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Operation UPSHOT-KNOTHOLE

NEVADA PROVING GROUNDS

March - June 1953

Project 3.6

TESTS ON THE LOADING AND RESPONSE OF RAILROAD EQUIPMENT

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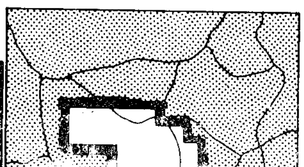

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OPERATION UPSHOT-KNOTHOLE

Project 3.6

TESTS ON THE LOADING AND RESPONSE OF RAILROAD EQUIPMENT

REPORT TO THE TEST DIRECTOR

by

Eugene Sevin
Armour Research Foundation

September 1955

REGRADED [redacted] DI Gp1

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BY B. Wade Jr, 28 Sep 64

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Office of Chief of Transportation
Department of the Army
Washington, D. C.

and

Wright Air Development Center
Wright-Patterson Air Force Base
Ohio

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ABSTRACT

This report deals with pre- and post-test work on the U. S. Army-U. S. Air Force jointly sponsored Project 3.6, <u>Tests on the Loading and Response of Railroad Equipment</u>. The general objectives of this test were to determine the effects of an atomic blast on railroad equipment from both a defensive and an offensive standpoint. The specific objectives were concerned with general damage to railroad cars, both loaded and empty; the bracketing of the shock overpressure causing damage; and the gathering of data relating to blast loading, response, dispersion criteria, correlation of response with damage, and thermal effects.

Sixteen items of standard Transportation Corps equipment, consisting of several types of boxcars, tank cars, and one diesel locomotive, were included in Shot 10 of Operation UPSHOT-KNOTHOLE. Instrumentation consisted of motion picture cameras, pressure gages, and accelerometer gages.

The test indicated that railroad cars of the type tested will be damaged severely at pressures in excess of about 7.5 psi for Shot 10 conditions (i.e., within the precursor region, which extended about 2500 ft from ground zero). A marked decrease in damage was noted between about 7.5 and 6 psi. Only minor damage was sustained by a wooden boxcar at 2 psi and by the diesel locomotive at 6 psi. Of the boxcars tested, the plywood overseas cars proved to be the most susceptible to blast damage, while cars of normal wooden construction and steel construction (i.e., steel roof and side panels) ranked in order of decreasing vulnerability. The trucks and underframe of the cars proved to be salvable in many instances, even though the car body was totally demolished. Thermal damage associated with blasts capable of demolishing wooden cars is negligible.

It is possible to compute with good accuracy the blast conditions, within the region of conventional Mach reflection, at which overturning of boxcars (and the diesel locomotive) will occur. A damage assessment scheme which relates the percentage of damage of boxcars to the effort required to repair or rebuild the car is presented in this report. According to this scheme, loaded and empty boxcars, each at the same distance from ground zero, suffered the same degree of damage in each instance. Plots of damage versus ground range are presented for Shot 10 conditions, and boxcar damage is correlated with overpressure and duration within the Mach region by means of a proposed damage prediction scheme.

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FOREWORD

This report is one of the reports presenting the results of the 78 projects participating in the Military Effects Tests Program of Operation UPSHOT-KNOTHOLE, which included 11 test detonations. For readers interested in other pertinent test information, reference is made to WT-782, Summary Report of the Technical Director, Military Effects Program. This summary report includes the following information of possible general interest.

a. An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the 11 shots.

b. Compilation and correlation of all project results on the basic measurements of blast and shock, thermal radiation, and nuclear radiation.

c. Compilation and correlation of the various project results on weapons effects.

d. A summary of each project, including objectives and results.

e. A complete listing of all reports covering the Military Effects Tests Program.

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PREFACE

In a letter dated 12 March 1952, the Air Materiel Command was requested by Air Research & Development Command to submit for testing in Operation UPSHOT-KNOTHOLE existing requirements for a structures program which would be based on the needs of the Air Force for Target Analysis and Indirect Bomb Damage Assessment information. Within the Air Materiel Command the responsibility for designing and executing such a program was delegated to the Special Studies Office, Engineering Branch of the Installations Division. The requirements which were submitted and approved became part of Program Three of the Operation and were designated as Projects 3.1, 3.3, 3.4, 3.5, 3.6 and 3.26.1. Mr. B. J. O'Brien of Special Studies Office was appointed project officer and as such coordinated and successfully directed the planning and operation phases of the six projects.

Due to the similarity in test objectives involving railroad equipment, the projects proposed by the Transportation Corps, U.S. Army and the Air Force were combined into Project 3.6. Lt Col Donald G. Dow, TC, USA, acted as project officer and Mr. O'Brien was the assistant project officer. Agreements reached between the two conducting agencies provided that the Transportation Corps would be responsible for the field phase and that the Air Force would be responsible for the reporting and analysis phase. The reports on damage to the Railroad equipment which are contained in Section 4.1 of this report were prepared by a Transportation Corps Damage Survey Team consisting of Lt Col Howard Martens, Capt. C. Bass, and Messrs. E. Caron, J. Costello, J. Holbrook, and Mr. Norman C. Thomas.

Armour Research Foundation (ARF) of the Illinois Institute of Technology was awarded a contract to assist the Special Studies Office in planning and designing the experiments, and in analysis and reporting of test results. During the period of planning, close liaison was maintained with other interested Air Force agencies, particularly the Physical Vulnerability Division, Directorate of Intelligence, Headquarters USAF. Many valuable suggestions were contributed by Colonel John Weltman, USAF, Lt Colonel John Ault, USAF, Messrs. R. G. Grassy and S. White, Dr. F. Genevese and other of that Division, and by Mr. Louis A. Nees, Chief of the Engineering Branch, Installations Division, AMC.

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Personnel of the Special Studies Section who were intimately connected with the program were Mr. Eric H. Wang, Chief, Special Studies, who was the technical and scientific monitor for the Air Force Program, Mr. Arthur Stansel, and Mrs. Maisie G. Ridgeway, secretary to Mr. Wang. Other members of the Office who were associated with the program were Messrs. R. R. Birukoff, P. A. Cooley, J. C. Noble, and Lts. T. M. Murray and G. A. Rockwell, USAF.

Most of the introduction section of this report was taken from the preface of the Preliminary Report, Operation UPSHOT-KNOTHOLE, Project 3.6, authored by Eric H. Wang and Bernard J. O'Brien.

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ACKNOWLEDGMENTS

This report covers the activities of the Armour Research Foundation in connection with the joint U. S. Army - U. S. Air Force Project 3.6 of Operation UPSHOT-KNOTHOLE. The work reported herein was sponsored by the Air Research and Development Command, and performed for Air Materiel Command, Wright-Patterson Air Force Base, Ohio, under the terms of Air Force Contract No. AF33(038)-30029. This program was technically monitored by the Special Studies Office of Installations Division, AMC.

A fine spirit of cooperation between personnel representing various agencies existed during the progress of this project. The successful completion of this project was due to their efforts.

Foundation personnel who have contributed to this report include: R. L. Calvin, S. J. Fraenkel, H. Himelblau, K. C. Gandy, R. L. Janes, M. S. Mass, K. McKee, R. W. Sauer, A. Sherman, T. Schiffman, L. A. Schmidt, E. Sevin and T. A. Zaker.

U. S. Army Project personnel included: Lt. Col. D. G. Dow, Transportation Corps (Project Officer), Lt. Col. H. W. Martens, Maj. W. J. Welsh, Jr., Capt. C. L. Bass, and N. C. Thomas, (Assistant Project Officers), E. Caron, J. A. Costello, and J. H. Holbrook. The Transportation Corps specialists who were responsible for the very thorough post test damage survey and evaluation presented in this report included: Brig. Gen. Calvin DeWitt, Jr., Brig. Gen. E. C. R. Lasher, Cols. W. C. Rogers, J. S. Heiss, A. W. Lyon, L. W. Anderson, E. L. Rehmann, and J. Kilpatrick, Lt. Cols. J. R. Truden, C. J. Rinker, G. W. Misevic, C. C. Mullen, and R. C. Conroy, Maj. F. W. Myers, and A. A. Fry and J. K. Tyson (ORO).

Air Force personnel included: Lt. B. J. O'Brien, AMC (Assistant Project Officer), Eric H. Wang, R. Birukoff, P. Cooley, B. Bryson, Lt. T. Murray, L. A. Nees, J. Noble, M. Ridgeway, Lt. G. Rockwell, and A. Stansel.

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE OF AIR FORCE TEST PROGRAMS

The series of tests conducted by the Air Force in Operation UPSHOT-KNOTHOLE is part of a continuing Air Force program designated as "Determination of Blast Effects on Buildings and Structures." The United States Air Force is mainly interested in the offensive aspects of such research.

The UPSHOT-KNOTHOLE projects sponsored by the Air Force, and their specific objectives, cannot be fully understood without some knowledge of the general objectives of the over-all program. The research results emanating from these studies and experiments conducted by the Air Force are used by a number of government agencies to improve their own systems of determining blast effects, or to further their own research.

One of these agencies is the Directorate of Intelligence, Headquarters, USAF, which feeds such results into its own system of vulnerability classes, thereby making it possible to analyze prospective enemy targets with greater accuracy, and to recommend the desired ground zero. Another principal user of the research results is the Strategic Air Command, which applies them toward improvement of an existing indirect bomb damage assessment system. The purpose of this system is to make it possible to dispense with the usual reconnaissance after a strike, using instead information on the actual ground zero, height of burst, and yield of the weapon, which is brought back to the operational base by the strike aircraft, to determine the damage inflicted.

The task of determining the effect of blast on various types of building structures and tactical equipment is a rather formidable one. However, its difficulty is somewhat relieved by the fact that, for the offensive purposes in which the Air Force is interested, it is not necessary to determine the effect of transient loads with the same accuracy as would normally be employed for static design purposes. In fact, even if it were possible to solve the dynamic problems satisfactorily, Intelligence information would be far too sketchy to furnish the information necessary to justify the use of an accurate analysis for items located in prospective enemy countries. From the experience that is so far available, it is expected that it will be

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possible within the foreseeable future to determine blast damage within broad limits with sufficient accuracy for planning as well as for operational purposes.

In view of the complex phenomena attending shock waves emanating from various types of atomic blasts and the uncertainties inherent in determining significant parameters, an investigator's first approach might be to obtain solutions through a long series of very elaborate and properly designed full-scale tests. However, neither funds nor time will allow such an approach. It has therefore been the objective of the agencies involved to obtain sufficiently accurate results by judicious use of theoretical analyses, laboratory tests, high-explosive field tests, and a small number of full-scale atomic tests.

Three of these research projects have involved full-scale atomic testing. The first was GREENHOUSE, the second was JANGLE (the first, and so far only, underground burst of an atomic weapon to which an Air Force structures program was subjected) and the third is the present UPSHOT-KNOTHOLE program.

From previous analysis, laboratory tests, and full-scale tests (the latter especially as conducted in GREENHOUSE), methods of damage prediction have been developed by Armour Research Foundation and others. These prediction methods have attempted to describe the character of the blast loads acting on a variety of items. Response computations based on the predicted loadings permit, in turn, an estimate of physical damage. However, the relation between the deflection or movement of a body and significant military damage has never been clearly established except for extreme cases, e.g., total destruction or no destruction. Another aim of these tests is, therefore, to establish the relationship between deflection and functional damage. A full-scale test also affords an excellent opportunity to determine scaling check points for laboratory tests.

In addition to the scientific aspects of the tests, most of the results of the Air Force projects can be used by other government agencies such as the Directorate of Intelligence to furnish "rough and ready" experimental answers to the behavior of various kinds of structures under blast. In many cases there is a statistically significant number of items involved which, added to previous experimental data such as those gathered at Hiroshima and Nagasaki, will help round out the present vulnerability picture. In other cases, mathematical analysis may have to rely on ad hoc information to furnish parameters which cannot be obtained in any other way.

The foregoing remarks are designed to furnish the background necessary for a full understanding of the objectives of this joint Army-Air Force project and other Air Force projects. The full significance and value of the results of each test will be realized only when they are correlated with results of past, current, and future analyses, laboratory tests, high-explosive field tests, and full-scale atomic investigations.

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1.2 SPECIFIC OBJECTIVES

Targets such as transportation center, marshaling yards, etc., are of great interest to the Air Force in its planning for offense. Other components of the Armed Forces, such as the Transportation Corps, U. S. Army, are primarily interested in damage to railroad rolling stock from a defensive point of view. In the explosion of an atomic weapon, damage to such target complexes results from many causes, including thermal radiation, direct effects of the shock wave, impact from overturning, and collision with other obstacles.

Shock effects can, to some extent, be predicted from current theory. However, whenever the shock wave bodily lifts up pieces of equipment and moves them for considerable distances, subjecting them to frequent impact, analytical means are generally inadequate for predicting the resulting damage. In such cases experimental and statistical methods must be employed. Thermal damage is also likely to be subject to a similar approach.

The railroad equipment layout, which is the subject of study under Project 3.6, was designed to achieve the following specific objectives with respect to the needs of the Air Force:

1. To obtain information necessary for the prediction of damage to empty and loaded railroad rolling stock.

2. To determine a correlation of damage with the various modes of response of railroad cars.

3. To determine the response of railroad rolling stock to the thermal pulse created by the explosion.

4. To obtain data on boxcars for the system of vulnerability classes as established by the Directorate of Intelligence, Hq., USAF.

5. To obtain blast loading data on railroad rolling stock so that existing schemes for load prediction can be confirmed or modified.

The test was also designed to yield information applicable to the following specific needs of the Transportation Corps:

1. To provide information on the effects of atomic blast and thermal energy on our own railroad marshaling yards and rolling stock.

2. To determine the effort and time required to restore service and replace equipment when it has been damaged as a result of an atomic explosion.

3. To collect damage data which can be used in formulating dispersion criteria for calculating risk formulae.

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4. To verify or modify existing damage criteria as found in TM 23-200, Capabilities of Atomic Weapons. The results of all testing, analysis, laboratory experiments, and general engineering judgment are fed into this collection of data, which is continually being improved.

1.3 RESPONSIBILITIES

Armour Research Foundation (ARF) was retained by the Air Materiel Command (AMC) of the United States Air Force to carry out the following work:

1. Consultation on the selection of the test items.
2. Specification of instrumentation requirements.
3. Location of the structures at the test site.
4. Theoretical and experimental analyses concerning pretest predictions of blast loading and response of the test items where required.
5. Analysis of the test results.
6. Submission of reports accounting for the Foundation's activities pursuant to the objectives of the program.

Detailed statements of the duties and obligations of the contracting parties can be found in the Statement of Work in Air Force Contract AF33(038)-30029.

The Transportation Corps, U. S. Army was responsible for the following:

1. Selecting and furnishing the test items.
2. Consultation in submission of Final Report.
3. Consultation and concurrence on location of the structures at the test site.
4. Supervision of construction at test site and furnishing of materials therefore.
5. Furnishing detailed post-test damage survey.

All electronic instrumentation was installed and operated by the Ballistic Research Laboratories (BRL) under Project 3.28.1 (Structures Instrumentation, WT-738). The BRL also was responsible for the reduction and presentation of the instrument records. Motion picture photography was handled by personnel connected with Project 9.1 (Technical Photography, WT-779).

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CHAPTER 2

GENERAL DESCRIPTION OF TEST

2.1 TEST ITEMS

Sixteen pieces of various types of railroad rolling stock were included in this test. The cars, supplied by the Transportation Corps, U. S. Army, represented standard equipment. These items are described as follows:

1. One welded tank car (empty).
2. One riveted tank car (empty).
3. Five wooden boxcars (empty).
4. Five wooden boxcars (loaded).
5. One steel boxcar (empty).
6. One 45-ton diesel electric locomotive.
7. Two plywood boxcars (empty, type used in U. S. Army overseas operation).

A more detailed description of these items is contained in Chapter 4. (See also Figs. 4.2 through 4.26.) The code number designation used throughout this report is given in Table 2.1. Loading of the cars in all cases consisted of 30 tons of sandbags stacked to a height of 34 in. above the floor of each car. Doorways were kept clear of cargo, and the load was evenly distributed on both ends of the cars. The hand brakes were set on all cars prior to the shot. The air brakes were set on the locomotive, whose engine was running during the test.

Each of the cars was on a separate track elevated about 2 ft above the lake bed. Six-inch stripes in the form of a cross were painted on the ends of the cars to give distinguishing marks where correlation was to be made with film measurements. Markers were also placed on the ground to give stationary reference points. Marks were painted on the bottom edge of the wheels through to the rails in order to determine any transverse displacement.

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There was no construction involved with the exception of placing the rail bed and rails with ties to standard specifications. A detailed description of the track construction as furnished by the Transportation Corps follows:

The rail used was second hand with a weight of 75 lb/yd. New 4-hole angle bars, bolts, and 6-1/2 in. spikes were used. No tie plates were used. Second hand ties with minimum dimensions of 6 in. by 8 in. by 9 ft were utilized throughout. Ballast used was procured locally in the vicinity of Frenchman Flat. Although it was coarser than lake bed silt, it was still very fine, would not compact well, and later required stabilization with sodium silicate to hold down dust for purposes of clear photography.

The subgrade was built up of the same material as the ballast. To obtain compaction it was laid down in 3 in. layers, wet down, and rolled. Fair compaction was obtained in this manner. Subgrade was built up to a height of 12 in. above the ground.

Ties were laid on top of the subgrade and spaced on 2 ft centers. Rail was then laid on top of the ties and the angle bars applied. One rail was spiked to every fourth tie by hand. The intervening ties were then spiked with an air hammer. The opposite rail was spiked down to the ties at the proper gage using the same procedure. The track was then leveled and lined and ballast dumped on it using a utility loader. Ballast was leveled by hand to the finished profile. The track was filled with ballast to the level of the top of the ties. The fill extended out from the end of the ties a distance of 12 in. before sloping off on a 1-1/2 to 1 slope to the lake bed.

2.2 INSTRUMENTATION

2.2.1 General

The motion of nine of the cars was recorded by motion picture photography. The soil was stabilized to the front and rear of these cars in an attempt to prevent the pictures from being obscured by dust. In addition, sodium silicate solution was sprayed on the roadbed and on the cars in the hope of cutting down dust and smoke interference still further.

In order to obtain information on the blast loading of boxcars and elevated structures in general, four pressure gages were mounted on each of two cars, 3.6m and 3.6g. (See Fig. 2.1.) Two accelerometers were located on car 3.6g (Fig. 2.1). It was hoped that this instrumentation would allow some correlation with measurements taken from the motion picture film and, in the event that the photography proved unsuccessful for one cause or another, would supply a portion of the desired response information.

2.2.2 Photographic Measurements

All photographs were taken from individual stations located in the immediate vicinity of the test items. Two cameras were provided at each location--one relatively close, and the other farther away, covering a wider field of vie[redacted]

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Bell and Howell Gun Sight Aiming Point Cameras (GSAP) with special-order Eastman Kodak film (Type 918 Emulsion) were used exclusively. Nominal film speed of the cameras was 64 frames per second, although this actually varied from 58 to 69 frames per second. No timing marks were provided and the cameras were calibrated by observing well-defined shock phenomena recorded on the film. More detailed information as to the equipment and field layout can be obtained from WT-779.

2.2.3 Air Pressure Measurements

All air pressure versus time measurements were obtained by the use of Wiancko type gages, a differential inductance bridge actuated by a pressure-sensitive Bourdon tube. The output of the gages was fed into modified Webster-Chicago magnetic tape recorders. The circuitry is described as a phase modulated system.

The pressure gages were calibrated statically in conjunction with the recording system just prior to the test. A regulated air pressure system was used for positive pressures and a vacuum pump was used for negative pressures. Accurately known pressures were applied in incremental steps of 10 per cent of full-scale deflection for each gage. The resulting record was then played back to establish a calibration curve.

The accuracy of the pressure values is estimated at 3 per cent of full-scale readings by the Ballistic Research Laboratories. The time resolution is in all cases within 2 ms. Complete details of the pressure gage installations are contained in WT-738.

2.2.4 Acceleration Measurements

Type 3AA-T Wiancko accelerometers were used for measurements of linear acceleration. The output of these gages was recorded on magnetic tape in the same manner as the pressure gage data. The gages were calibrated statically by means of a spin table. Complete details of this instrumentation can also be found in WT-738.

2.2.5 Instrument Records

The BRL handled all of the instrumentation, with the exception of photographic measurements. The output of the pressure and accelerometer gages was recorded initially on magnetic tape, and later played back from the tape onto oscillographic paper. The records in this form exhibit certain undesirable characteristics (e.g., the ordinate scale is markedly non-linear) which makes them ill-suited for purposes of interpretation and comparison. For that reason all of the records were converted to linear form.

The BRL reduced, calibrated, and plotted to linear scales all of the instrument records. The ARF was responsible for fairing final curves through the plotted points. The BRL also submitted tabulated listings of the points, as well as the original playbacks.

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2.3 LOCATION OF TEST ITEMS

The disposition of the test items at the site is shown in Fig. 2.2. Ground ranges from actual ground zero are given in Table 2.1, along with other pertinent information.

TABLE 2.1 - Test Conditions

Item	Code	Ground Range (ft)	Over-pressure (psi)	Duration (sec)	Thermal Flux (cal/cm^2)
Wooden Boxcar, E	3.6a	6600	1.9	0.99	9
Diesel Locomotive	3.6b	3400	6.0	0.76	33
Wooden Boxcar, E	3.6c	3400	6.0	0.76	33
Wooden Boxcar, L	3.6d	3400	6.0	0.76	33
Plywood Boxcar, E	3.6e	3400	6.0	0.76	33
Wooden Boxcar, E	3.6f	2820	7.5	0.70	50
Wooden Boxcar, L	3.6g	2820	7.5	0.70	50
Steel Boxcar, E	3.6h	2820	7.5	0.70	50
Wooden Boxcar, E	3.6i	1870	9.3 P	0.55	100
Wooden Boxcar, L	3.6j	1870	9.3 P	0.55	100
Plywood Boxcar, E	3.6k	1870	9.3 P	0.55	100
Wooden Boxcar, E	3.6l	4400	4.0	0.86	22
Wooden Boxcar, L	3.6m	1520	13.3 P	0.45	125
Steel Tank Car, RE	3.6n	1520	13.3 P	0.45	125
Steel Tank Car, WE	3.6o	1520	13.3 P	0.45	125
Wooden Boxcar, L	3.6p	4400	4.0	0.86	22

Notes -

A detailed description of test items is given in section 4.1.
Blast data for Shot 10 were taken from WT-782.
E signifies empty car; L one loaded with 30 tons of sandbags; RE a riveted tank shell, empty; WE a welded tank shell, empty; P the precursor region, otherwise Mach region.

