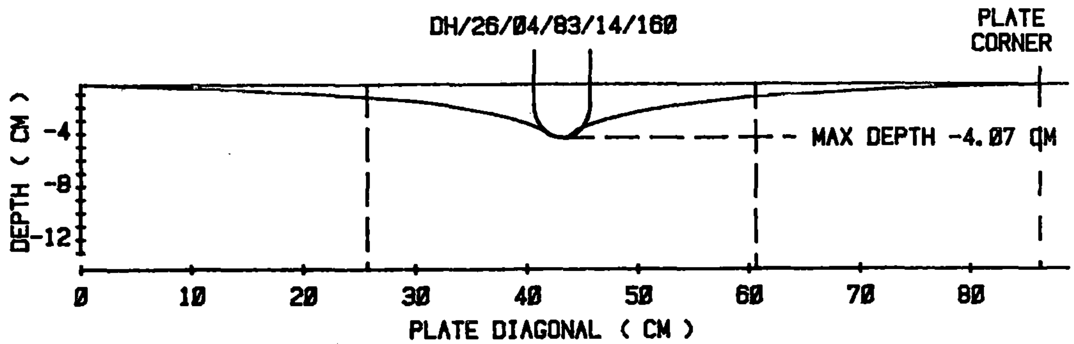

Figure C58: Dial Micrometer Measurements of Dent Depths for Test Number 69

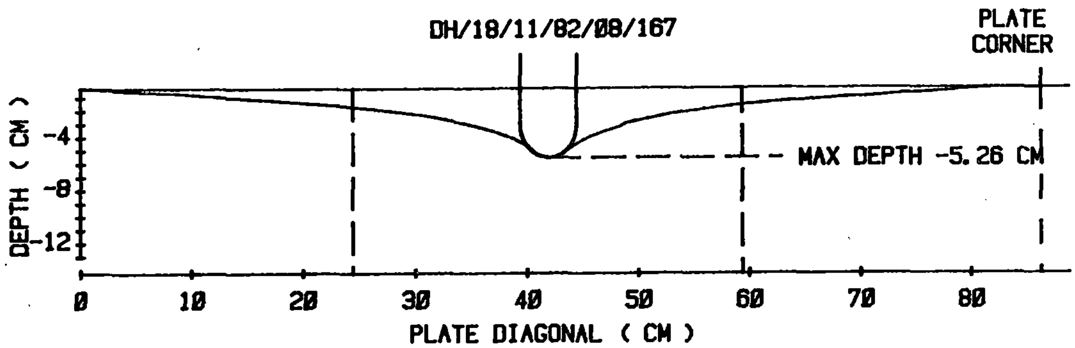

Figure C59: Dial Micrometer Measurements of Dent Depths for Test Number 70

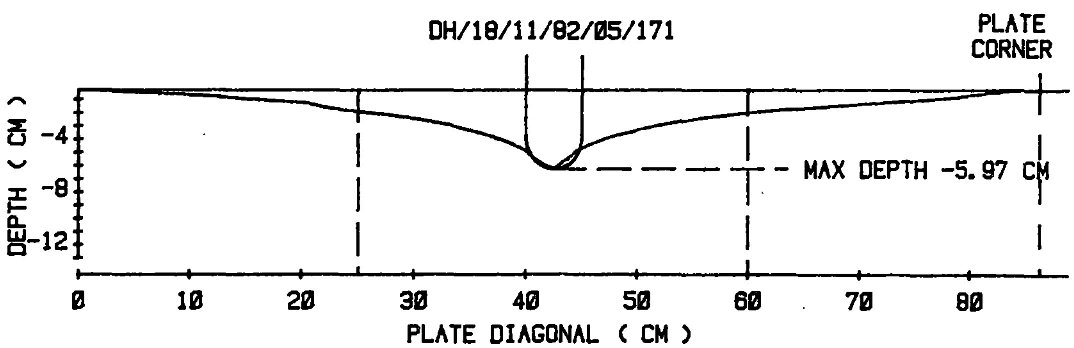

Figure C60: Dial Micrometer Measurements of Dent Depths for Test Number 71

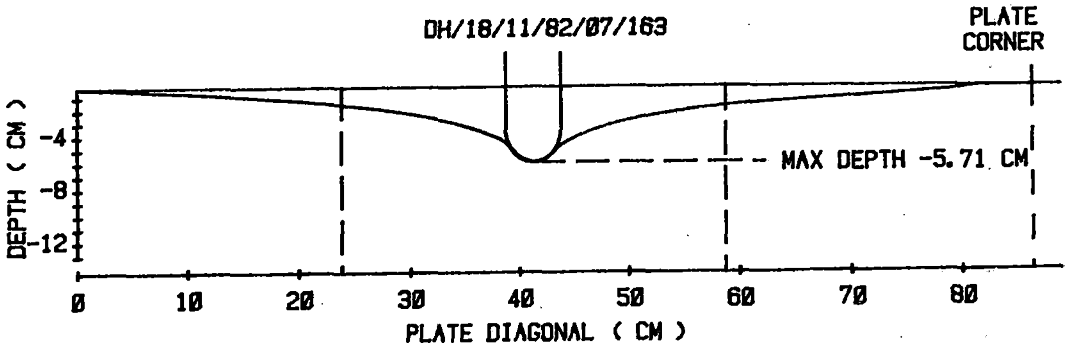

Figure C61: Dial Micrometer Measurements of Dent Depths for Test Number 72

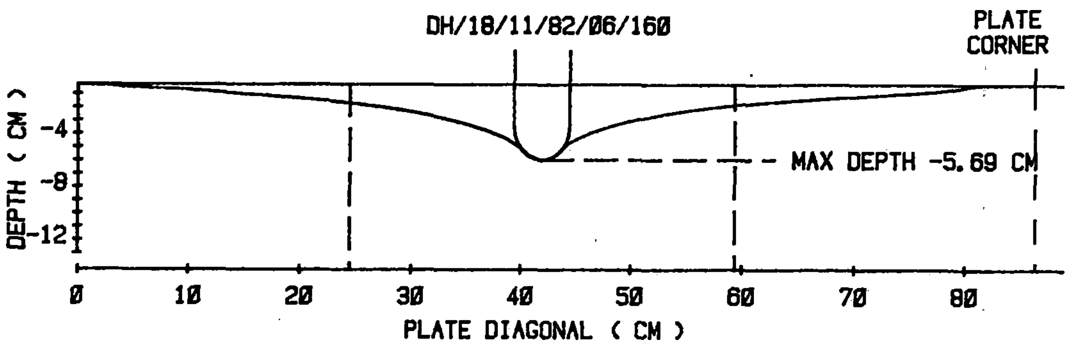

Figure C62: Dial Micrometer Measurements of Dent Depths for Test Number 73

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