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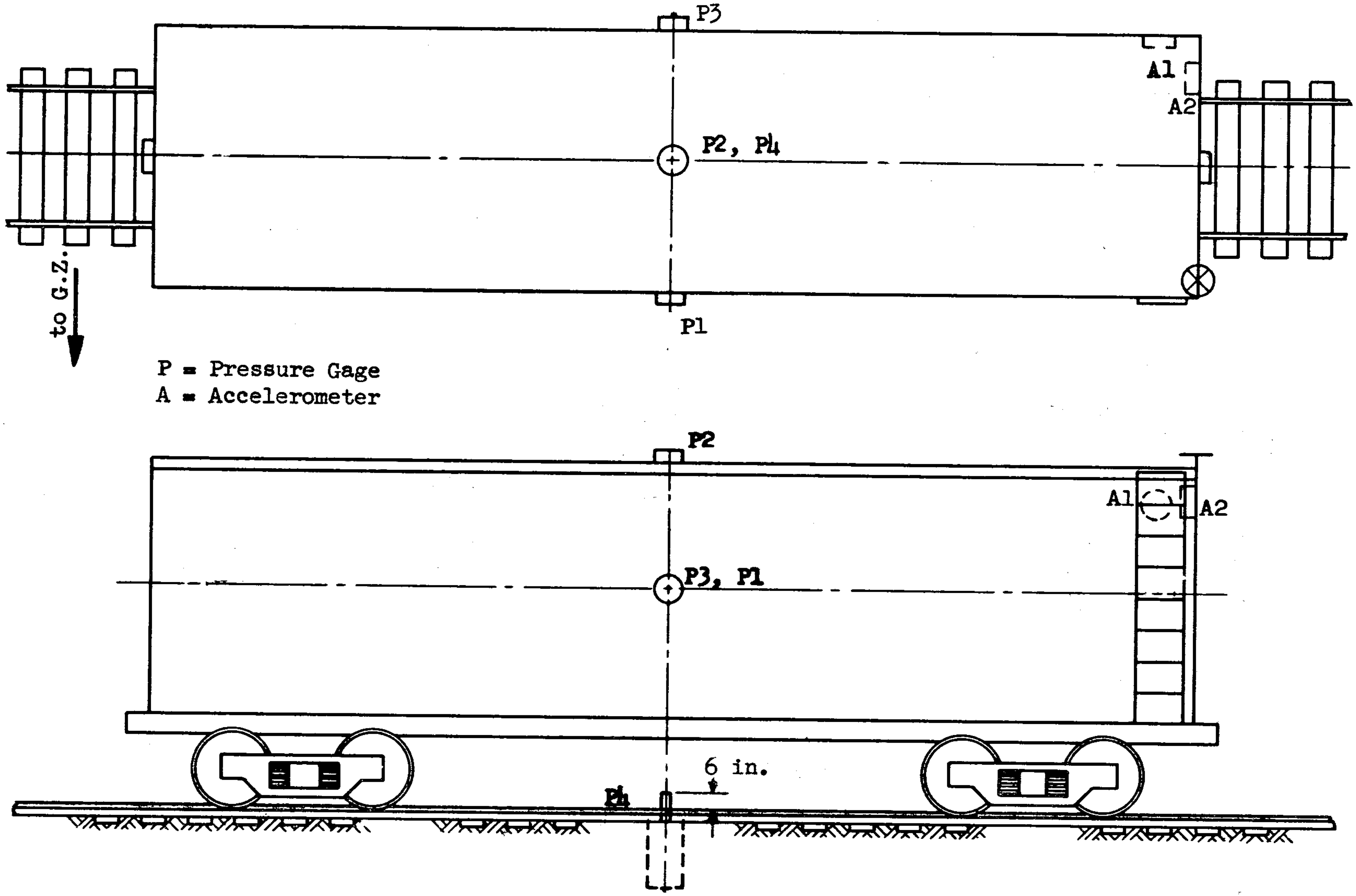

Fig. 2.1 Location of Pressure Gages and Accelerometers on Boxcars

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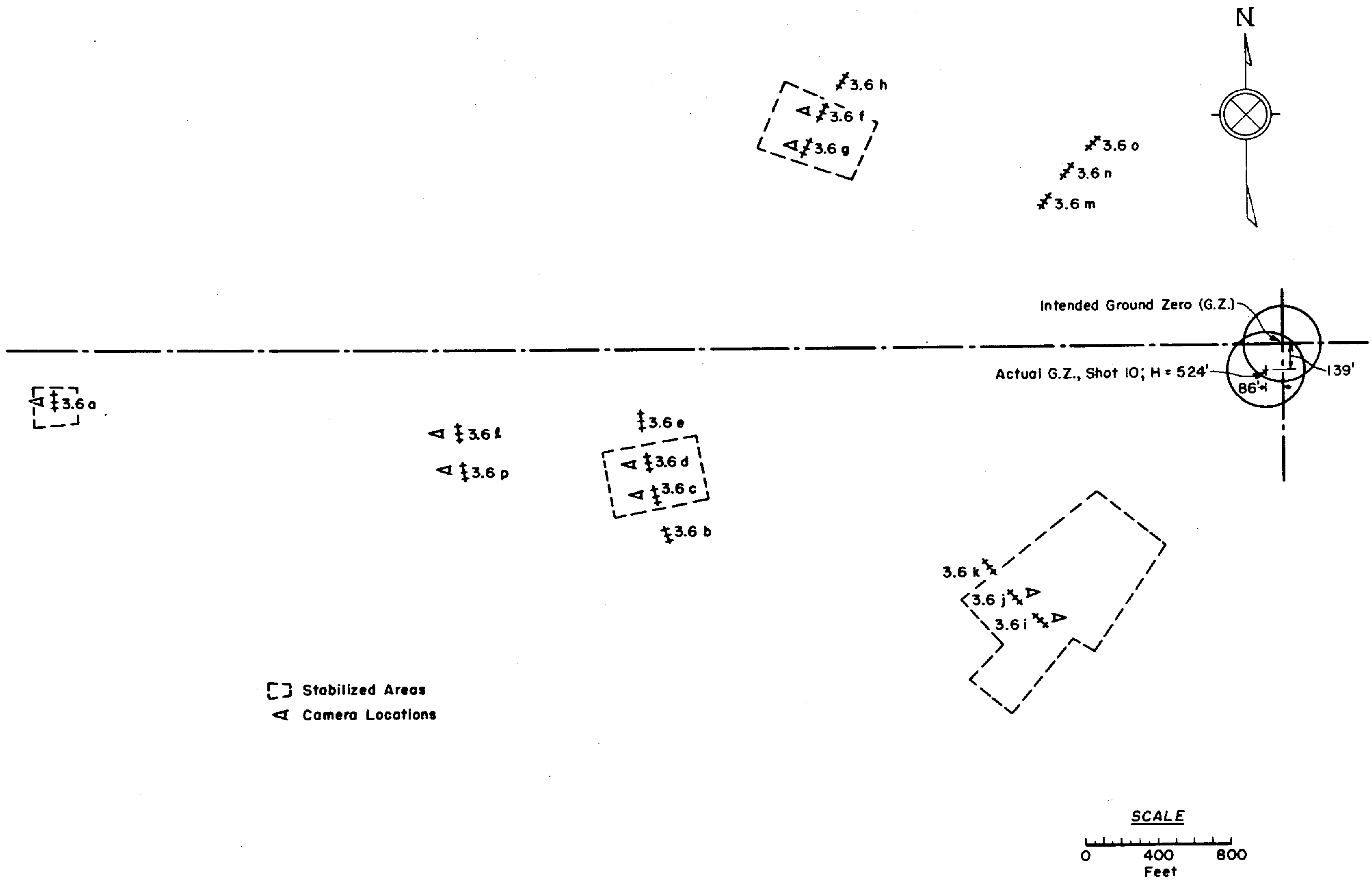

Fig. 2.2 Location of Cars at Test Site

CHAPTER 3

PRETEST CONSIDERATIONS

3.1 INTRODUCTION

Work carried out during the planning, or pretest, phase of this program is presented in Part II of the ARF's final pretest report on Contract No. AF33(038)-30029, Tests of Railroad Equipment. The items tested were selected by the Transportation Corps and were satisfactory for the specific needs of the Air Force. The instrumentation requirements proved to be fairly straightforward and did not comprise a major effort during the pretest phase.

The analytical work, which is summarized in this chapter, was conducted solely for the purpose of determining the most desirable location of the cars at the test site. It was intended that the majority of test items show a definite gradation of damage, ranging through light, moderate, and severe. Thus, even the cars positioned farthest from the blast were intended to suffer some minimum amount of damage. The pretest problem, therefore, reduced to one of specification and prediction of minimum damage. Prior to solution of this problem it was necessary to predict the blast loading on each car for the anticipated test conditions.

It was decided that either gross overturning of the cars or local damage, such as failures of the boxcar roof or side panels (or incipient buckling of a tank car shell), would constitute minimum damage. Accordingly, these were the response modes investigated.

It was concluded that failure of the boxcar panels would occur at somewhat lesser blast pressures than would cause overturning of an empty car. Inasmuch as the computation of local failure was the more approximate, and at best indicated minimum loading conditions for damage, it was decided to place the farthermost cars at a position where overturning appeared to be imminent. With respect to the tank cars, it was indicated that both overturning and collapse of the tank would occur for approximately the same blast conditions. Again, since the overturning computation appeared to be the more reliable, the tank cars were also positioned where overturning was anticipated. The locations of the remaining cars were determined more or less arbitrarily, the closest positions

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being where severe damage appeared likely. The one exception to this was in the case of the locomotive, which was not intended to overturn.

In the analytical work described below, it should be emphasized that, with the exception of the minimum damage conditions, no attempt was made to predict over-all damage to the equipment as a result of the anticipated test conditions. In fact, at the time of the pretest report was prepared, knowledge of Shot 10 conditions was not known to the ARF. Accordingly, changes in the location of the test items had to be made once this information became available.

3.2 BLAST LOADING OF CARS

A detailed analysis of the net blast loads acting on a typical boxcar and tank car within the Mach reflection region1/ was carried out. These results were presented in symbolic form in terms of the car dimensions, and the incident overpressure and positive phase duration of the blast. The basic loading theory was built up from methods first described in the ARF GREENHOUSE reports and from shock tube tests and other studies performed at the ARF during the course of the pretest work, (Parts I, II, IV of final pretest report on Contract No. AF33-(038)-30029). The load prediction scheme is summarized in this section.

The component horizontal and vertical loadings on the various surfaces of a typical boxcar and tank car are shown symbolically in Figs. 3.1 through 3.7. Net pressures are obtained by subtracting these components, i.e., rear from front and top from bottom. As indicated on the figures, the net vertical pressures on the boxcar vanish after the diffraction period, whereas they are identically zero for the tank car during the entire loading period. (Based on pretest work, the effects of ground reflection can be neglected since the tank shell is elevated above the ground a distance greater than one cylinder radius.) For boxcars similar to the types tested, the impulse of the net vertical forces is found to be small as compared to the impulse of the net horizontal forces during the diffraction period.

The shock wave is assumed to strike the sides of the cars normally. In addition, the following assumptions were made:

1. The boxcar is considered to be a rigid rectangular parallelepiped supported above ground level. Special cases of cars with open doors were not considered.

2. The tank car is considered to be a rigid cylinder supported above the ground level.

3. The loadings are not affected by any motion of the cars.

4. The loading on the projected area of the trucks, as well as the influence of small protuberances on the car surfaces, is ignored.

1/ See Chapter 5, Note 1.

[redacted]

The blast quantities given in the figures are defined below. The loading scheme applies only for the conditions of conventional Mach reflection.

L = length of boxcar or tank car, ft.
ℓ = width of boxcar, ft.
h = height of boxcar from track to roof, ft.
$2\bar{h}$ = height of boxcar side, ft.
$2r$ = diameter of tank car, ft.
$p_\sigma(t)$ = free stream overpressure, psi

$$= p_\sigma e^{-t/t_o}\left[1 - (t/t_o)\right].$$

p_σ = peak free stream overpressure, psi.
P_o = atmospheric pressure, psi.
ξ = shock strength

$$= \frac{p_\sigma}{P_o} + 1.$$

f_r = peak reflected pressure, psi

$$= \left[\frac{8\xi + 6}{\xi + 6}\right] p_\sigma .$$

$p_d(t)$ = free stream drag pressure, psi

$$= p_d e^{-2t/t_o}\left[1 - (t/t_o)\right]^2 .$$

$$p_d = \frac{2.5\, p_\sigma^2}{7P_o + p_\sigma} .$$

U = shock front velocity, ft/sec
$= 422\sqrt{1 + 6\xi}$ (standard ambient temperature).
t_o = duration of positive phase of blast, sec.

h^* 2/ = average clearing distance for boxcars, ft

$$= \frac{h + \bar{h}}{2} .$$

$\bar{C}_{rh}$ = average horizontal reflection coefficient for a cylinder. A plot of $\bar{C}_{rh}$ as a function of shock strength is given in Fig. 3.8. The values of the various drag coefficients are indicated on the schematic loadings.

2/ This relationship is approximate and is intended to apply to boxcars of standard dimensions only. It does not satisfy the limiting values of h^* as the car approaches the ground or becomes infinitely removed from it.

[redacted]

3.3 RESPONSE OF CARS

3.3.1 Rigid Body Overturning

The characteristic mode of response of both a boxcar and a tank car was assumed to be overturning. While the suspension system of the cars makes possible a variety of motions, the cars were assumed to rotate as rigid bodies about an axis formed by the wheel flange and rail head. The following assumptions were made in considering the overturning motion:

1. The entire car assembly moves as a rigid body. That is, no relative motion occurs between the car body and the trucks or between the components of the trucks.

2. The moment arm of the forces about the axis of rotation remains constant.

3. Gross motion of the car or failure of the car components has no effect on the predicted loads.

4. The horizontal loading on the trucks and vertical projection of the exposed undersurface of the car as it rotates is neglected.

5. The only effect of the total diffraction loading is to impart an initial velocity to the car.

6. All trigonometric functions of the angle of rotation can be approximated in a linear fashion.

Following is the differential equation which governs the motion of the car until it reaches the critically unstable position from which it will overturn of its own weight.

$$\ddot{\theta} - \Omega^2\theta = \Gamma e^{-2t/t_o}\left[1 - (t/t_o)\right]^2 - \Omega^2\theta_c \qquad (3.1)$$

with initial conditions that

$$\theta = 0 \text{ and } \dot{\theta} = \dot{\theta}_o \text{ at } t = 0.$$

The parameters appearing in Eq. 3.1 are defined later.

The effect of the diffraction loading has been lumped into an equivalent initial angular velocity, $\dot{\theta}_o$. The remaining loading is proportional to the drag forces and is represented by an analytical form. Therefore, it is unnecessary to consider the detailed loading scheme for the response computations. The trigometric functions have been linearized to result in a second order linear differential equation.

The complete solution of Eq. 3.1 is given in Part II of the ARF's pretest report on Contract No. AF33(038)-30029. However, recent work conducted at the ARF on Contract No. AF33(600)-25583, (Study of the Vulnerability of Steam Locomotive to Blast) indicated that the analytical representation of the drag forces can be considerably simplified without introducing significant error. The simplified form of the equation is given by

$$\ddot{\theta} - \Omega\,\theta = \Gamma\, e^{-kt} - \Omega^2\,\theta_c \qquad (3.2)$$

with

$$\theta = 0,\ \dot{\theta} = \dot{\theta}_o \text{ at } t = 0$$

The value of k is chosen as $k = 4.63/t_o$ so that the simplified drag representation preserves the total impulse of the drag forces. The general solution of Eq. 3.2 is given below:3/

$$\theta(t) = \frac{1}{2\Omega}\left[\dot{\theta}_o - \Omega\,\theta_c + \frac{\Gamma}{k+\Omega}\right] e^{\Omega t}$$

$$- \frac{1}{2\Omega}\left[\dot{\theta}_o + \Omega\,\theta_c + \frac{\Gamma}{k-\Omega}\right] e^{-\Omega t} + \frac{\Gamma\, e^{-kt}}{k^2 - \Omega^2} + \theta_c \qquad (3.3)$$

$$\dot{\theta}(t) = \tfrac{1}{2}\left[\dot{\theta}_o - \Omega\theta_c + \frac{\Gamma}{k+\Omega}\right] e^{\Omega t}$$

$$+ \tfrac{1}{2}\left[\dot{\theta}_o + \Omega\,\theta_c + \frac{\Gamma}{k-\Omega}\right] e^{-\Omega t} - \frac{k\,\Gamma\, e^{-kt}}{k^2 - \Omega^2}$$

where

$$k = \frac{4.63}{t_o},\ 1/\text{sec.}$$

$$\Gamma = \frac{C_d A p_d\, b}{I_o},\ 1/\text{sec.}^2$$

3/ The exceptional case for which $k = \Omega$ requires a separate solution of Eq. 3.2.

[redacted]

$$\Omega^2 = \frac{Wa}{I_o \theta_c}, \; 1/\mathrm{sec}^2 .$$

$$\dot{\theta}_o = \frac{i_h b + i_v a}{I_o} - \Omega^2 \theta_c t_d, \quad \mathrm{rad/sec}.$$

A = projected frontal area of car, in^2.
W = total weight of car, lb.
I_o = moment of inertia of entire car about axis of rotation, lb sec^2 ft.
b, a = moment arms of horizontal and vertical forces about axis of rotation, respectively, ft.
θ_c = angle which car must rotate so that its center of gravity is over the axis of rotation, i.e., critical angle, rad.
$\theta(t), \dot{\theta}(t)$ = angular displacement (rad) and velocity (rad/sec) of car, respectively.
i_h, i_v = horizontal and vertical components of diffraction impulse, respectively, lb sec.
t_d = duration of diffraction loading, sec

$$= \frac{\ell + 6h^*}{U}, \text{ for a boxcar,}$$

$$= \frac{5r}{U}, \text{ for a tank car.}$$

The equivalent initial angular velocity, $\dot{\theta}_o$, is given in terms of the car and blast parameters as follows:

For boxcars (or any box-like structure, e.g., the diesel locomotive, 3.6b)4/

$$\dot{\theta}_o = \frac{3h^*}{I_o U} \left\{ \frac{Ab}{2} \left[\frac{(8 - 2.5\, C_d) p_\sigma^2 + 14\, P_o p_\sigma}{p_\sigma + 7\, P_o} \right] - AW \right\} . \qquad (3.4a)$$

For tank cars,5/

$$\dot{\theta}_o = \frac{5\Omega}{I_o U} \left\{ \frac{Ab}{2} \left[\frac{0.36\, p_\sigma^{3/2}}{P_o} + \frac{(1.63 - 2.5 C_d)\, p_\sigma^2 + 11.4 P_o p_\sigma}{p_\sigma + 7 P_o} \right] - AW \right\} . \quad (3.4b)$$

4/ The diffraction impulse of the net vertical forces is neglected.

5/ This expression is based on a parabolic approximation of the reflection coefficient, $\bar{C}_{rh}$ (see Fig. 3.8).

[redacted]

For average car dimensions, i.e., for a boxcar with

$A = 50{,}000 \text{ in.}^2$
$W = 25{,}000$ lb (empty car, neglecting weight of trucks)[6]
$I_o = 54{,}000 \text{ lb sec}^2 \text{ ft}$
$h^* = 8$ ft
$a = 2.4$ ft
$b = 7.5$ ft
$C_d = 1.0,$

$$\dot{\theta}_o = \frac{83.4}{U}\left(\frac{5.5\,p_\sigma^2 + 14\,P_o p_\sigma}{p_\sigma + 7\,P_o} - 0.32\right) . \tag{3.5a}$$

For a tank car with

$A = 27{,}000 \text{ in}^2$
$W = 27{,}000$ lb (empty car, neglecting weight of trucks)
$I_o = 30{,}000 \text{ lb sec}^2 \text{ ft}$
$r = 3.25$ ft
$a = 2.4$ ft
$b = 6$ ft
$C_d = 0.35$

$$\dot{\theta}_o = \frac{44}{U}\left(\frac{0.36\,p_\sigma^{3/2}}{\sqrt{P_o}} + \frac{0.75\,p_\sigma^2 + 11.4\,P_o p_\sigma}{p_\sigma + 7\,P_o} - 0.8\right) . \tag{3.5b}$$

A simple criterion which determines the loading at which the car just overturns can be derived from the above solution, Eq. 3.3. If the coefficient of $e^{\Omega t}$ in these equations is positive, both angular displacement and velocity increase indefinitely with time and overturning is assured. Conversely, if this coefficient is negative, the displacement will reach a maximum value and eventually decrease to zero. Therefore, a necessary and sufficient condition for overturning is that the coefficient of $e^{\Omega t}$ be greater than zero, that is,

$$\dot{\theta}_o - \Omega\theta_c + \frac{\Gamma}{k + \Omega} > 0 . \tag{3.6}$$

If the inequality is replaced by an equal sign, Eq. 3.6 defines the minimum value of the equivalent initial velocity, $\dot{\theta}_o$, required for overturning. The corresponding values of overpressure and duration are most easily found by means of a simple trial and error solution of

[6] This seems reasonable on the basis of the test results.

[redacted]

the implicit relationships between $\dot{\theta}_0$ and the blast variables given in Eq. 3.4 or 3.5 and in the nomenclature.

3.3.2 Structural Damage

An estimate was made of the loads causing local damage to the car sides and tank shell. In these analyses the roof and side panels of the boxcar were assumed to act as simply-supported beams with mass and stiffness uniformly distributed across width and span. The tank shell was assumed to be a uniform closed tube, without initial ellipticity, whose ends are held circular but not otherwise constrained. The blast loadings were assumed to be uniformly distributed over the roof and side panels and around the tank shell. While the actual pressure distribution is certainly other than uniform, consideration of a more realistic distribution is not justified by the approximate nature of the response analysis.

The damage criterion for the panels was assumed to be a displacement of the order of magnitude of the static yield deflection. While it seemed likely that the panels could sustain greater deflections without failing, there appeared to be no better or more rational criterion of damage available. Also, damage predictions based on yield values provide a lower bound to the problem. That is, damage is not expected at pressures below those causing static yield displacements.

Utilizing the above damage criterion, the roof and side panels were expected to fail at loadings of from 0.3 to 0.5 psi. The time of failure was computed to be from 20 to 30 ms after the beginning of the blast pulse. This time is close to the end of the diffraction loading and considerably less than the time of overturning (i.e., from 0.2 to 0.3 sec). The failure loads are also much less than those associated with overturning (e.g., about 2 psi would be required to overturn an empty boxcar). No attempt was made to estimate the damage to the cars resulting from overturning and subsequent impact.

The damage criterion for the tank cars was assumed to be elastic buckling of the tank shell. The analysis was very approximate in that the static buckling load was modified by a so-called dynamic load factor to account for the behavior of the tank shell under dynamic load. The factor was determined by considering a simple mass-spring system having the same period of vibration and static displacement as the shell. These computations led to an overpressure of about 13 psi for collapse. This is in the range of overturning so that the tank cars were not expected to be damaged without overturning. No attempt was made to treat the case of a filled tank or damage resulting from impact of the tank shell with the ground.

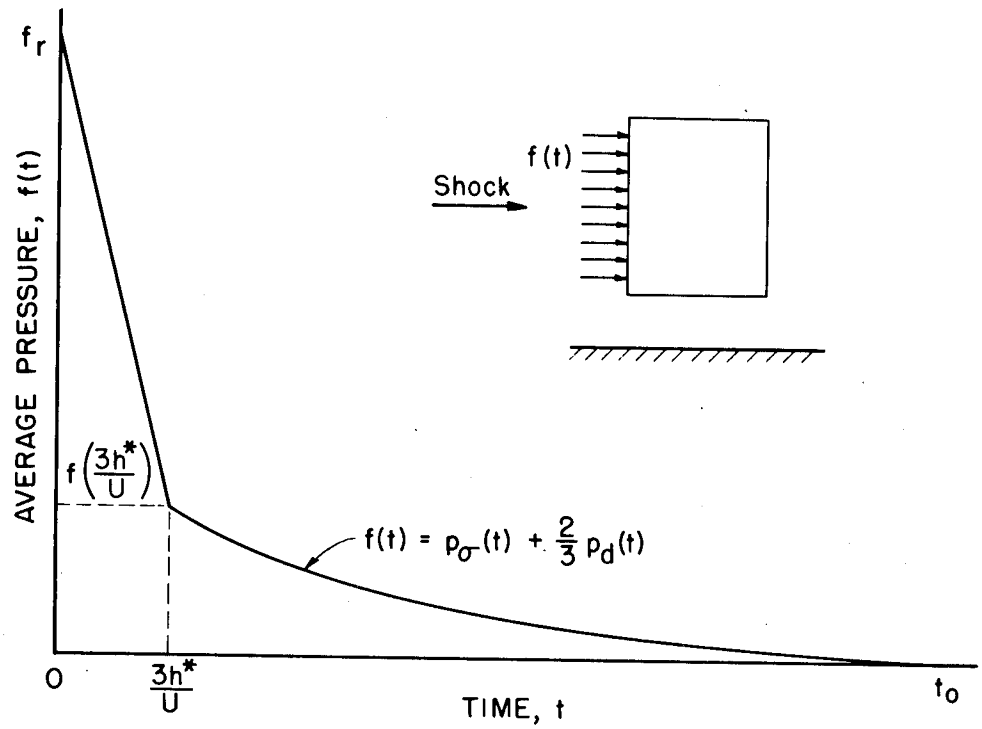


Fig. 3.1 Average Horizontal Pressure on Front of Boxcar

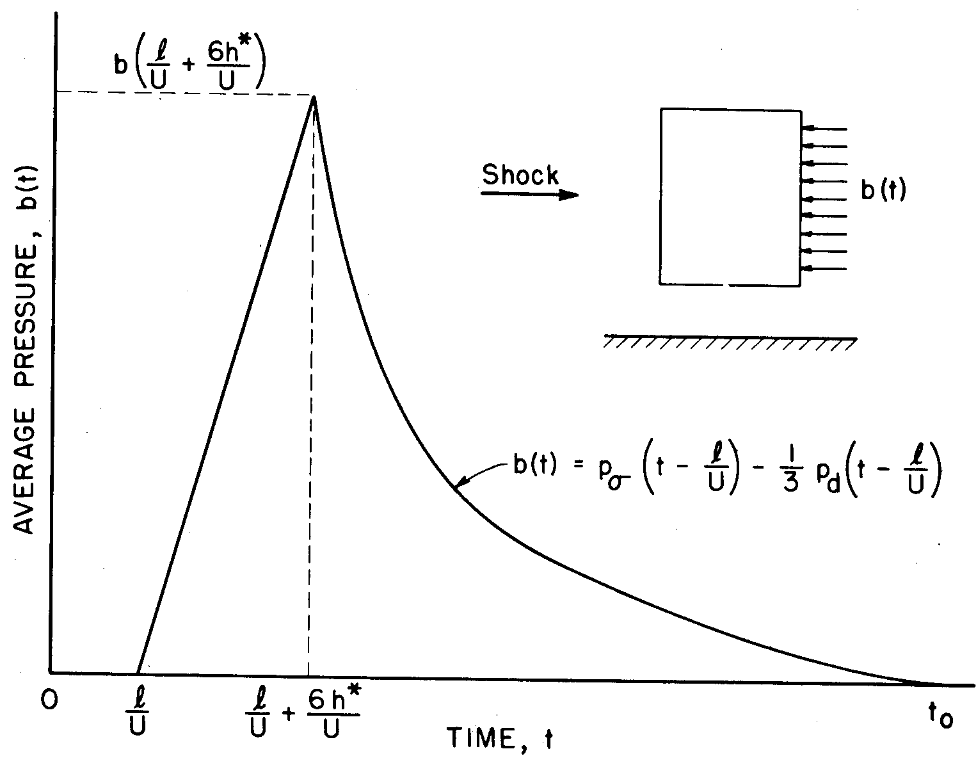


Fig. 3.2 Average Horizontal Pressure on Back of Boxcar

[redacted]

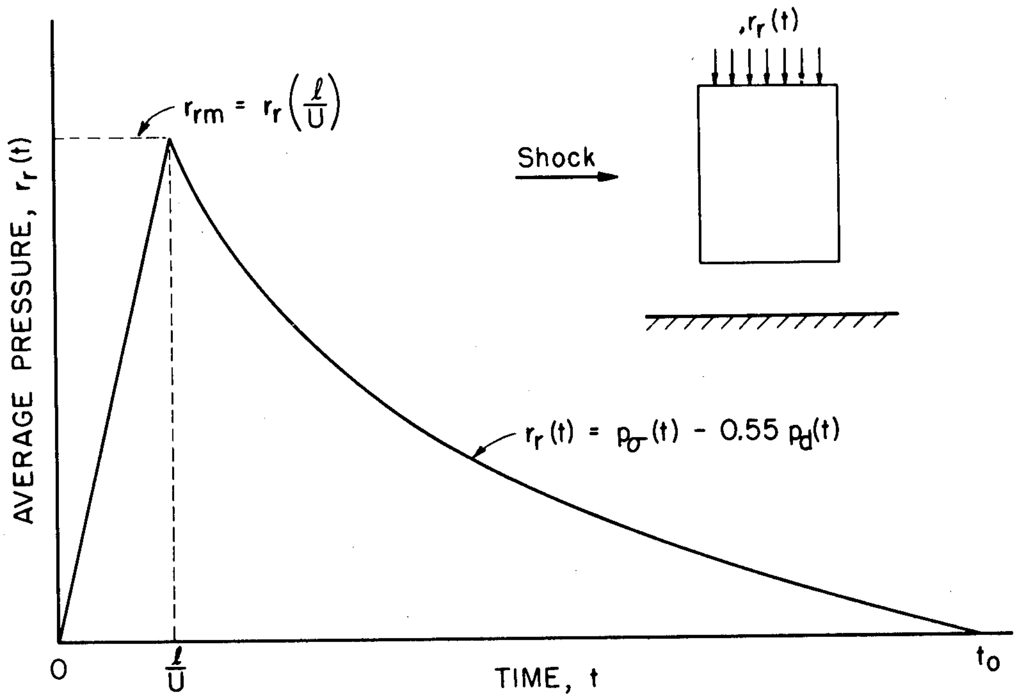


Fig. 3.3 Average Vertical Pressure on Top of Boxcar

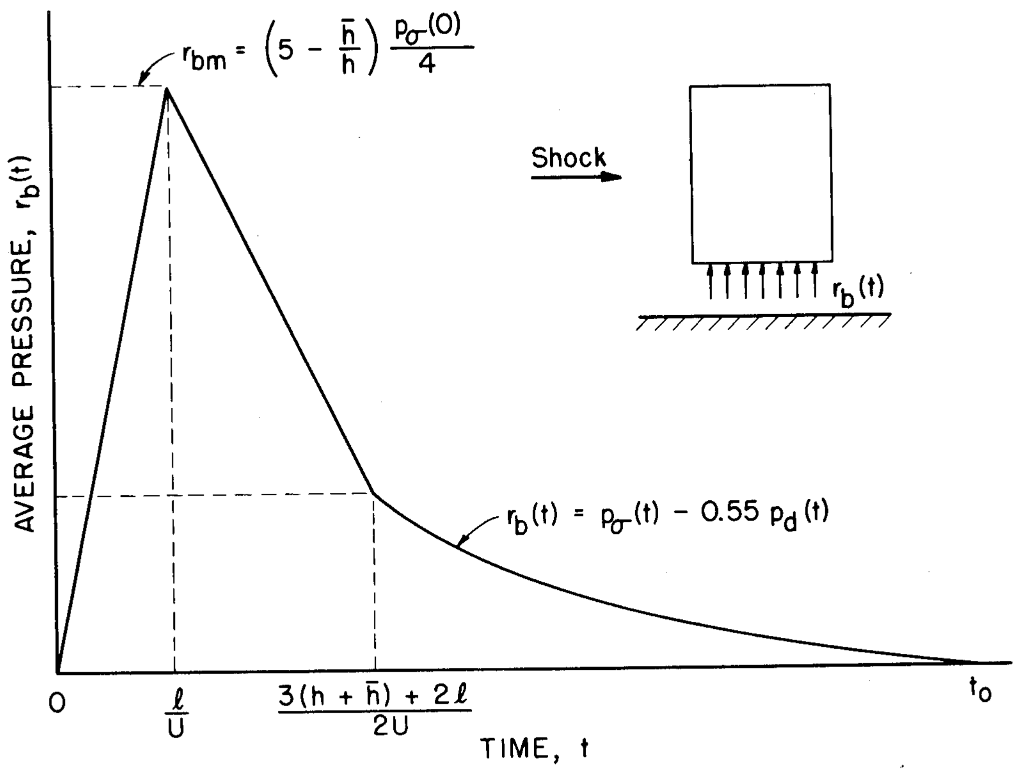


Fig. 3.4 Average Vertical Pressure on Bottom of Boxcar

[redacted]

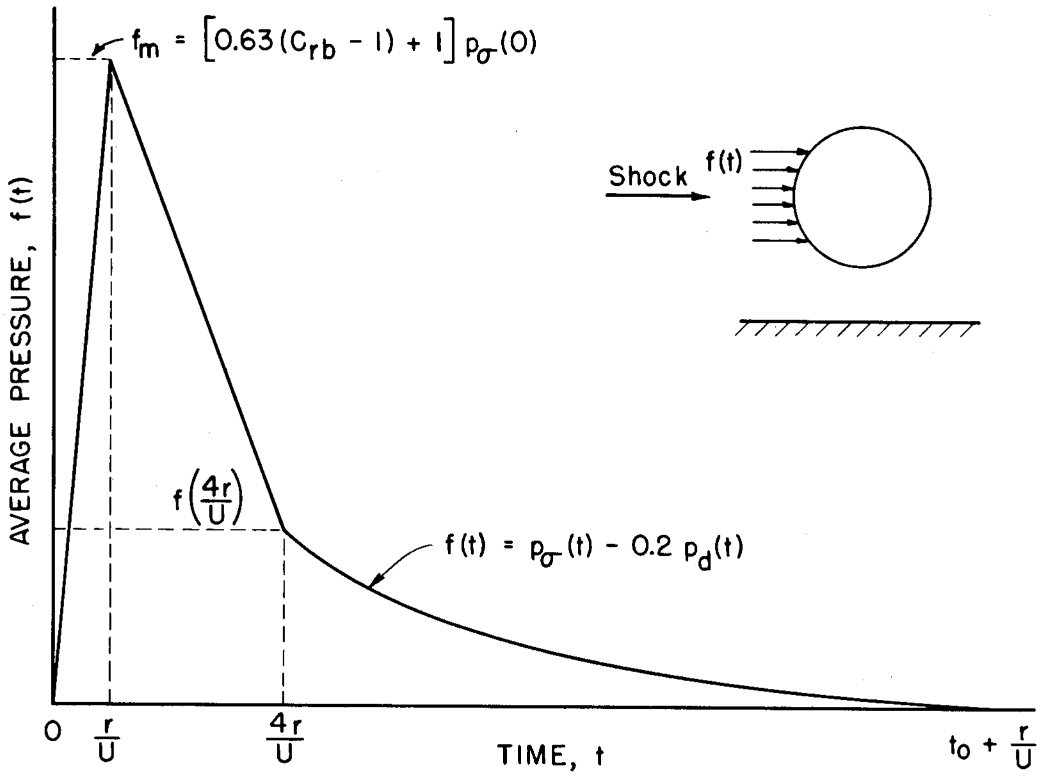


Fig. 3.5 Average Horizontal Pressure on Front of Tank Car

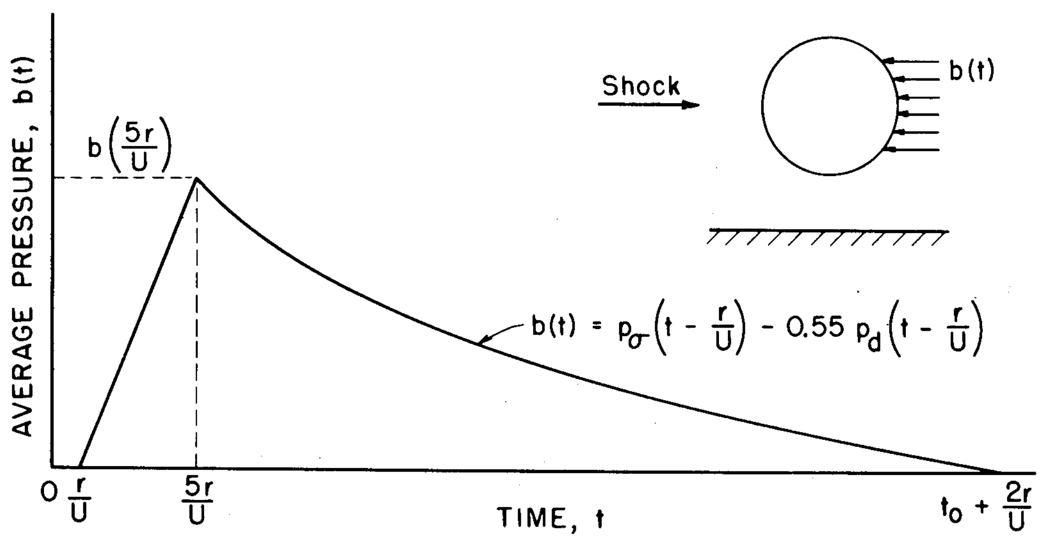


Fig. 3.6 Average Horizontal Pressure on Back of Tank Car

[redacted]

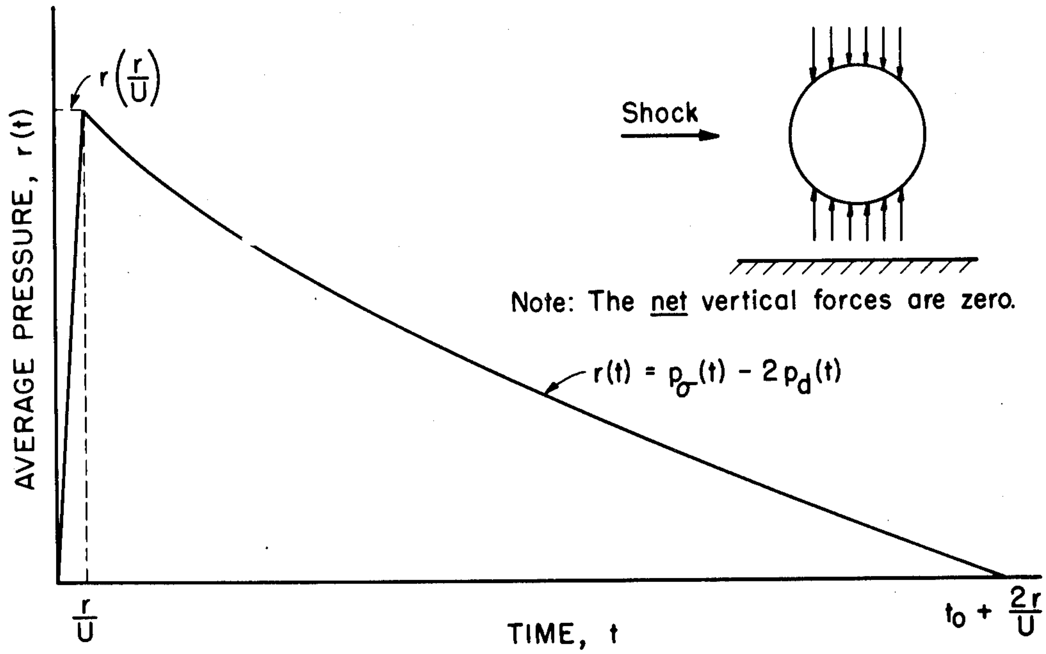


Fig. 3.7 Average Vertical Pressures on Top and Bottom of Tank Car

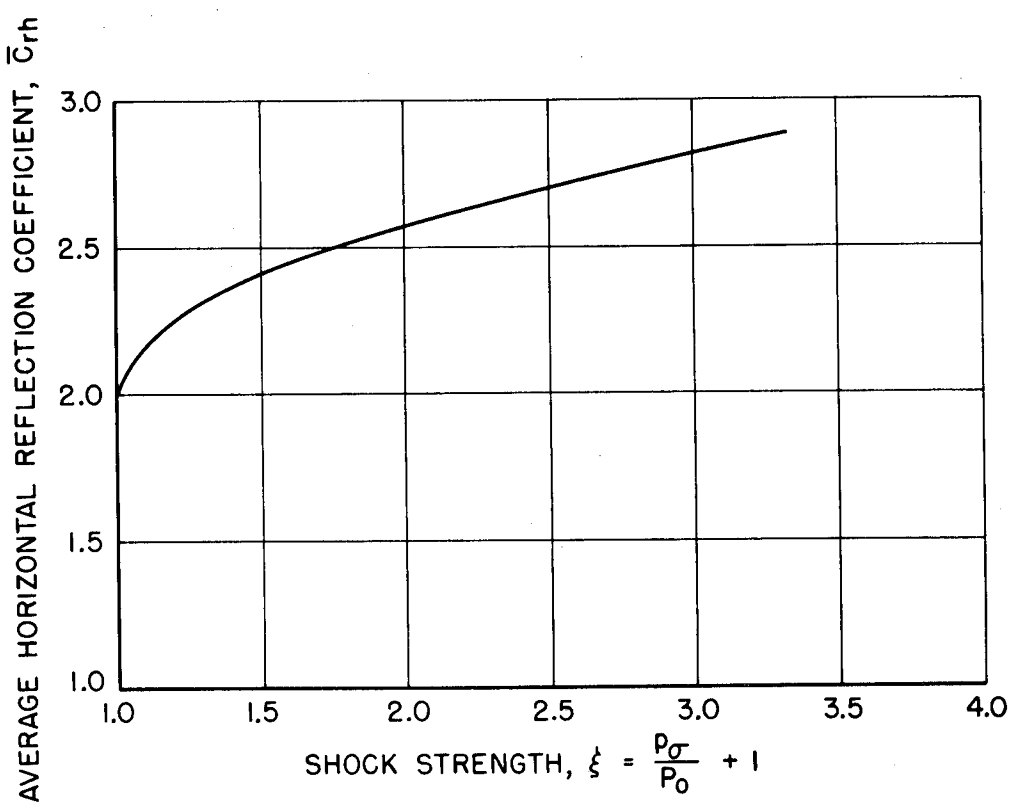


Fig. 3.8 Average Horizontal Reflection Coefficient, $\bar{C}_{rh}$

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 VISUAL OBSERVATIONS

4.1.1 Introduction

All test items received at least minor damage, as intended. Those located within the precursor region (within about 2500 ft of ground zero) suffered an extreme amount of damage. A qualitative idea of the severity of the blast in this region is indicated by the fact that a loaded boxcar located at 1870 ft from ground zero (3.6j) was hurled about 100 ft through the air; the shell of a tank car at 1520 ft (3.6n) from ground zero came to rest about 2800 ft from its original position. Those cars located outside of the precursor region showed a definite gradation of damage, ranging through light, moderate, and severe, to both cars and cargo. In this respect the test was highly successful.

A detailed description of the results and observations with respect to each item of equipment was prepared by Transporation Corps specialists. For convenience in making the damage survey, a plan diagram of the equipment was prepared and marked off into sections for each reference. This diagram is shown in Fig. 4.1. The identification symbols used in the following discussion refer to the points indicated in the figure. In some instances the left side of the car (L) was oriented toward ground zero, and in others the right side (R) was so oriented. Pre- and post-test photographs are shown in Figs. 4.2 through 4.25.

4.1.2 Boxcar 3.6a

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 6600 ft.
Overpressure: 1.9 psi.
Thermal flux: 9 cal/cm^2.

[redacted]

Equipment: wooden boxcar (USA24837) (empty), Fig. 4.2.
Weight: 41,500 lb.

Damage -

1. Car door on left side destroyed.
2. Two broken side posts on left side.
3. Sheeting on left side damaged.
4. Minor damage to lining on left side.

Brief -

Car remained upright on track and would have been capable of continued operation without repair. No damage to track. No indication of movement of car on track. Estimated that 50 man-hours would be required to put car back into preblast condition. Damage due to blast considered slight, and that due to thermal effects negligible.

4.1.3 Locomotive, 3.6b

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 3400 ft.
Overpressure: 6.0 psi.
Thermal flux: 33 cal/cm^2.
Equipment: diesel electric locomotive (USA8527), Figs. 4.3, 4.4, 4.5.
Weight: 92,160 lb.

Damage -

1. Left rear kickboard destroyed.
2. All windows in cab blown out.
3. High-voltage cabinet doors slightly sprung.
4. Left door window frame broken and door slightly sprung.
5. Cab facing on left side dished in 1 in. under window.
6. Cab light blown out of socket.
7. Left side of front engine cowling doors and door framing dished in 3-1/2 in.
8. Sand door on left front struck by flying object and bent.
9. Left side of rear engine cowling doors and door framing dished in 3 in.
10. Sand door on left rear bent and one hinge broken.
11. Battery compartment doors dished in 1 in.
12. Auxiliary generator and compressor compartment doors dished in 2 in.
13. Compressor air filter jarred loose.

[redacted]

14. Two panels on shutter on front end jarred loose.
15. All window wipers broken.
16. Flexible exhaust on No. 2 engine broken.
17. Brackets for muffler on No. 1 engine broken loose.
18. All rocker arm housing covers on the blast side damaged due to cowling framing being bent in against them. Covers on Nos. 1 and 3 cylinders on both engines ruptured in this manner. Rocker arms rubbing on housing due to this.
19. Main generator shrouds on both engines bent. Damage on No. 1 engine generator shroud occurred on the blast side and that on No. 2 engine occurred on side away from blast.

Brief -

Locomotive remained upright on track and would have been capable of continued operation after dents had been straightened in rocker arm housing covers. Locomotive engine running at time of blast; still running 1-1/2 hours after blast. Inspection of instruments after blast indicated that engines had been operating normally in every respect. Engine was running at speed of approximately 500 rpm. Engine again run two days later and operated normally in every respect. No damage to track at this location. Two hundred and fifty man-hours would be required to fabricate and install new cowling where damaged.

4.1.4 Boxcar 3.6c

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 3400 ft.
Overpressure: 6.0 psi.
Thermal flux: 33 cal/cm^2.
Equipment: wooden boxcar (USA 24343)(empty), Figs. 4.6, 4.7.
Weight: 40,300 lb.

Damage -

1. Journal bearings and wedges displaced on L-1, L-2, R-1, and R-2.
2. Knuckle pin displaced 3 in. on B end of car.
3. Wooden sub-flooring split on A end of car and steel flooring slightly bowed at the middle of the car.
4. Doors demolished and scattered 100 ft.
5. Side posts and diagonal bracing demolished on the blast side.
6. Siding on blast side demolished and scattered; siding on off side severely damaged.

[redacted]

7. Side posts and diagonal bracing, on off side bent.
8. Lining on blast side demolished and scattered; lining on off side moderately damaged.
9. B-end of car slightly dished in.
10. Roof demolished and scattered over a radius of approximately 100 ft.
11. Hand brake wheel and rod bent.

Brief -

Appeared that car body had been lifted slightly, rotating about the side bearings and landing on its side approximately 6 ft from the track. Trucks appeared to have been pulled from the rail by brake rods connecting car body and trucks. No damage to track. To place car in original condition would require approximately 600 man-hours. In a theater of operations it is probable that the superstructure would be removed from this car and that it would be made into a flatcar rather than rebuilt as a boxcar. Damage due to blast severe. Thermal damage negligible.

4.1.5 <u>Boxcar 3.6d</u>

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 3400 ft.
Overpressure: 6.0 psi.
Thermal flux: 33 cal/cm^2.
Equipment: wooden boxcar (USA 24711)(loaded with 30 tons of sandbags), Fig. 4.8.
Weight: tare, 41,300 lb; total, 101,300 lb.

Damage -

1. Flooring moderately damaged in center of car between loads.
2. Stringers moderately split in center of car.
3. Door on blast side demolished; door on off side severely damaged.
4. Side posts and diagonal bracing severely damaged on blast side, moderately damaged on off side.
5. Siding demolished.
6. Lining demolished except on off side below the load line.
7. Roof demolished.
8. Roof carlines slightly damaged.

Brief -

Car remained upright on track and would have been capable of being moved on its own wheels for shipping. No damage to track. Damage due to blast severe, and that due to thermal effects negligible. Cargo would have been slightly damaged. Approximately 600 man-hours would be required to place car in original condition. In a theater of operations it is doubtful if this car would be rebuilt as a boxcar.

4.1.6 Boxcar 3.6e

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 3400 ft.
Overpressure: 6.0 psi.
Thermal flux: 33 cal/cm^2.
Equipment: plywood boxcar, overseas type (USA 370001)(empty), Fig. 4.9.
Weight: 35,700 lb.

Damage -

1. Wedges out of place on L-1 and R-1.
2. Doors demolished and scattered over wide area.
3. Siding demolished on blast side and severely damaged on off side; pieces scattered over wide area.
4. B-end slightly sprung due to contact with ground on overturning.
5. Roof demolished and scattered over wide area.

Brief -

Appeared that car body had been lifted slightly, rotating about the side bearings and landing on its side approximately 3 ft from track. Trucks appeared to have been pulled from rail by brake rods connecting car body and trucks. No damage to track. Car body severely damaged by blast, but underframe, trucks, and decking salvable. Thermal damage negligible. This plywood construction seems to be extremely susceptible to blast damage.

4.1.7 Boxcar 3.6f

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 2820 ft.
Overpressure: 7.5 psi.
Thermal flux: 50 cal/cm^2.

[redacted]

Equipment: wooden boxcar (USA 25097)(empty), Fig. 4.10.
(See Fig. 4.26 for sequence of motion.)
Weight: 50,100 lb.

Damage -

1. Floor moderately damaged.
2. Stringers split.
3. Doors demolished.
4. Side posts and diagonal bracing demolished.
5. Siding demolished and scattered over wide area.
6. Lining demolished.
7. Car ends sprung outward and moderately damaged.
8. Roof demolished and scattered over a distance of 100 yd.
9. Brake rod bent and broken loose from car.

Brief -

Appears that car overturned about the point of contact between wheel flanges and rail, coming to rest on its side, with roof edge on ground and the edge of the flooring supported by trucks. No track damage. Underframe and running gear of car salvable. Car severely damaged by blast. Thermal damage negligible.

4.1.8 Boxcar 3.6g

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 2820 ft.
Overpressure: 7.5 psi.
Thermal flux: 50 cal/cm^2.
Equipment: wooden boxcar (USA 25437)(loaded with 30 tons of sandbags), Fig. 4.11.
Weight: tare, 41,900 lb; total, 101,900 lb.

Damage -

1. Some displacement of truck springs.
2. Floor slightly damaged.
3. Stringers slightly damaged.
4. Doors demolished.
5. Siding and lining demolished on blast side, severely damaged on the off side.
6. Car ends slightly bulged out.
7. Roof demolished and scattered over wide area.

Brief -

Appeared that car body had been lifted slightly, rotating about side bearings and landing on its side next to track. Trucks appeared to have been pulled from rail by brake rod connecting car body and trucks. No damage to track. Car severely damaged by blast. Thermal damage negligible. Underframe and trucks salvable, although car was not repairable.

4.1.9 Boxcar, 3.6h

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 2820 ft.
Overpressure: 7.5 psi.
Thermal flux: 50 cal/cm^2.
Equipment: steel boxcar (USA 25938)(empty), Fig. 4.12.
Weight: 44,840 lb.

Damage -

1. Side frame sprung on A-end of car.
2. Brasses and wedges displaced on L-1 and R-1.
3. Knuckle pin out on A-end of car.
4. One side bearing missing.
5. Flooring slightly damaged.
6. Door on blast side severely damaged; door on off side moderately damaged.
7. Side posts and diagonal bracing destroyed on blast side.
8. Siding on blast side severely damaged, on off side slightly damaged.
9. Lining on blast side destroyed, severely damaged on off side.
10. Both ends slightly buckled due to contact with the ground when overturning.
11. Steel roof moderately damaged.
12. Running boards destroyed.
13. Hand brake severely bent and inoperable.

Brief -

Appeared that car body had been lifted slightly, rotating about the side bearings and coming to rest on its roof after making a half turn about 12 ft from the track. Trucks pulled from track by brake rods. Tracks slightly damaged. Spikes loosened and track bent away from point of blast at center of track. Approximately 300 man-hours would be required to repair the car. Damage by blast severe. Thermal damage negligible. This car had an unusually strong roof structure, which is not standard for all steel boxcars.

[redacted]

4.1.10 Boxcar 3.6i

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 1870 ft.
Overpressure: 9.3 psi, precursor region.
Thermal flux: 100 cal/cm^2.
Equipment: wooden boxcar (USA 25100)(empty), Fig. 4.13.
Weight: 49,000 lb.

Damage -

Car completely demolished. Approximately 50 per cent of the truck component parts considered salvable.

Brief -

Appeared that entire car had been blown laterally through the air. Trucks found at 75 ft and 150 ft, respectively, from track. Car body hit ground at approximately 200 ft from track and was demolished. One end of car found approximately 1000 ft from track. Rail on off side blown from track and/or torn off by lateral thrust of car and displaced approximately 75 ft from track. Ballast slightly disturbed by blast. Car demolished by blast. Thermal damage negligible.

4.1.11 Boxcar 3.6j

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 1870 ft.
Overpressure: 9.3 psi, precursor region.
Thermal flux: 100 cal/cm^2.
Equipment: wooden boxcar (USA 24730)(loaded with 30 tons of sandbags, Fig. 4.24), Figs. 4.14 and 4.15.
Weight: tare, 41,300 lb; total, 101,300 lb.

Damage -

Car completely demolished. Approximately 50 per cent of truck and coupler component parts salvable.

Brief -

Appeared that entire car had been blown laterally through the air. Trucks found approximately 30 ft from track. Car body and underframe came to rest approximately 125 ft from track. Appears to have struck the ground first about 75 ft from the track and then made one complete turn before stopping. Rail on off side of track displaced at the center away from point of blast but remained fastened at the ends. Ballast slightly disturbed by blast. Car demolished by blast. Thermal damage negligible. Cargo would have been severely damaged or demolished.

4.1.12 Boxcar 3.6k

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 1870 ft.
Overpressure: 9.3 psi, precursor region.
Thermal flux: 100 cal/cm^2.
Equipment: plywood boxcar, overseas type (USA 370002) (empty), Fig. 4.16.
Weight: 35,900 lb.

Damage -

Car completely demolished. Some parts of the trucks and air brake equipment salvable.

Brief -

Appeared that entire car had been blown laterally through the air. Trucks found approximately 50 ft from track. Car body and underframe came to rest approximately 660 ft from track. Frame badly twisted. Track remained in place with slight bulge toward point of blast. Spikes loosened to some extent. Slight shift of ballast on blast side of track. Car completely demolished by blast. Thermal effects negligible.

4.1.13 Boxcar 3.6ℓ

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 4400 ft.
Overpressure: 4.0 psi.
Thermal flux: 22 cal/cm^2.
Equipment: wooden boxcar (USA 24344)(empty), Fig. 4.17.
Weight: 40,200 lb.

Damage -

1. Displaced journal bearings on L-1, L-2, R-1, and R-2.
2. Steel flooring slightly loose.
3. Door on blast side destroyed; door on off side moderately damaged.

[redacted]

4. Side posts and diagonal bracing badly damaged on blast side, and slightly damaged on off side.
5. Siding demolished on blast side, and slightly damaged on off side.
6. Lining demolished on blast side, and slightly damaged on off side.
7. Roof completely demolished and scattered over wide area.
8. Roof carlines bent.
9. Hand brake rod bent.

Brief -

Appeared that car body had been lifted slightly, rotating about the side bearings and coming to rest on its side next to the track. One truck derailed by being pulled from track by brake rod. Car would require 200 man-hours to repair. Damage by blast severe. Thermal damage negligible. No damage to track.

4.1.14 <u>Boxcar 3.6m</u>

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 1520 ft.
Overpressure: 13.3 psi, precursor region.
Thermal flux: 125 cal/cm^2.
Equipment: wooden boxcar (USA 25433)(loaded with 30 tons of sandbags), Fig. 4.18.
Weight: tare, 42,200 lb; total, 102,200 lb.

Damage -

Car completely demolished. Some component parts of trucks and couplers salvable.

Brief -

Car appeared to have been blown laterally through the air. Trucks found approximately 90 ft from track. Balance of car came to rest against a concrete structure approximately 400 ft from track. Cargo scattered over wide area. Any real cargo would have been demolished. Rail on off side of track torn loose and found approximately 150 ft from track. Appeared bent and unusable. Balance of track (rail and ties) bent into an "S" shape. Car completely demolished by blast. Thermal damage negligible.

4.1.15 Tank Car 3.6n

Parameters -

Side exposed to blast: right.
Distance from actual ground zero: 1520 ft.
Overpressure: 13.3 psi, precursor region.
Thermal flux: 125 cal/cm^2.
Equipment: steel tank car, riveted (USAX 14208)(empty), Figs. 4.19, 4.20, and 4.21.
Weight: 42,200 lb.

Damage -

Car completely demolished. No value other than scrap metal.

Brief -

Car appeared to have been blown laterally from track. Trucks found approximately 125 ft from track. Tank shell of car found 2800 ft from track. Apparently struck ground at point 1300 ft from track. It bounded across the ground, striking 14 times before coming to rest. A part of the underframe was found as a twisted mass approximately 600 ft from the track. The other part of the underframe was found approximately 300 ft from track. The two parts of underframe separated by a lateral distance of approximately 200 ft. Tank anchor pulled loose from underframe by shearing of rivet heads. Rail from off side of track torn loose and found approximately 150 ft from track. Rail on blast side and ties bent into an "S" shape. Car completely demolished by blast. Thermal damage negligible.

4.1.16 Tank Car 3.6o

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 1520 ft.
Overpressure: 13.3 psi, precursor region.
Thermal flux: 125 cal/cm^2.
Equipment: steel tank car, welded (USAX 14316)(empty), Figs. 4.22 and 4.23.
Weight: 42,900 lb.

Damage -

Car completely demolished. No value other than scrap metal.

[redacted]

Brief -

Car appeared to have been blown laterally from track. Trucks found approximately 100 ft from track. Tank shell found 1200 ft from track. Underframe broke into two parts, which were found approximately 600 ft from track. Welded tank shell appears to have withstood blast damage somewhat better than riveted tank shell even though both were severely damaged. Rail on off side of track torn loose and found lying near car trucks approximately 100 ft from track. Rear rail was distorted, but not as much as at sites 3.6m and 3.6n. Car completely demolished by blast. Thermal damage negligible.

4.1.17 Boxcar 3.6p

Parameters -

Side exposed to blast: left.
Distance from actual ground zero: 4400 ft.
Overpressure: 4.0 psi.
Thermal flux: 22 cal/cm^2.
Equipment: wooden boxcar (USA 25435)(loaded with 30 tons of sandbags), Fig. 4.25.
Weight: tare, 41,800 lb; total, 101,800 lb.

Damage -

1. Side bearing right side of B-end cracked.
2. Floor intact under load, but separated and loose in center of car between loads.
3. Stringers damaged in center of car between loads.
4. Doors demolished.
5. Side posts and diagonal bracing bent on the blast side and undamaged on the off side.
6. All siding on blast side damaged beyond repair. On the off side, siding was damaged on the B-end of the car.
7. Lining was damaged on the blast side beyond repair. On the off side it was only slightly damaged.
8. Roof demolished and scattered over a wide area.
9. Roof carlines slightly bent.
10. Brake rod bent.

Brief -

Car remained upright on track and could have been moved on its own wheels to a shop for repair. Approximately 200 man-hours would be required to repair car. No damage to track. Damage by blast severe. Thermal damage negligible.

4.2 INSTRUMENTATION RESULTS

4.2.1 Photographic Measurements

Films were obtained from each of the cameras, except for one camera each at locations 3.6i and 3.6j. These were the closest locations at which cameras were provided and the camera towers were blown down. Even though there was considerable dust obscuration, it was possible to take some measurements from all films and this type of instrumentation proved to be very valuable. Enlargements of selected frames from the film are shown in Fig. 4.26. The dust interference and difficulties involved in taking accurate measurements from the films are evident from these pictures. Figure 4.26 represents every second consecutive frame of car 3.6f; the action is progressing at approximately 0.03 sec. The film shows clearly the separation of the trucks from the car body and the failure of the roof and side panels prior to complete overturning.

4.2.2 Air Pressure Measurements

Seven pressure-time records were obtained from the eight pressure gages provided (four each on 3.6m and 3.6g). The missing gage was P3 on 3.6m. Both boxcars were overturned and severely damaged by the blast.

Table 4.1 lists the individual gages and gives comments concerning each. It should be noted that there are only three records which had observation times in excess of about 20 ms and that one of these is unreliable. These short observation times may well have been due to cable failures since, as is evident in Fig. 4.26, the gaged cars rotated by as much as 20 deg or more during the first 30 ms after shock arrival. (Figure 4.26 refers to the motion of car 3.6f, which was at the same ground range as the gaged car 3.6g; the other gaged car was still closer to the blast.) Representative pressure records are shown in Figs. 4.27 and 4.28.

The load prediction methods cannot be checked on the basis of the records obtained, principally because of the short observation time on most of the records. It should also be noted that at least two of the fundamental assumptions of the prediction method proved to be invalid in that: (1) one boxcar (3.6m) was struck by a precursor wave rather than by a single clean shock wave, and (2) both of the instrumented boxcars, just prior to being struck by the blast wave, were in a region of extreme temperature gradients. It is believed that these variations were of sufficient magnitude so as to disallow a legitimate evaluation of the load prediction method, even if perfect records had been obtained.

The only really usable records obtained from the test were those located at the bottom of the cars (3.6mP4 and 3.6gP4). Unfortunately, due to the conditions of the test, all that can really be said about these is that some data have been obtained, but they refer to a very particular set of circumstances.

[redacted]

The comparison between predicted and observed motion of the cars discussed in Chapter 5 following tends to support in a general fashion the loading methods used in the response computations. However, certain of the assumptions regarding car response proved to be involved, and this type of comparison cannot be thought of as a conclusive or necessarily meaningful check on the loading methods. If additional verification of these methods is desired in the future, it is believed that this can most advantageously be done by means of shock tube studies.

4.2.3 Acceleration Measurements

Records were obtained from both of the accelerometers placed on car 3.6g. These gages were expected to record the time history of the acceleration of the car after being struck by the blast wave. An analysis of these records indicates the following:

1. The major portion of each record shows a signal of uncertain origin during the time interval between the detonation of the bomb and the arrival of the shock at the car. The desired accelerated motion was not recorded. This conclusion seems to be well justified since the time between the electromagnetic disturbance and the major oscillation at the end of the trace is measured to be about 1.3 sec, which checks very closely with the time of arrival of the shock at this position. The signal observed during this time may be noise in the instrumentation system.

2. The brief portion at the end of each record which shows the actual response of this car is indicative of the fact that either initial accelerations exceeded the limits of the accelerometer used or some other sort of gage or even cable failure occurred.

Thus, the acceleration data do not afford any additional information as to the motion of the cars. However, it is believed that an adequate amount of knowledge has been gained from the motion picture films, and that the additional information which might have been obtained from the accelerometer records is not now necessary in order to achieve the test objectives. One accelerometer record is shown in Fig. 4.29.

TABLE 4.1 - Comments on Individual Pressure Gages

Record No.	Diffraction Phase	Drag Phase	Pressure Scale	Remarks
3.6 P1 (Front)	Exhibits reflection of compression wave with sudden drop to pseudo steady state value.	Reasonable in form initially.	Approximately 1/2 of expected value.	This gage indicates a pressure of 5 psi at a time of 1 sec, which is not correct. (Positive wave duration was only 0.5 sec.) The gage may have been damaged and taken a new zero value.
3.6 P2 (Roof)	Slow rise to reasonable value of pressure.	Does not exist.	Reasonable.	Record stops at t = 23 ms.
3.6 P3 (Back)	- - - - - -	- -	- -	No record obtained.
3.6 P4 (Bottom) (On Post)	Slow rise, which may be reasonable.	Reasonable until t = 100 ms.	Reasonable initially.	Record had extreme amount of "hash." Pressure is greatly influenced by the motion of the boxcar. Fast and slow playbacks had pressure scales which differed by a factor of 10. This obvious error was easily corrected.
3.6 P1 (Front)	Slow rise to approximate reflected value; then an extremely fast decay to pseudo steady state pressure.	Does not exist.	Reasonable.	Record stops at t = 15 ms.
3.6 P2 (Roof)	Slow rise, as expected; then evidence of vortex. Form reasonable.	Does not exist.	Approximately 1/2 of expected pressure.	Record stops at t = 32 ms.
3.6 P3	Much faster rise to pseudo steady state value than expected (rise time = 15 ms).	Does not exist.	Reasonable.	Record stops at t = 20 ms.
3.6 P4 (Bottom) (On Post)	First 20 ms of record reasonable; then gage indicates second pressure pulse, after which it decays to pseudo steady state value. Second pressure pulse may be due to boxcar motion.	Reasonable.	Reasonable.	The two playbacks reviewed were consistent and indicated a positive phase duration of approximately 0.66 sec, which is also reasonable.

[redacted]

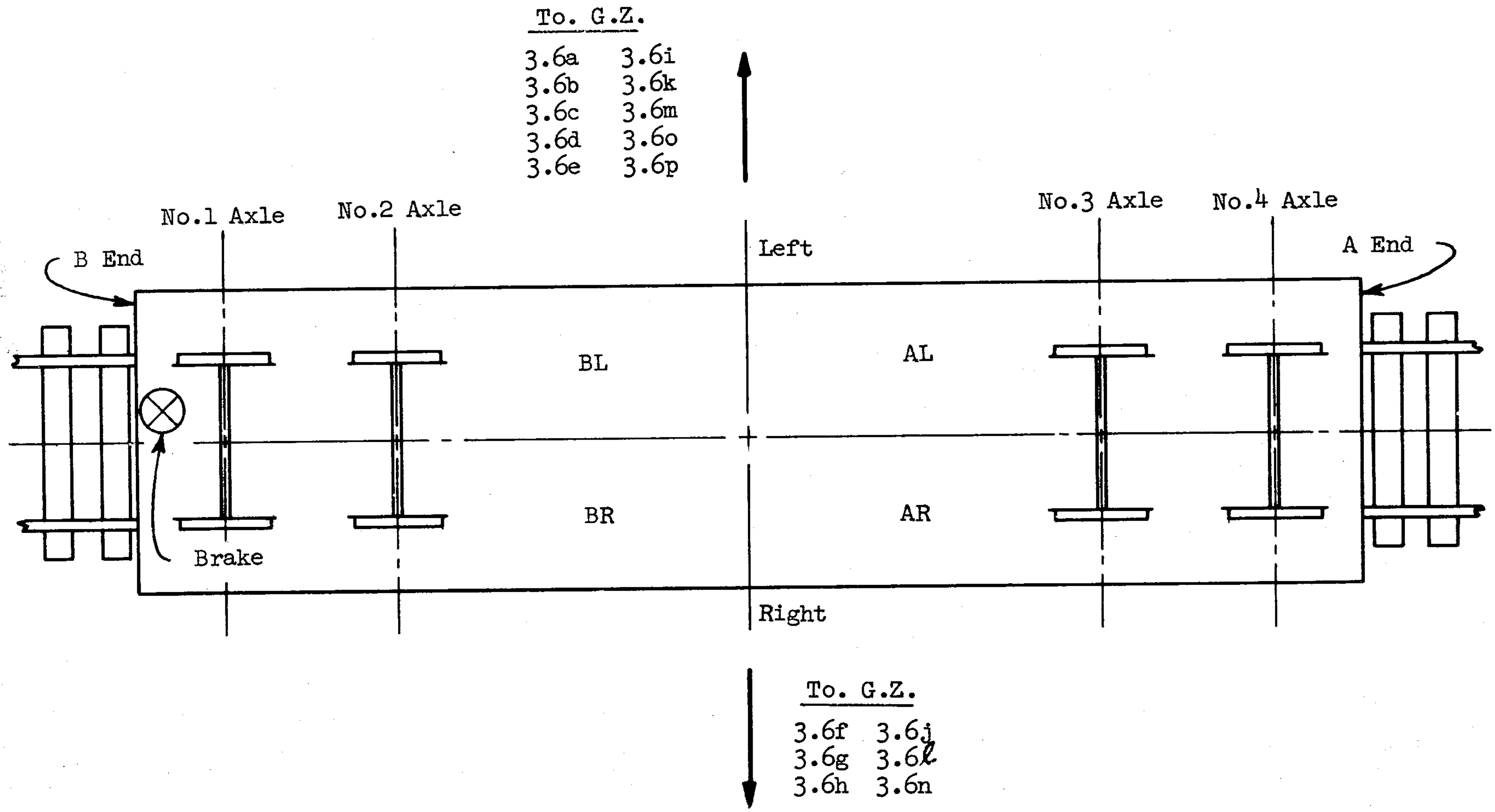


Fig. 4.1 Identification Symbols Used in Damage Survey

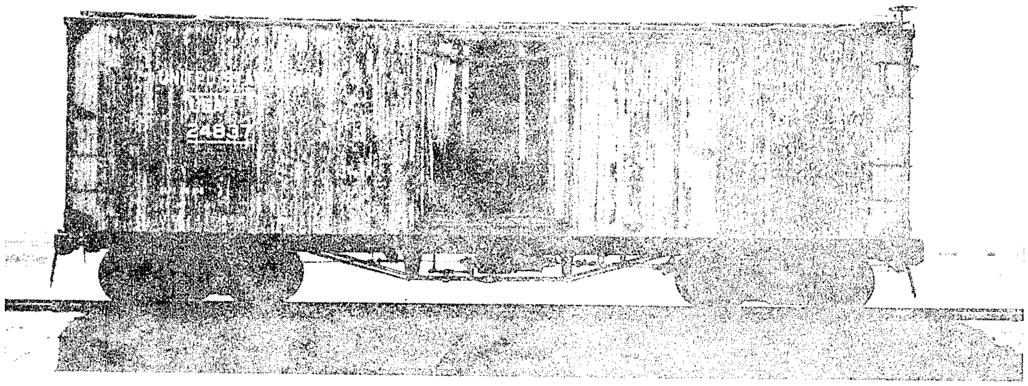


Fig. 4.2 Postshot, Wooden Boxcar, 3.6a (Opposite side sustained no visible damage)

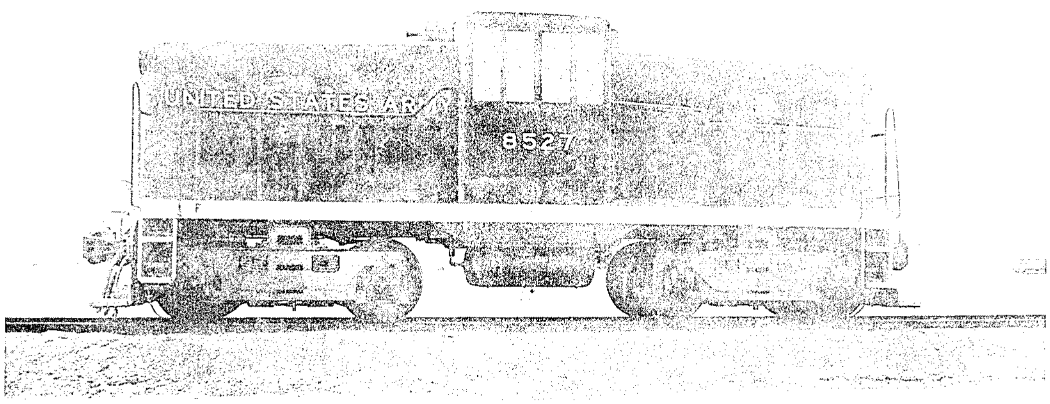


Fig. 4.3 Preshot, Locomotive, 3.6b

Fig. 4.4 Postshot, Damage to Cowling of Locomotive, 3.6b

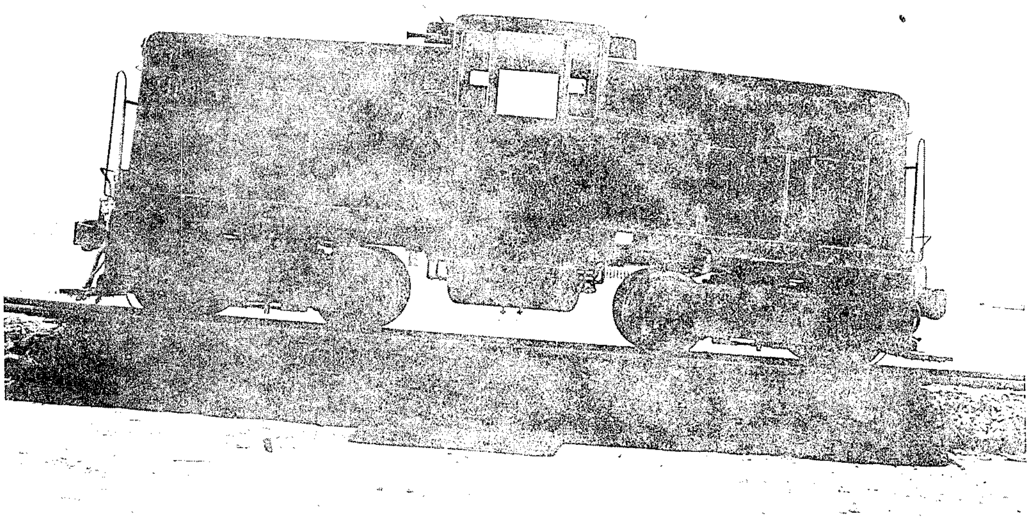


Fig. 4.5 Postshot, Thermal Damage to Locomotive, 3.6b

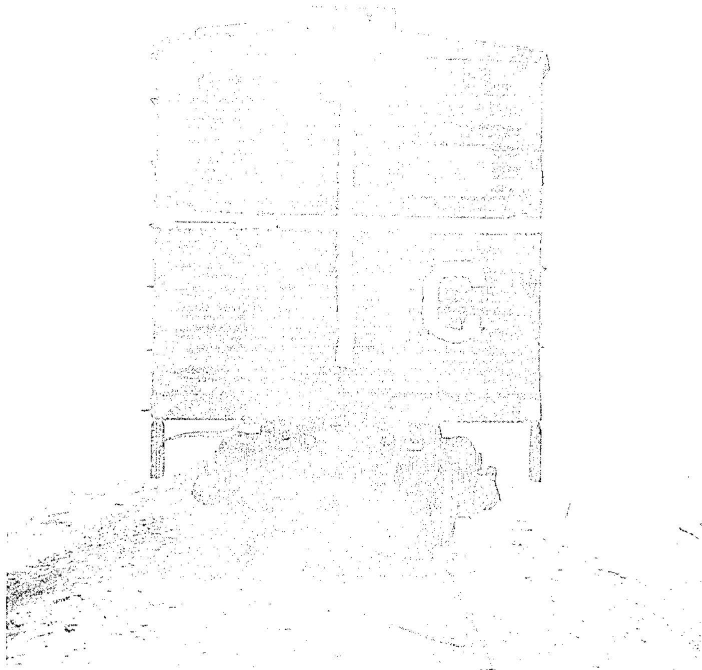


Fig. 4.6 Preshot, Wooden Boxcar, 3.6c

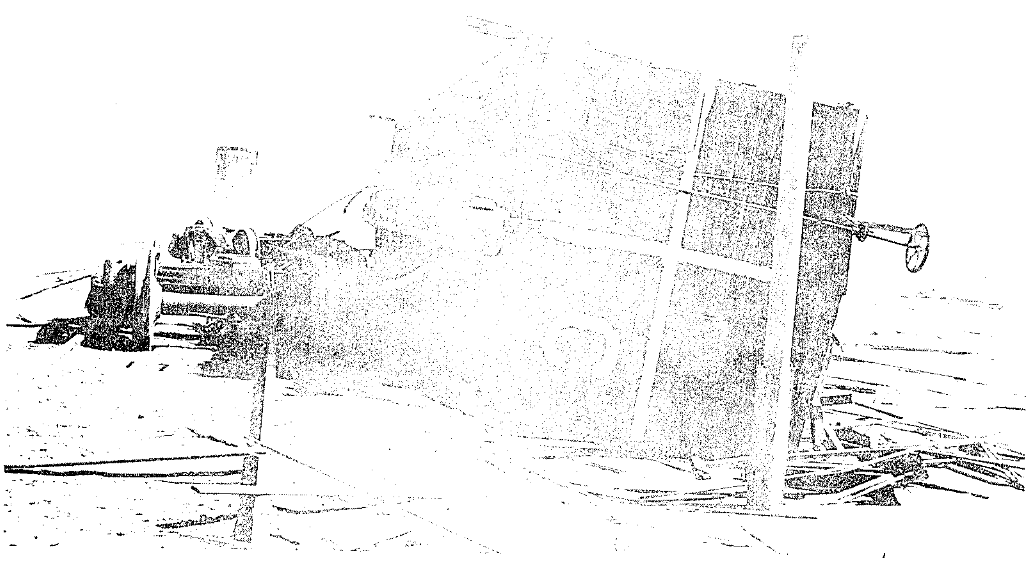


Fig. 4.7 Postshot, Wooden Boxcar, 3.6c (Note camera marker in front of car)

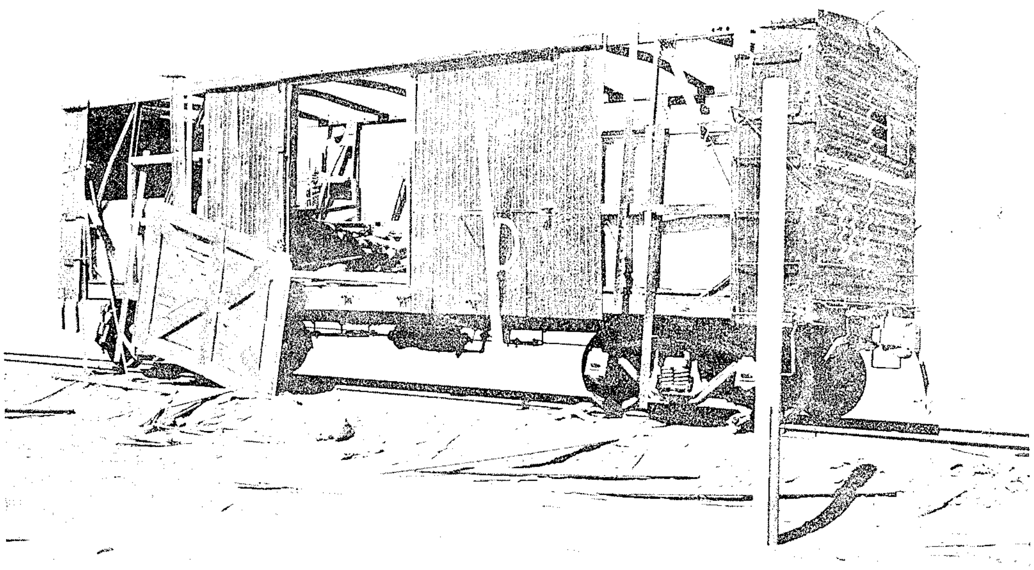


Fig. 4.8 Postshot, Wooden Boxcar, 3.6d
(Car side away from blast)

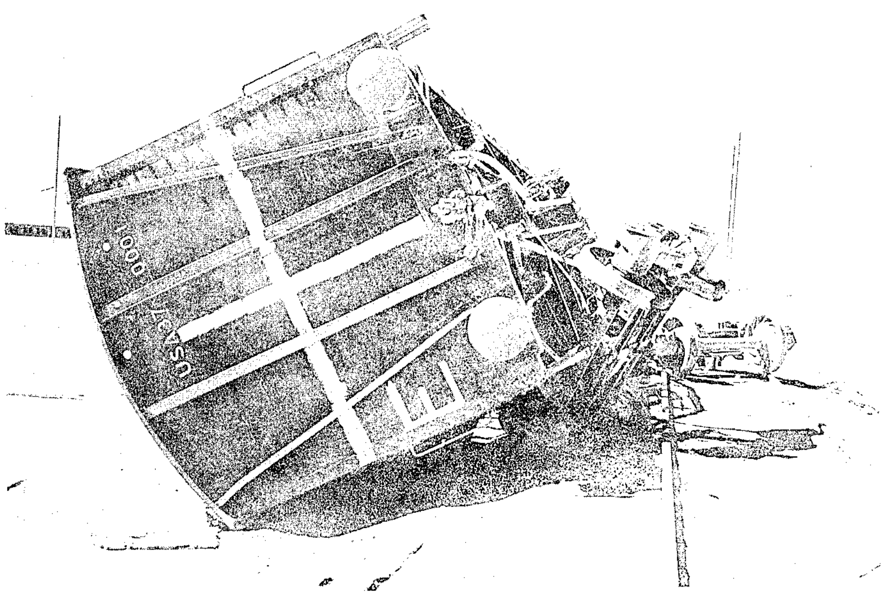


Fig. 4.9 Postshot, Plywood Boxcar, 3.6e

Fig. 4.10 Postshot, Damage to Wooden Boxcar, 3.6f

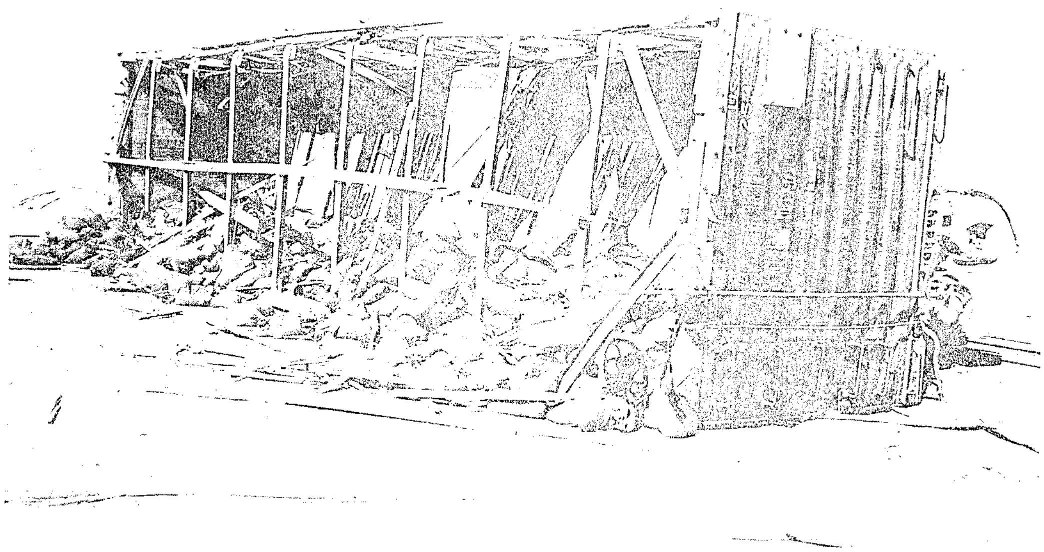


Fig. 4.11 Postshot, Loaded Wooden Boxcar, 3.6g
(Note relatively undamaged cargo)

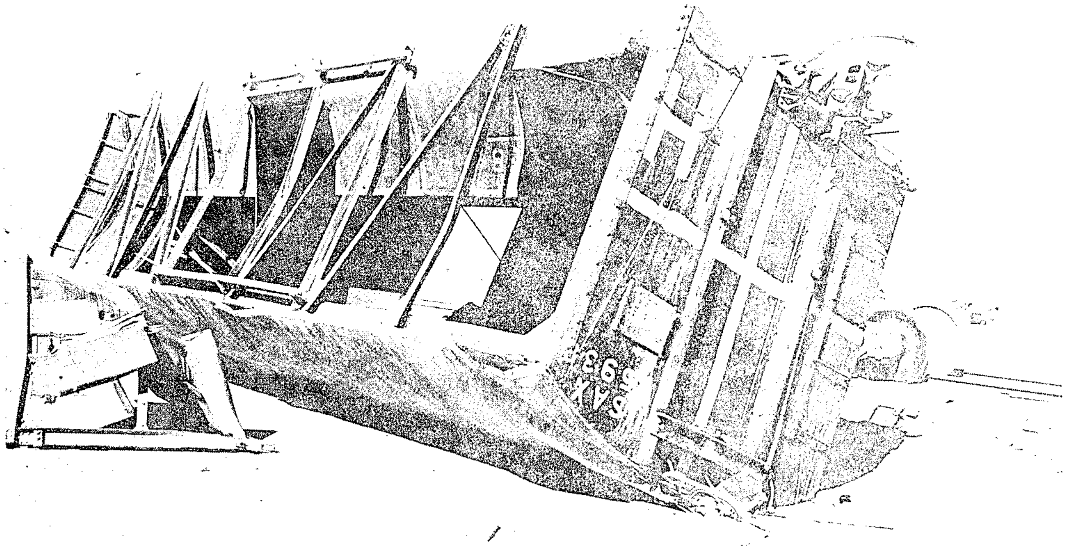


Fig. 4.12 Postshot, Damage to Steel Boxcar, 3.6h
(Side away from blast)

Fig. 4.13 Postshot, Site of Wooden Boxcar, 3.6i

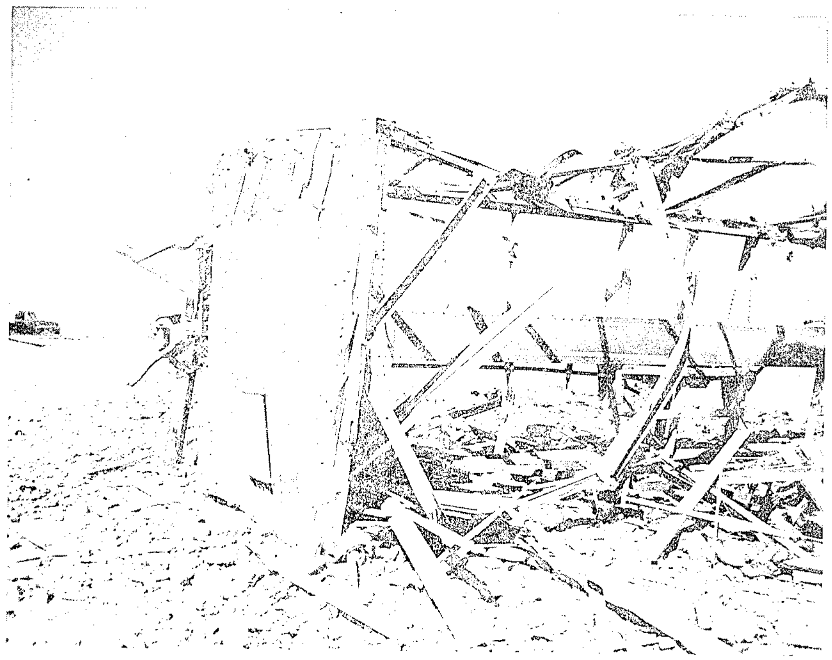


Fig. 4.14 Postshot, Damage to Loaded Wooden Boxcar, 3.6j (Note bowed ends and severe damage to box structure and frame)

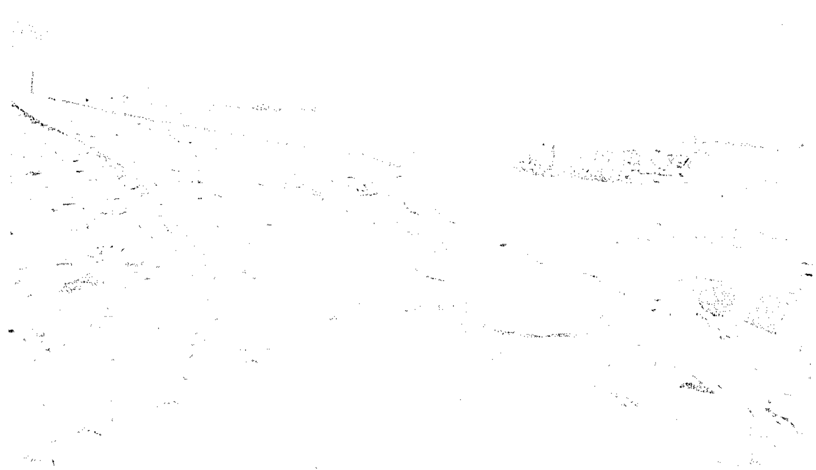


Fig. 4.15 Postshot, Damage to Track, 3.6j

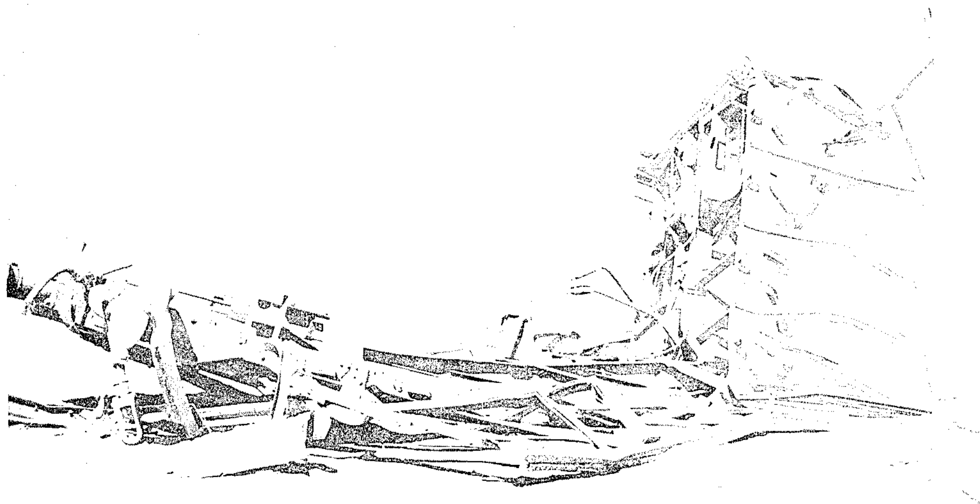


Fig. 4.16 Postshot, Damage to Frame of Boxcar, 3.6k

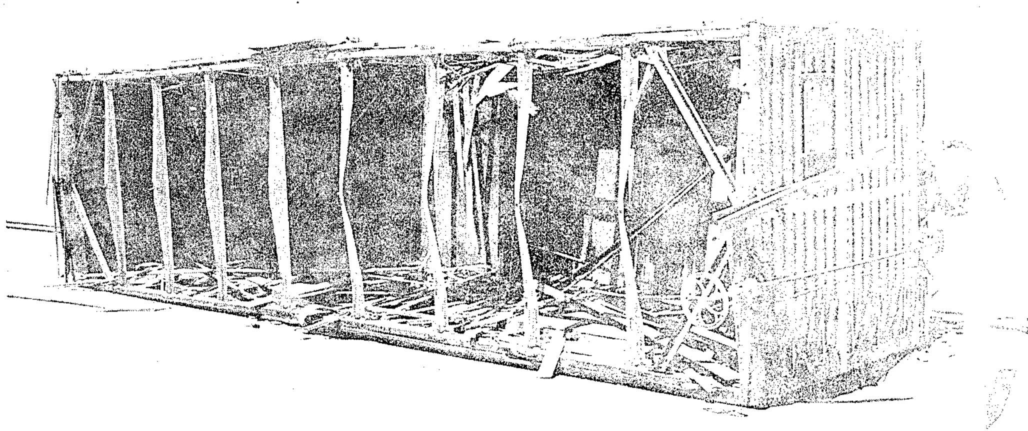


Fig. 4.17 Postshot, Damage to Wooden Boxcar, 3.6ℓ
(Side away from blast)

Fig. 4.18 Postshot, Damage to Frame of Loaded Wooden Boxcar, 3.6m (Thrown against 3.5c structure)

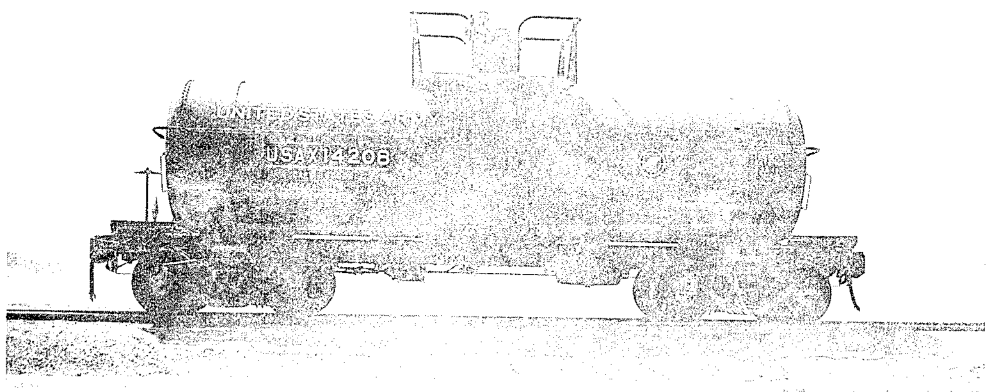


Fig. 4.19 Preshot, Riveted Tank Car, 3.6n

Fig. 4.20 Postshot, Damage to Shell of Riveted Tank Car, 3.6n

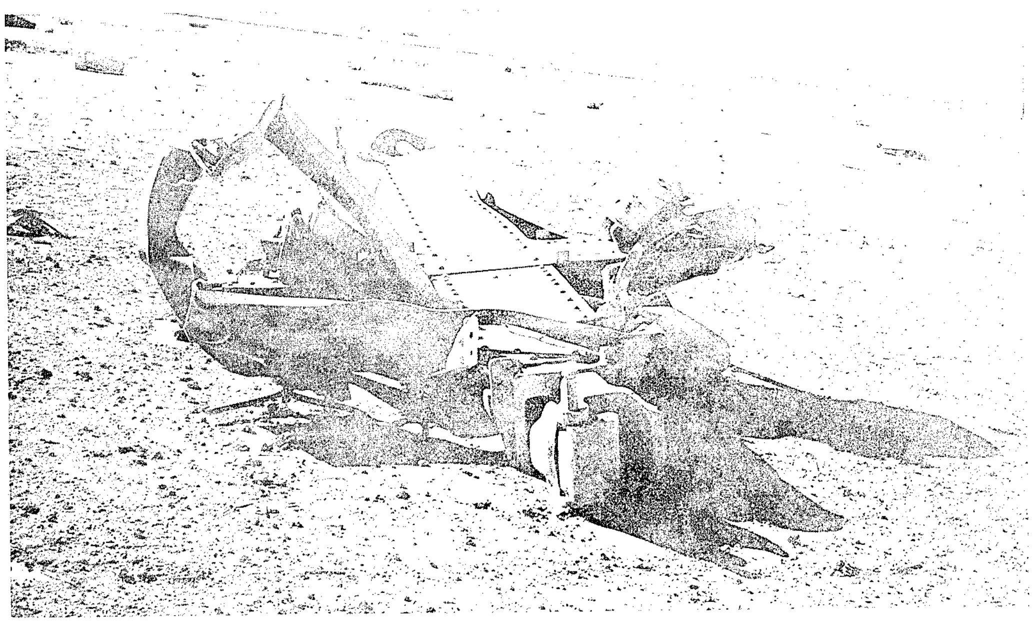


Fig. 4.21 Postshot, Damage to Frame of Riveted Tank Car, 3.6n

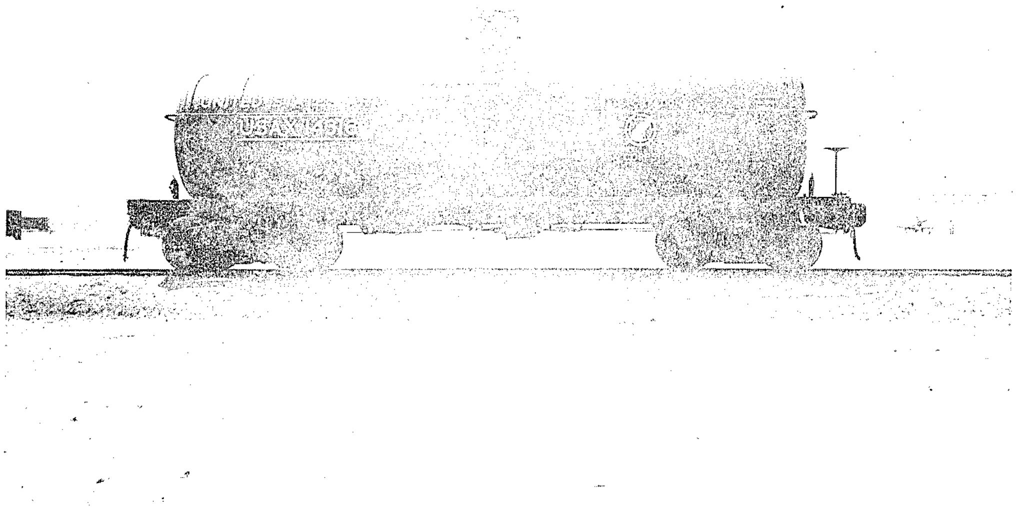


Fig. 4.22 Preshot, Welded Tank Car, 3.60

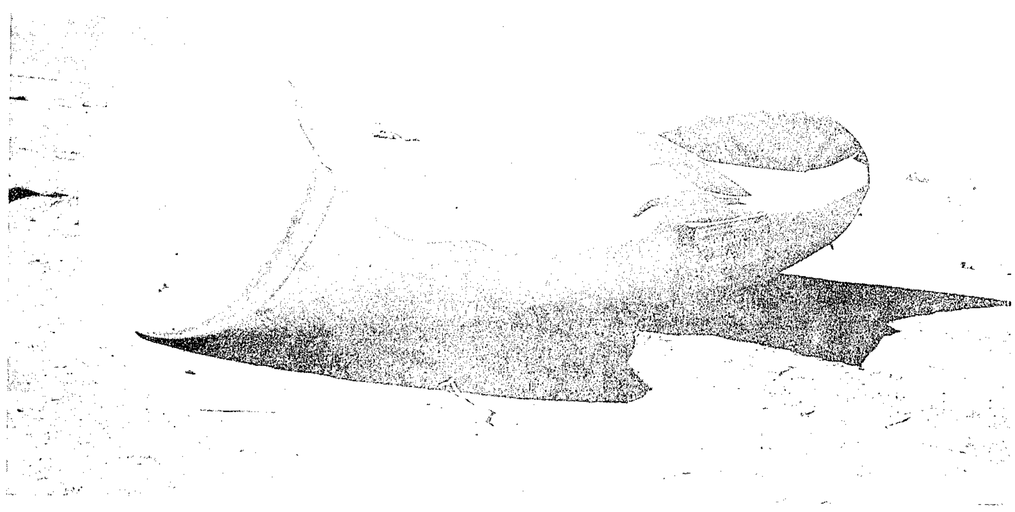


Fig. 4.23 Postshot, Damage to Shell of Welded Tank Car, 3.60 (Note complete removal of paint)

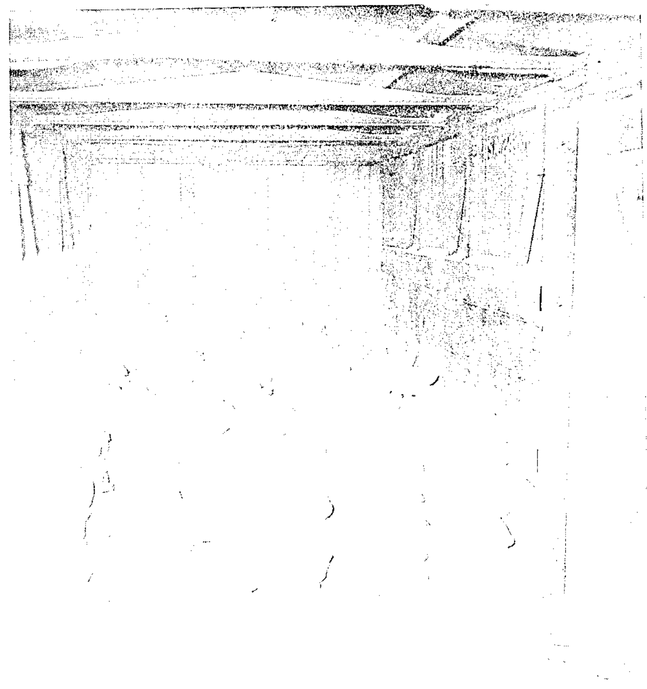


Fig. 4.24 Preshot, Interior of Typical Loaded Boxcar, 3.6j (Similar to 3.6p)

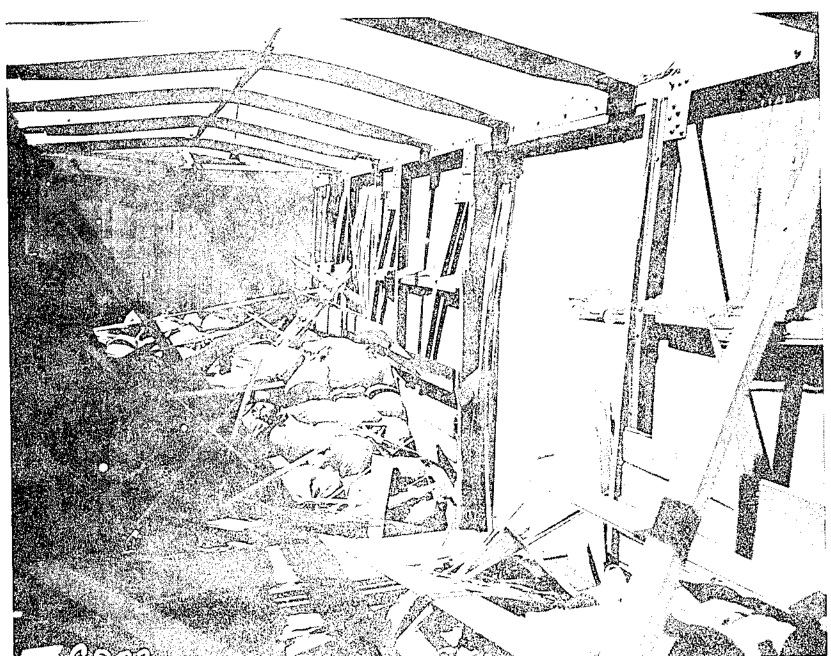
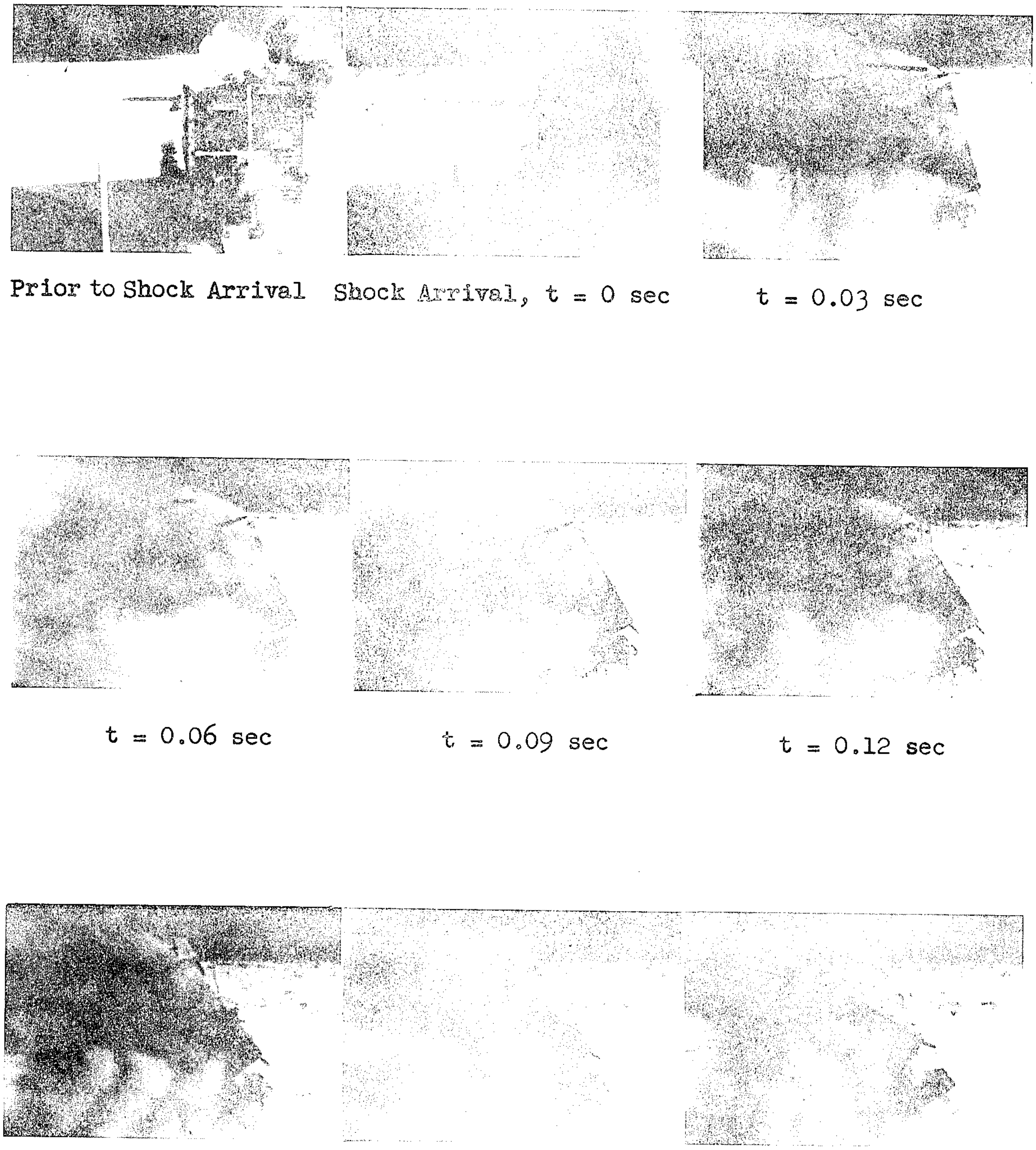


Fig. 4.25 Postshot, Interior of Loaded Wooden Boxcar 3.6p



Prior to Shock Arrival | Shock Arrival, t = 0 sec | t = 0.03 sec

t = 0.06 sec | t = 0.09 sec | t = 0.12 sec

t = 0.15 sec | t = 0.18 sec | t = 0.21 sec

Fig. 4.26 Overturning Motion of Wooden Boxcar 3.6f

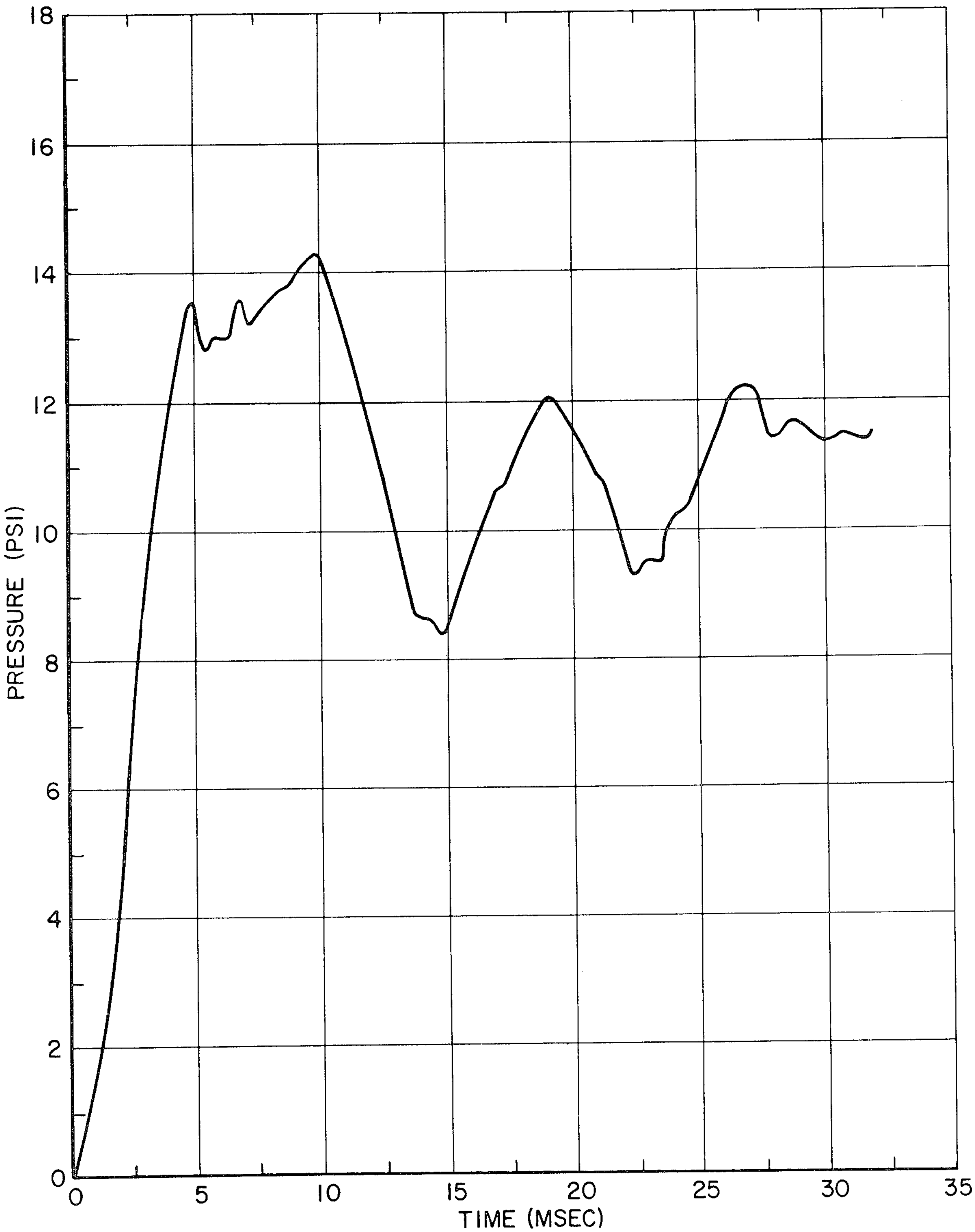


Fig. 4.27 Linearized Pressure Record 3.6 gP2

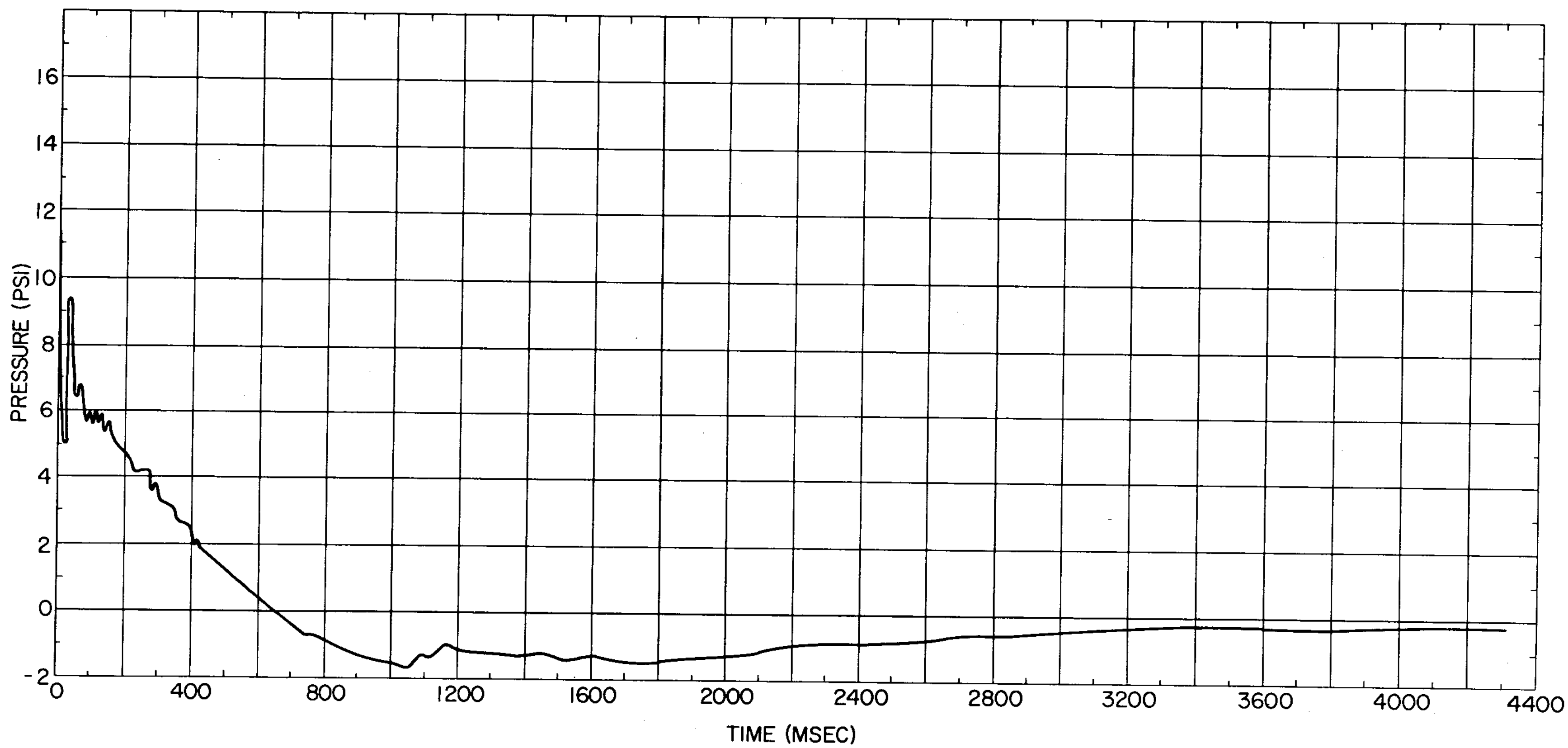


Fig. 4.28 Linearized Pressure Record 3.6 gP4

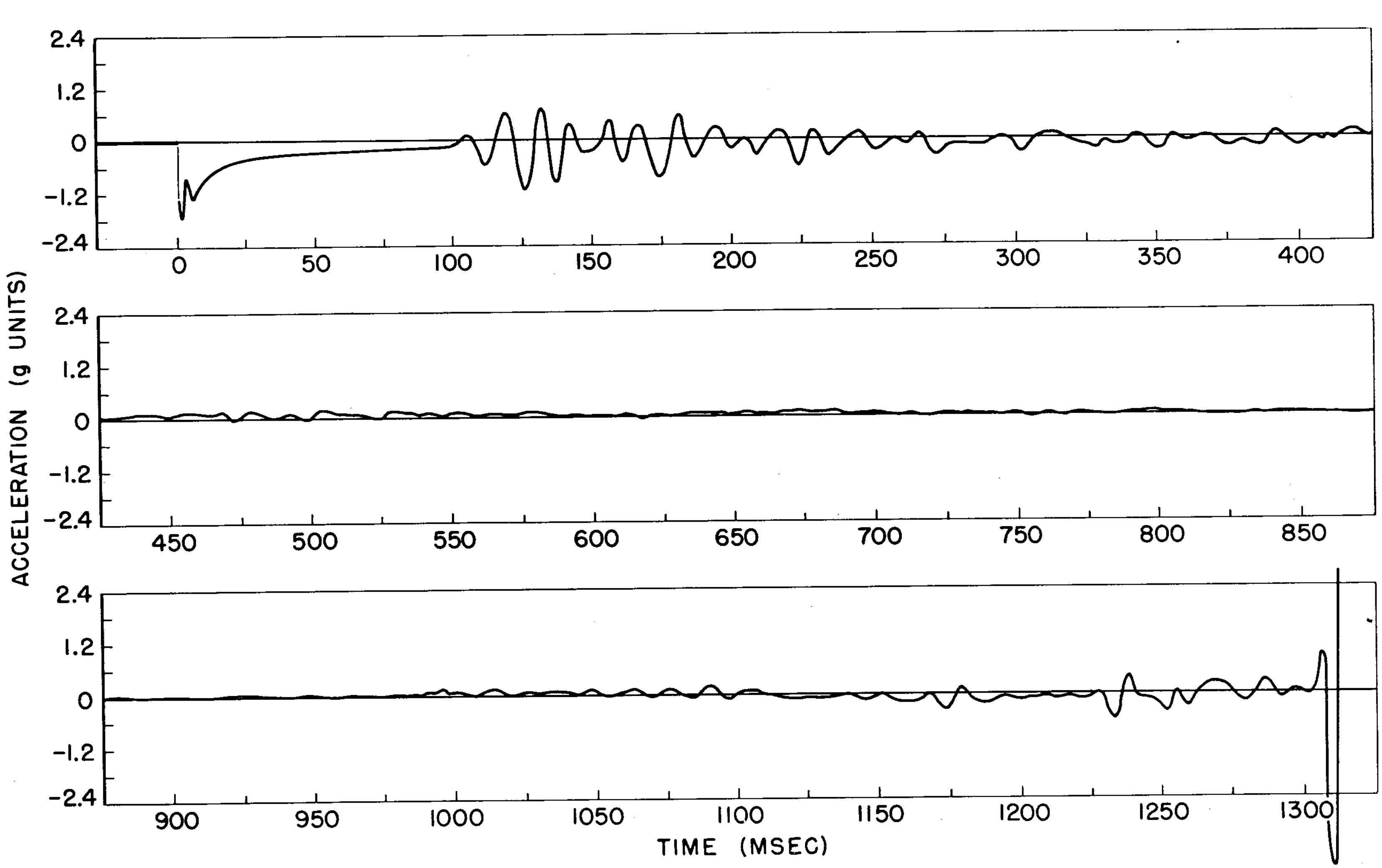


Fig. 4.29 Trace of Original Playback of Accelerometer Record 3.6 g Al

CHAPTER 5

POST-TEST CONSIDERATIONS

5.1 COMPARISON WITH PRETEST WORK

5.1.1 Introduction

The only theory developed during the course of the pretest work was for the purpose of predicting the blast conditions (i.e., overpressure and duration) within the region of Mach reflection[1/] for which either overturning or local component damage to the test

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1/ The term "Mach reflection" referred to throughout this report is used in the conventional sense to indicate a well-defined shock front that is known to occur over an "ideal" surface at ground ranges equal to or greater than the height of burst. In Shot 10, a relatively low height-of-burst detonation, a precursor (i.e., an auxiliary pressure wave which is propagated outward along the ground ahead of the main blast wave) was observed to extend out to a ground range of about 2500 ft. In this report, wherever the alternative to the precursor region is indicated to be the Mach region, the implication is that a conventional shock (i.e., a Mach stem) would have formed in the absence of the precursor. Consideration of precursor phenomena as such is beyond the intended scope of this project. However, it might be noted that within this region the drag forces are believed to be much larger than those generally associated with a conventional blast wave of the measured overpressure; the response of the test cars would certainly tend to support this observation. There is general belief that the excessive drag forces were due largely to the heavy dust content of the air at the test site. There is some indication that, as a general rule-of-thumb, the drag forces within the precursor region are comparable to those associated with a conventional Mach wave at a given ground location over an ideal surface. These few comments regarding precursor action are intended only to convey a quantitative feeling for this phenomenon; the present test is not relevant to this subject, which is treated in other UPSHOT-KNOTHOLE project reports.

[redacted]

cars would occur. This work was brought about by the desire to inflict at least this amount of damage to even those cars located farthermost from ground zero. No attempt was made to account for precursor phenomenon insofar as the response of the cars was concerned (the actual test conditions were not known to the ARF during the preparation of the pretest report), nor was any effort directed toward the prediction of gross motion or over-all physical damage to even those cars which were expected to be within the region of conventional Mach reflection.

The following subsections deal with the correlation between predicted and actual results in those cases where the pretest work is applicable, i.e., for the test items outside of the precursor region. which extended about 2500 ft from ground zero.

5.1.2 Gross Motion

Within the limitations of the pretest work, the results of the test were in general agreement with what had been anticipated. That is, a primary mode of response was indeed overturning for those cars beyond the precursor region. However, it was observed that the cars which overturned became separated from their trucks during the early portion of the motion. The pretest analysis had assumed the car body and trucks to rotate about the wheel flange and rail head as a rigid body.

Measurements were taken from the films of several cars in an attempt to locate the path of the instantaneous center of velocity of the car body. The paths of three points on the car body were determined and normal lines to these curves constructed at the same values of time. However, the intersection of the three lines failed to define a unique point at each instant of time. This was probably due to a combination of errors; that is, inaccuracies in determining (1) the true position of the points being measured from the film, and (2) the curve through these points and the corresponding normals. In addition, it is quite probable that the points being measured were moving relative to one another due to distortion of the car body. In any event, it was not possible to determine the instantaneous center of velocity or the motion of this point with time. It appeared, however, that the cars did rotate about a point in the vicinity of the wheel flange, and the axis of rotation originally assumed is probably a sufficiently good estimate of the actual conditions even though the car body and trucks move independently.

The angular displacement of the car about an axis formed by the wheel flange and rail head was determined from the films at three locations (i.e., 3.6f, 3.6c, and 3.6ℓ). These results were compared with computations based on the pretest overturning analysis and are shown in Figs. 5.1, 5.2, and 5.3. For the purposes of this comparison the pretest analysis incorporated the actual car dimensions and weights, as well as the measured overpressures, durations, and ambient conditions. The pretest loading scheme was maintained, but the weight of the trucks was neglected in the response computations.

[redacted]

The comparison of results is remarkably good, as indicated in Table 5.1. Actually this agreement is somewhat surprising, considering that a major pretest assumption now appears to be invalid, i.e., rigid body action of the car. Also, certain of the loading assumptions (see section 4.2.2) were invalidated. The severe damage to the roof and side panels during the early portion of the loading period (as observed from the films) undoubtedly results in actual loads which differ from the predicted values. Since the area exposed to the blast is thereby reduced, it would be suspected that the predicted response exceeds the measured values. Inspection of Table 5.1, however, shows that this is not always the case, in that the cars at the higher overpressures respond more quickly than predicted. Of course, the film measurements are subject to some error.

Apparently the errors introduced into the overturning analysis due to uncertainties in the loading and car behavior tend to compensate one another, and the analysis yields very nearly the correct results.

The larger discrepancy noted between measured and predicted results for the car at position 3.6f deserves additional comment. This location (2820 ft from actual ground zero) was at the tail end of the precursor region, and thus, the pretest loading scheme may be invalid in this case for still another reason. However, as discussed later, the damage to this car is not believed to have been influenced by the precursor.

TABLE 5.1 - Comparison of Measured and Computed Response

Car	Angular Velocity at Overturning, $\dot{\theta}$ (rad/sec)		Time of Overturning t_c (sec)		Percentage Differences, (relative to measured values)	
	Measured	Computed	Measured	Computed	$\dot{\theta}_c$	t_c
3.6ℓ	1.30	1.39	0.330	0.288	-6.9	12.7
3.6c	2.73	2.06	0.185	0.201	24.5	-8.6
3.6f	3.13	1.91	0.154	0.218	39.0	-41.6

5.1.3 Overturning Criterion, Drag Coefficient

The validity of the overturning criterion given by Eq. 3.6 can be checked by applying it to certain of the test cars. Table 5.2 shows this comparison in those cases where the criterion is applicable and the comparison appears to be significant, i.e., where the computed

[redacted]

overpressure is close to the actual measured overpressure. The computed overturning pressures are consistent with the pressure-duration relationship for Shot 10. The criterion is seen to be valid in every case, which indicates that, within the region of Mach reflection, overturning of box-like structures can be predicted with good accuracy. This result is again somewhat surprising, since the boxcars certainly did not respond as rigid bodies during the loading period as was assumed in the analysis.

The locomotive, being a rigid box-like structure and located well within the region of Mach reflection, satisfies most of the requirements of both the load prediction and response analyses. Thus, it would seem that the response in this case could serve as a valid check on certain aspects of the analyses themselves. The overturning pressure (and duration) determined by Eq. 3.6 is found to be rather sensitive to the value of drag coefficient, which is not surprising since the drag impulse is about 60 per cent of the total impulse (of the net loading) for this case.

Following the pretest assumptions, the pressures given in Table 5.2 are based on an over-all drag coefficient of 1. There has been some indication that a more correct value is 2. It is interesting to note, however, that the response of the locomotive lends support to the lesser value of C_d insofar as application to the response analysis is concerned.

TABLE 5.2 - Comparison of Predicted Pressure Causing Overturning, and Actual Pressure

Car*/	Overpressure (psi)		Overturn
	Computed from Eq. 3.6**/	Actual	
3.6a	2.9	1.9	No
3.6d	7.3	6.0	No
3.6g	6.6	7.5	Yes
3.6ℓ	2.6	4.0	Yes
3.6p	6.6	4.0	No
3.6b (locomotive)	7.5	6.0	No

*/ See Table 2.1 for car description.

**/ Pressures are consistent with the pressure-duration relationship for Shot 10.

[redacted]

Figure 5.4 is a plot of minimum overturning pressure for the locomotive (according to Eq. 3.6) versus positive wave duration. The pressure-duration relationship for Shot 10 conditions is also shown on the figure. The points of intersection represent predicted overturning pressures depending on the value of C_d selected. These pressures are seen to vary between about 7.5 and 5.7 psi for values of C_d between 1 and 2. Since the locomotive was struck by a 6 psi shock and gave no indication of gross motion, much less overturning, it appears that a proper value of C_d to be used in connection with the overturning analysis is close to 1 or less.

If a drag coefficient of 2 is used with reference to the boxcars, the results of Table 5.2 are reversed only in the case of 3.6d (a loaded wooden boxcar) where a pressure of about 5.5 psi is found for overturning. All pressures in the table are reduced, but not enough to invalidate the overturning criterion. However, most of the cars are then indicated to have just overturned, which is not generally supported by post-test inspection of the cars. Thus, the a value of C_d around 1 appears to be applicable to the boxcars also.

It should be clear that no attempt is made here to argue that the test results necessarily point to the "true" value of the drag coefficient. Indeed, it is not at all certain that the entire concept of the steady-state drag coefficient is applicable in the case of transient loading. Rather, it is argued that in terms of the proposed load and response prediction schemes, using a drag coefficient of $C_d = 1$ is more realistic than using a value substantially higher, say $C_d = 2$. Considered in this respect, the present test has yielded information of considerable importance, and from a source not originally anticipated.

According to Eq. 3.6, the tank cars were expected to overturn at about 11 psi. The measured overpressure was about 13 psi (well within the precursor region) and to say that the cars simply overturned is hardly adequate -- one tank shell (3.6n) was found about 2800 ft from the track. Such extreme motion is not at all consistent with what might be inferred from the overturning analysis at 13 psi for these cars. The obvious inapplicability of this analysis is undoubtedly due to the fact that the load prediction scheme, based on a conventional Mach wave, is quite inadequate within the precursor region. This is simply to say that, within the precursor region, the drag forces are not characterized by overpressure and duration as assumed in the load prediction method. Until an adequate load prediction scheme is developed for the precursor region, Eq. 3.6 (actually Eq. 3.4 or 3.5) should not be applied to this case. The limitations of the overturning criterion are for the most part those discussed in connection with the load prediction scheme in Chapter 3.

5.1.4 Structural Damage

The empty wooden boxcar at 6600 ft (3.6a) was subjected to a pressure of about 2 psi and remained both upright and intact, with only slight blast damage. According to the pretest considerations, both the side and roof panels should have failed at this loading.

In evaluating the significance of the pretest work, it is necessary first to consider the criterion of failure used. This was taken to be a deflection corresponding to the static yield displacement of the panels, which were assumed to act as simple beams. According to pretest calculations, a displacement of between five and six times the yield value for these members (e.g., about 5 in. at the center of the side panel) would be expected for a blast loading of 2 psi under Shot 10 conditions. The next closest cars (3.6ℓ, 3.6p) were in about a 4 psi region, at which position the blast damage was severe. Thus, the pretest analyses of local damage would appear to be reasonable if a larger displacement of the side and roof panels is associated with structural damage.

The tank cars were expected to collapse at between 13 and 15 psi under conditions of Mach loading. The measured overpressures at these locations were about 13 psi, well within the precursor region, and buckling -- indeed, total destruction -- occurred. No correlation with the pretest work is possible in this case.

5.2 ASSESSMENT OF OVER-ALL DAMAGE

Up to now the term "damage" as applied to the test cars has not been used in a precise sense. In this section a method based on the time and material needed to repair or rebuild the car (without regard to cargo damage) is presented for assessing the percentage of over-all damage. According to this scheme, loaded and empty boxcars of the same type and at the same ground range were found to have been equally damaged, although in several instances the empty car overturned while the loaded car remained upright. Now, it can be argued that in a military situation there would be a significant difference in damage between a car that remained upright on the tracks and one that overturned. Also, the degree of damage to a complex of cars such as found in a marshaling yard might not be related in a simple fashion to individual car damage in the present sense. However, the damage assessment scheme presented herein is acceptable to the Transportation Corps within certain limitations that are best indicated by the particular application of these results which might arise.

The following approach is based on the damage assessment made by Transportation Corps personnel and constitutes a unique way in which a value of over-all damage to the car proper may be prescribed. No attempt is made to assess cargo damage.

The over-all damage is represented by the cost of the car components destroyed and the cost of labor involved in rebuilding the car. The material cost is assumed to be proportional to the weights of the components, and the labor cost has been estimated at $2.50 per man-hour. The total cost of a boxcar is set at $6000; the labor and material costs represent $4000 and $2000 of the total price, respectively. The components destroyed and the labor involved for repair were taken from the results of the Transportation Corps damage survey presented in Chapter 4. The component weights were taken from the Report of the Mechanical Advisory Committee to the Federal Coordinator of Transportation, 27 December 1935. Whenever no estimate of repair time was given, it was assumed that the entire cost of labor had been expended, which represents two-thirds of the total damage to the car itself.

As an example of this procedure, consider the case of the empty steel boxcar at location 3.6h. According to the damage survey, 300 man-hours are required to repair the car, and the components destroyed were found to represent 14.2 per cent of the total weight of the car. The cost of repair labor is then $750, or 18.7 per cent of the total cost of labor. The material damage represents one-third and the labor damage represents two-thirds of the over-all damage, respectively. Thus, the over-all damage for this car is computed to be $[(1/3)(14.2)] + [(2/3)(18.7)] = 17.2$ per cent.

According to this scheme, whenever the underframe and trucks (which represent about 50 per cent of the total weight of an empty car) are the only salvable components, the car has been 83 per cent damaged; total damage implies that the entire car was reduced to scrap metal. Since the labor cost is equivalent to two-thirds of total damage, the percentage of damage is markedly dependent on the repair time determined by the Transportation Corps specialists responsible for the damage survey.

5.3 DISCUSSION OF RESULTS

5.3.1 Damage Plot

Based on the above scheme, a plot of per cent damage versus ground range is shown in Fig. 5.5 for the conditions of Shot 10. The data are also shown in Table 5.3. The estimated extent of the precursor region (i.e., to about 2500 ft), as well as the overpressure at points in the Mach region, is also indicated in the figure. While points corresponding to all of the test items are shown, the solid curve has been drawn through those points representing the empty wooden boxcars, since only these items showed a clear gradation of damage. The curve is seen to be of a characteristic statistical shape, but no attempt is made here to investigate either the best fit or such properties as the mean and standard deviation.

Figure 5.5 (or Table 5.3) represents in essence the experimental results of the test within the concept of damage discussed previously. The extreme gradation of damage and relative behavior of the various test items can easily be seen. A question which naturally arises concerns the extent to which the test results are dependent on the precursor loading of Shot 10. Inspection of Fig. 5.5 reveals that the answer to this question depends largely on the behavior of the two wooden boxcars located at 2820 ft (3.6f, 3.6g), since they are about at the extent of the precursor region. Had a precursor not formed, a Mach stem of appreciable height (relative to the height of the boxcar) would certainly have been present at this distance and for all purposes the entire damage plot would be representative of car behavior in the Mach region (at least for wooden boxcars).[2]

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[2] This assumes that the damage curve would not drop off at closer distances in the absence of a precursor, e.g., within the region of regular reflection.

TABLE 5.3 - Correlation of Damage with Overpressure

Test Item	Code	Ground Range (ft)	Overpressure (psi)	Damage (%)
Wooden Boxcars, Empty	3.6a	6600	1.9	2
	3.6ℓ	4400	4.0	14
	3.6c	3400	6.0	32
	3.6f	2820	7.5	84
	3.6i	1870	9.3 P	95
Wooden Boxcars, Loaded (30 tons of Sandbags)	3.6p	4400	4.0	14
	3.6d	3400	6.0	32
	3.6g	2820	7.5	84
	3.6j	1870	9.3 P	94
	3.6m	1520	13.3 P	97
Plywood Boxcars, Empty	3.6e	3400	6.0	84
	3.6k	1870	9.3 P	98
Steel Boxcar, Empty	3.6h	2820	7.5	17
Tank Cars, Empty	3.6n	1520	13.3 P	100
	3.6o	1520	13.3 P	100
Diesel Locomotive	3.6b	3400	6.0	1

Notes -

A detailed description of the cars is given in section 4.1.
P signifies the precursor region, otherwise Mach region.

From the results of other UPSHOT-KNOTHOLE programs concerned with precursor action, it seems reasonable to conclude that the effects noted at 2820 ft were due to an essentially clean shock. According to the SRI report of Project 1.1b (Air Pressure Versus Time, WT-711), the precursor apparently disappeared entirely before reaching a ground range of 2916 ft, since the free air pressure records were conventional at this and subsequent stations. Work conducted by the ARF under Program 3.1 (Tests on Building and Equipment Shapes, WT-721), indicates that precursor effects were already small at a ground range of 2416 ft.

Another point concerning the character of the blast wave might also be mentioned. It will be recalled that soil stabilization was provided at locations where motion pictures were taken in the hope of

[redacted]

decreasing dust interference. The question might well be asked as to the effect of the soil stabilization on the blast wave and, hence, on the damage to the cars. This problem was treated as a part of the SRI Project 3.28.3 (Pressure Measurements on Structures, WT-740). It is concluded definitely there that the stabilized ground surface had no measurably different effect on the blast wave in a distance of 200 ft than had the natural surface. It also appears that the unstabilized surface did not distort the wave front appreciably in the Mach stem region. Although in the present test the stabilization extended for a distance greater than 200 ft, it seems reasonable to conclude that, at least at the farther stations, the effects of soil stabilization were negligible. At the closer stations, such as the 2820 ft location discussed previously, there may well have been some effect. However, it would appear that stabilized ground tends to decrease dust in the air and otherwise cause a cleaner wave front, so that the damage observed might be even more representative of ideal conditions at those positions where a Mach stem formed had the soil not been stabilized.

5.3.2 Boxcars

As discussed above, the wooden boxcars show a clear gradation of damage from light through total destruction. Evident in Fig. 5.5 is the fact that empty and loaded cars of the same type were similarly damaged. For the boxcars located at 3400 ft (3.6c, 3.6d) and 4400 ft (3.6ℓ, 3.6p) from ground zero, the loaded ones remained upright, while the empty ones overturned; still, the damage was the same at each distance. While both cars overturned at the 2820 ft location, the empty one appeared to do so much more violently. The motion picture films indicate that most of the damage to these cars was due to the blast, and occurred before the boxcar struck the ground. The subsequent impact with the ground apparently contributed little additional damage. While it was not possible to determine the full extent of the damage due to impact, this conclusion appears to be reasonable when it is based on the results of this test. (The response of the cars within the precursor region was undoubtedly spectacular; yet, as can be seen from Fig. 5.5, the wooden boxcars at 2820 ft, which did not suffer excessive displacements, were heavily damaged and could not have been repaired. The only significant difference in damage between these latter cars and those in the precursor region was to component parts of the trucks and couplers, which were salvable.)

It should be emphasized that possible exceptions to the above might occur in those cases where the present damage concept does not apply (e.g., where overturning constitutes significant damage in itself), and where the cargo serves to strengthen the car body to an appreciably greater extent than it did under the test conditions. Although the structural bracing afforded by the sandbag cargo is believed to be representative, the latter condition could well invalidate any general conclusions which might be drawn concerning the similarity in damage noted between the empty and loaded cars.

Thermal damage to the cars was negligible, even at those positions where total destruction occurred.

[redacted]

Of the car types tested, the plywood cars (3.6e, 3.6k) commonly used in overseas service proved to be the most vulnerable to blast damage. One of the two cars was totally demolished (3.6k) and the other suffered damage in excess of 80 per cent. Thus no gradation of damage was obtained, and all that can be reasonably said concerning plywood cars on the basis of this test is that severe damage can be expected for overpressures in excess of 6 psi, under conditions similar to those of Shot 10.

The one steel boxcar tested (3.6h) proved to be substantially more resistant to blast damage than either of the two types of wooden cars. However, it must be noted that this car had an unusually strong roof structure, which is not standard for all steel boxcars. Even so, at a loading at which the plywood car was virtually destroyed and the standard wooden cars were about 30 per cent damaged (6 psi), the steel car is estimated to have been only about 10 per cent damaged.[3] While obviously no gradation of damage can be obtained from a single test item, the test tends to support the intuitive feeling that steel cars are the least vulnerable, and the damage curve shown in Fig. 5.5 (drawn through one point) does not appear to be unreasonable.

5.3.3 Tank Cars

The two tank cars included in the test (3.6n, 3.6o) were located well within the precursor region. In both cases the tank shell collapsed, and the cars were reduced to scrap metal after being hurled through the air for remarkably large distances. While the test did not indicate a primary mechanism of damage other than the obvious collapse of the shell, it seems likely that overturning can play an important part in damaging cars of this type. From the pretest work, collapse of an empty shell appears unlikely at pressures substantially less than those which cause overturning, and additional damage probably results from impact with the ground. This is, of course, an intuitive feeling, not directly supported by the test.

No comparison of damage was possible between the welded and riveted shells because of the extreme degree of damage sustained by each. However, inspection of Figs. 4.18 and 4.21 suggests the possibility that the welded tank might have been somewhat less vulnerable.

No appreciable thermal damage was noted for either of the tank cars.

5.3.4 Diesel Locomotive

The diesel locomotive was located within the Mach reflection region and struck by a shock of about 6 psi overpressure. Only relatively minor damage occurred and the locomotive engine was still running 1-1/2 hours after the test. It would have been capable of continued operation after dents in the rocker arm housing covers had been straightened. Thus, only a lower bound pressure for damage to this type of equipment has been established as a result of the test, but

[3] The steel car was actually at 7.5 psi (see Fig. 5.5).

[redacted]

this alone should be valuable information. As in the case of the tank cars, one has the intuitive feeling that significant damage will not occur at pressures less than those capable of overturning the locomotive, but again this was not directly supported by the test. In the event that overturning is a meaningful damage criterion, Eq. 3.6 should prove most useful. As discussed previously, for the type of locomotive tested, overturning is expected to occur for overpressures of about 7.5 psi or greater under conditions similar to those of Shot 10, i.e., in the Mach region where the duration is not substantially less than that of Shot 10.

5.4 DAMAGE PREDICTION SCHEME

5.4.1 Introduction

An attempt is made in the present section to derive somewhat more general information, in the form of damage criteria, from the limited results of this one test. The discussion is restricted to the vulnerability of wooden boxcars, since little, if any, generalization is warranted in the case of the other items of equipment. The formulation of damage criteria is of particular use to the target analyst and others who must treat the damage prediction problem under conditions differing in various degrees from those of the present test. In fact, it is toward results of just this nature that the Air Force structures programs are for the most part directed.

Clearly evident in Fig. 5.5 and Table 5.3 is the large damage gradient which occurred between about 2800 ft and 3400 ft, or between about 8 psi and 6 psi. Now, it might be argued that since damage occurs early in the loading period (i.e., overturning and subsequent ground impact do not appear to be the significant mechanism of damage for boxcars), peak pressure alone is a reasonable criterion for damage. From this point of view it might be concluded that for free stream overpressures in excess of 8 psi[4/] extreme damage to loaded or unloaded boxcars of the type tested would be expected; for pressures less than 6 psi, only minor damage would be expected (with the possible exception of the plywood car). Thus, Table 5.3 might be taken as a rather general set of damage criteria based on peak overpressure. In an even more restricted sense, the obvious conclusions can be drawn that most any type of railroad equipment would be severely damaged if located within, say, 2000 ft of ground zero under Shot 10 conditions.

Now a peak pressure criterion is generally a logical first approximation approach to the complex problem of damage prediction. Certainly it is not seriously argued here that the present results necessarily support a more sophisticated approach. Nevertheless, since peak pressure criteria have been more or less discredited in a number of instances, it is desirable to explore the problem further. The anticipated failure of a peak pressure criterion is, of course, the

4/ Eight psi is just within the precursor region for Shot 10, while 6 psi is not. However, as is evident in Fig. 5.5, extreme damage has already occurred at about 7.5 psi (2820 ft), where an essentially clean wave is believed to have occurred.

intuitive feeling that under certain circumstances two blast waves of the same peak pressure, but substantially different shape or duration, incident upon the same car will inflict different degrees of damage. In other words, can a criterion be formulated which accounts in a reasonable fashion for the actual blast loading on the car?

In the following subsection a damage criterion for wooden boxcars based on the angular velocity of the car at the point of static overturning (i.e., the position at which the car will overturn of its own weight) is presented. The criterion is applicable only to conditions of Mach reflection, and relates damage to the overpressure and duration of the blast. It is shown that for durations in excess of about 1 sec, damage is dependent only upon overpressure. Thus, for these conditions the proposed scheme reduces to the more simple overpressure criterion.

The fact that overturning of itself apparently does not lead to significant damage is not believed to discredit the method. However, any theory based on extremely limited data has to be accepted with caution and evaluated accordingly. Thus it is felt to be unnecessary to continually warn the reader as to this state of affairs, or to qualify virtually every statement although such qualification is often admittedly deserved.

5.4.2 Damage Criterion

The damage prediction scheme will be discussed for the case of empty wooden boxcars and then extended to the loaded cars. Let the angular velocity of the car be denoted by V. The quantity V may be computed for any car and blast loading (within the limitations of the load prediction method) by means of Eq. 3.3, since $V = \dot{\theta}(t_c)$ where $\theta(t_c) = \theta_c$. When the car does not overturn, V is not defined: for $V = 0$ the car reaches a position of unstable equilibrium; for $V > 0$ overturning is assured. The farthermost car, 3.6a, nearly satisfied the second condition, as is indicated in Table 5.2, and the damage to this car was negligible. As the loading increases (i.e., as the pressure and/or duration increases), the quantity V will increase and so, it is assumed, will physical damage. Thus, while V may be an artificial parameter insofar as damage is concerned, the trends and one end point ($V = 0$) agree. Also, V can be computed with relatively good accuracy. The test results may immediately be generalized by plotting damage versus V, where V is computed for the pressures and durations pertaining to each car. The major assumption made here is that similar cars having similar values of V resulting from different values of pressure and duration (i.e., different bomb conditions) will be similarly damaged. In order to apply these results to another case, it is only necessary to compute V for the appropriate loading and determine the damage from the above plot. The quantity V will be referred to as the <u>damage parameter</u>.

Now consider the loaded boxcars. Since the mass of a loaded car is greater than that of an empty car of the same type, the values of V for the two will differ at the same blast loadings. However, the test results indicate that, at the same blast loading, the over-all damage to the two cars will be nearly identical. Thus, if V is computed for an empty car, the above presentation will yield the over-all damage incurred by a loaded car, at least for the results of the present test. But a similar assumption as in the case of empty cars can be made: loaded and empty cars of the same type subjected to similar blasts will be similarly damaged.[5] This is the essence of the prediction scheme. Curves of damage versus V, and V versus pressure and duration are given. The curves have been constructed for the data pertaining to empty wooden boxcars, but they may be used for both loaded or unloaded wooden cars of the type tested.

These results are shown in Figs. 5.6 and 5.7. Figure 5.6 is simply the data of Fig. 5.5 replotted to the appropriate V-scale. The solid curve represents the results of both the loaded and unloaded cars of wooden construction. Tentative curves taken from Fig. 5.5 are also shown for the other types of boxcars. The upper dashed curve, which pertains to the plywood cars, was drawn through two points (3.6k, 3.6e). These cars are apparently the most vulnerable of the types tested. The lower dashed curve, which pertains to the car having steel roof and side panels, was drawn through one point (3.6h). As a result of the limited amount of data, the dashed curves represent only the crudest estimate of expected damage in other instances. This is true to an even greater extent in the case of the steel car, which had a heavier roof construction than normally found in steel boxcars.

Inspection of Fig. 5.7 indicates that the damage parameter becomes increasingly less sensitive to duration with increasing values of t_o. That is, for durations in excess of, say, $t_o = 1$ sec, V depends only on the value of p_σ, and the damage criterion reduces to the simple overpressure criterion discussed previously. As the duration decreases, the damage parameter also decreases for a constant overpressure, and this effect becomes pronounced at the shorter durations.

As an example, consider the empty wooden boxcar designated as 3.6f, which was located at 2820 ft. The overpressure and duration at this location were about 7.5 psi and 0.7 sec, respectively; damage was estimated at about 84 per cent and the corresponding value of the damage parameter is V = 2.1. The significance of duration variations according to the present prediction scheme for this car is indicated in Fig. 5.8 at a constant overpressure of 7.5 psi. It is seen that substantially less damage would be predicted at the lower durations, and that increasing the duration beyond about 1 sec has little additional effect. Of course, it is assumed that the load prediction scheme is valid for the combination of pressures and durations indicated in Fig. 5.8.

The information contained in Fig. 5.8 obviously could not be obtained from a direct overpressure criterion of damage. The dependence of damage on duration is seen to be quite marked. While the general trend seems to be a reasonable one, it is not possible to assess these results in a quantitative sense. For one thing, the

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5/ An additional assumption should probably be added to the effect that, for loaded cars, the cargo does not lend any greater rigidity to the car body than did the sandbag loading employed in this test.

[redacted]

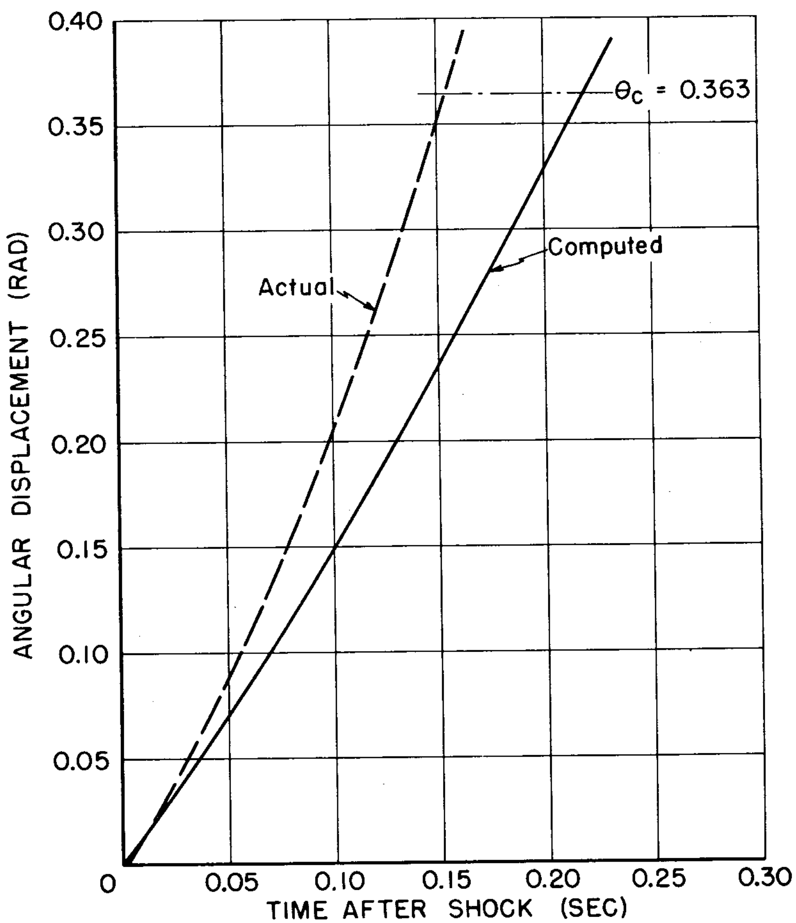

Fig. 5.1 Measured and Predicted Response, 3.6f

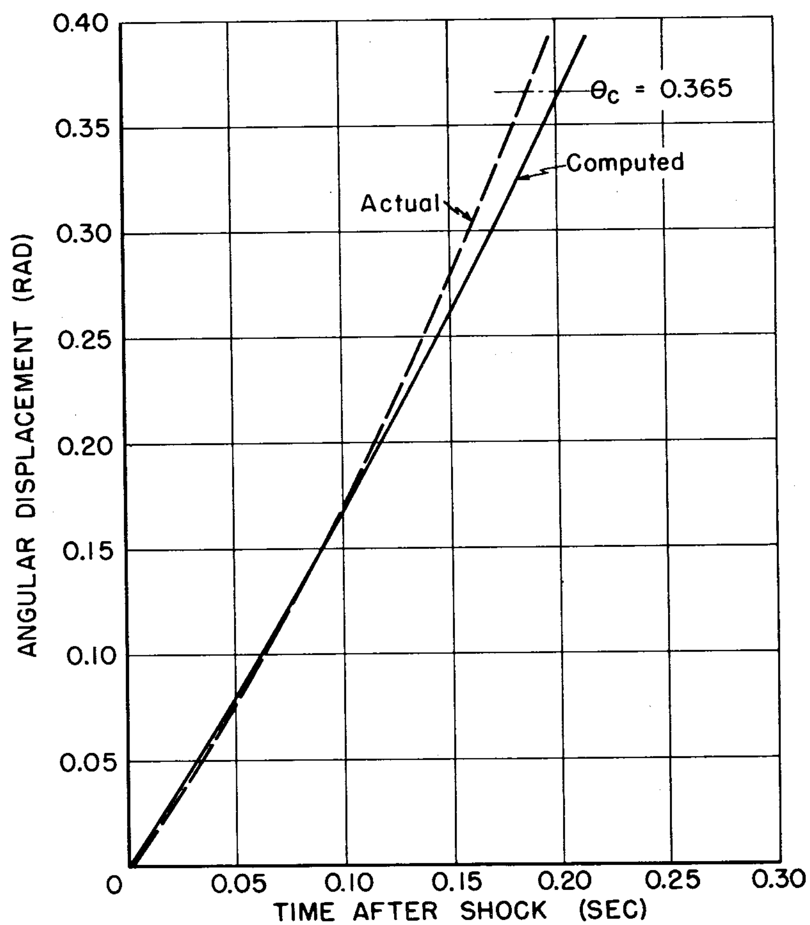

Fig. 5.2 Measured and Predicted Response, 3.6c

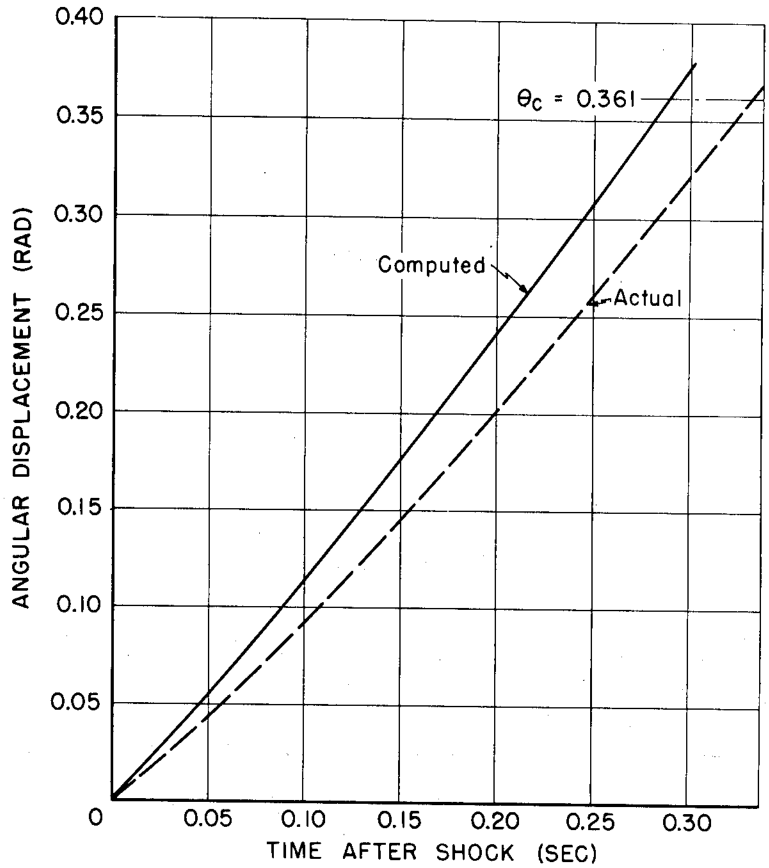

Fig. 5.3 Measured and Predicted Response, 3.6

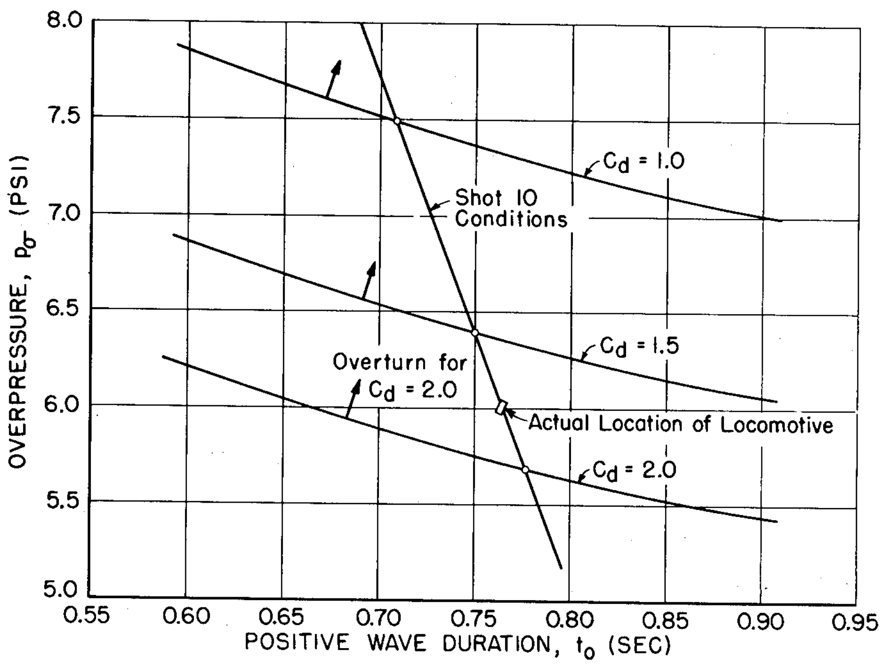

Fig. 5.4 Predicted Overturning Pressure for Diesel Locomotive for Several Drag Coefficients

[redacted]

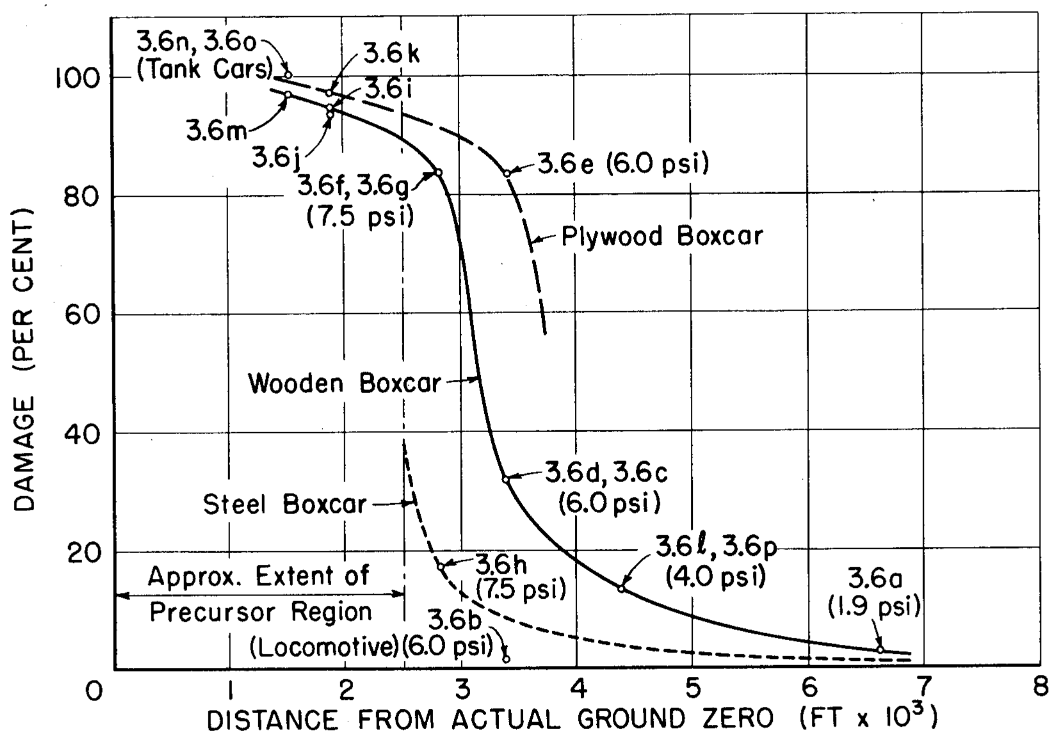

Fig. 5.5 Distribution of Damage versus Ground Range

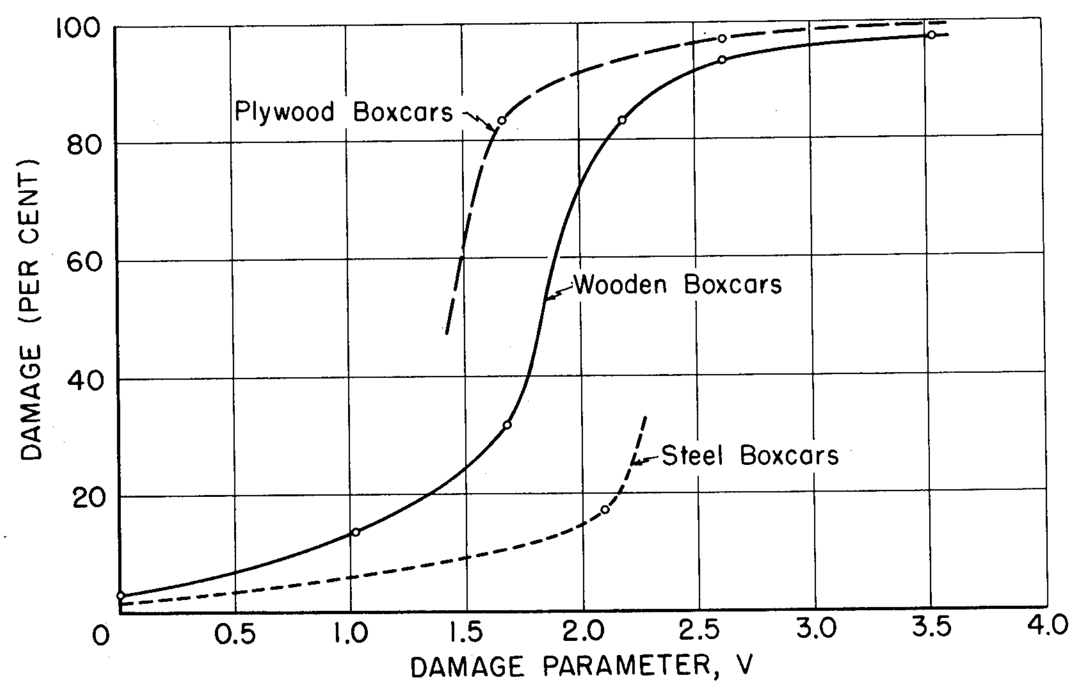

Fig. 5.6 Distribution of Damage versus Damage Parameter, V

[redacted]

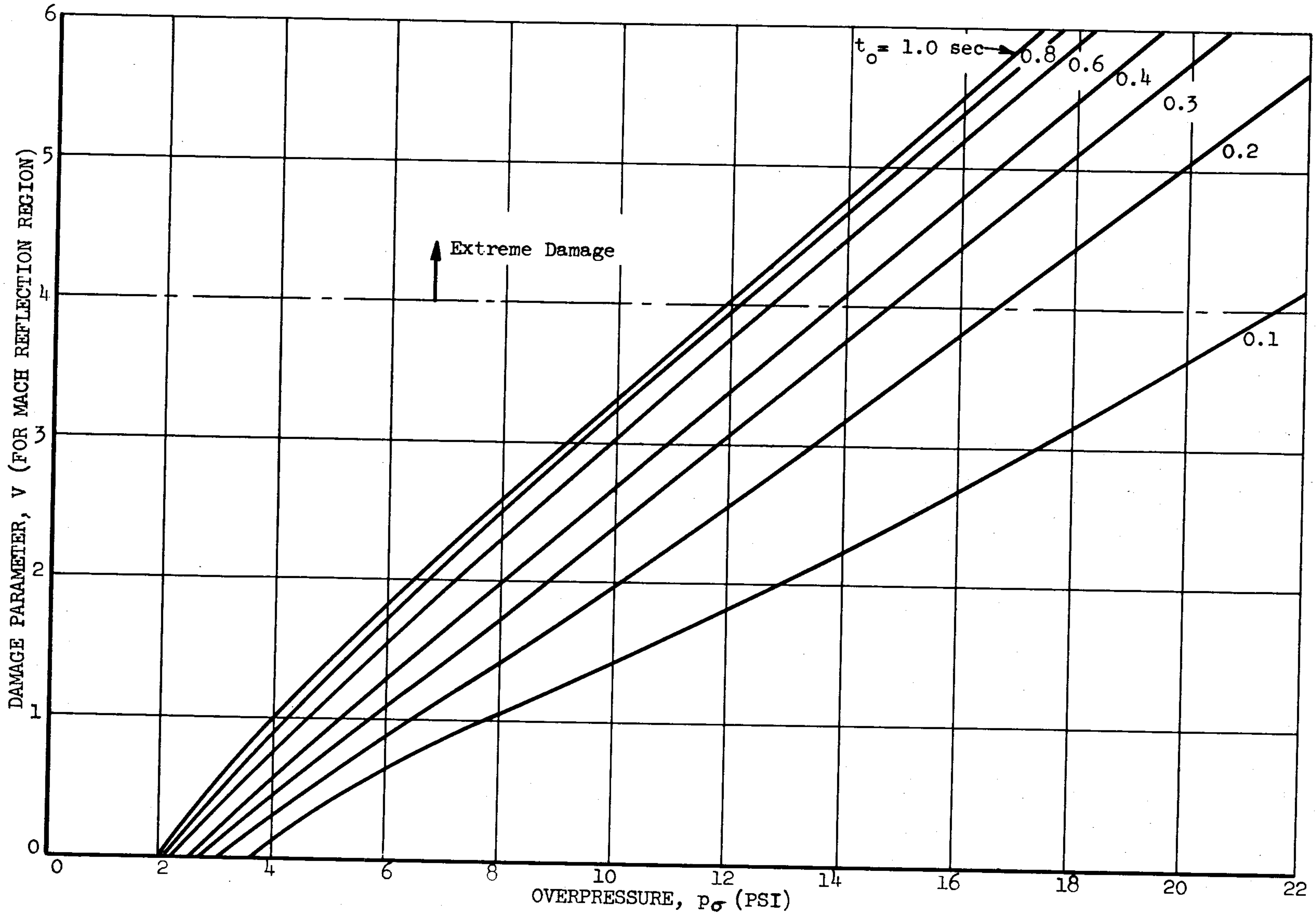

Fig. 5.7 Damage Parameter, V, vs Blast Parameters

[redacted]

present scheme is tied to a particular method of damage evaluation which is itself subject to revision in certain cases. Until additional experimental data become available the validity of the proposed scheme cannot be judged and it should be applied with this fact kept clearly in mind.

It should also be mentioned that the above criterion is by no means the only one that can be formulated. Another approach might be one in which the response of, say, a side panel is computed, and a certain number of elastic displacements taken to be a measure of damage. The blast parameters causing this displacement could then be associated with the observed damage in exactly the manner employed above. This scheme, too, would lead to essentially the same results as embodied in Fig. 5.8. However, in order to carry out this type of analysis, it would be necessary to define many more details of car construction than in the overturning approach. While the inherent mechanism of damage might be somewhat more realistic, the computation would be considerably more involved and, the author feels, no more conclusive.

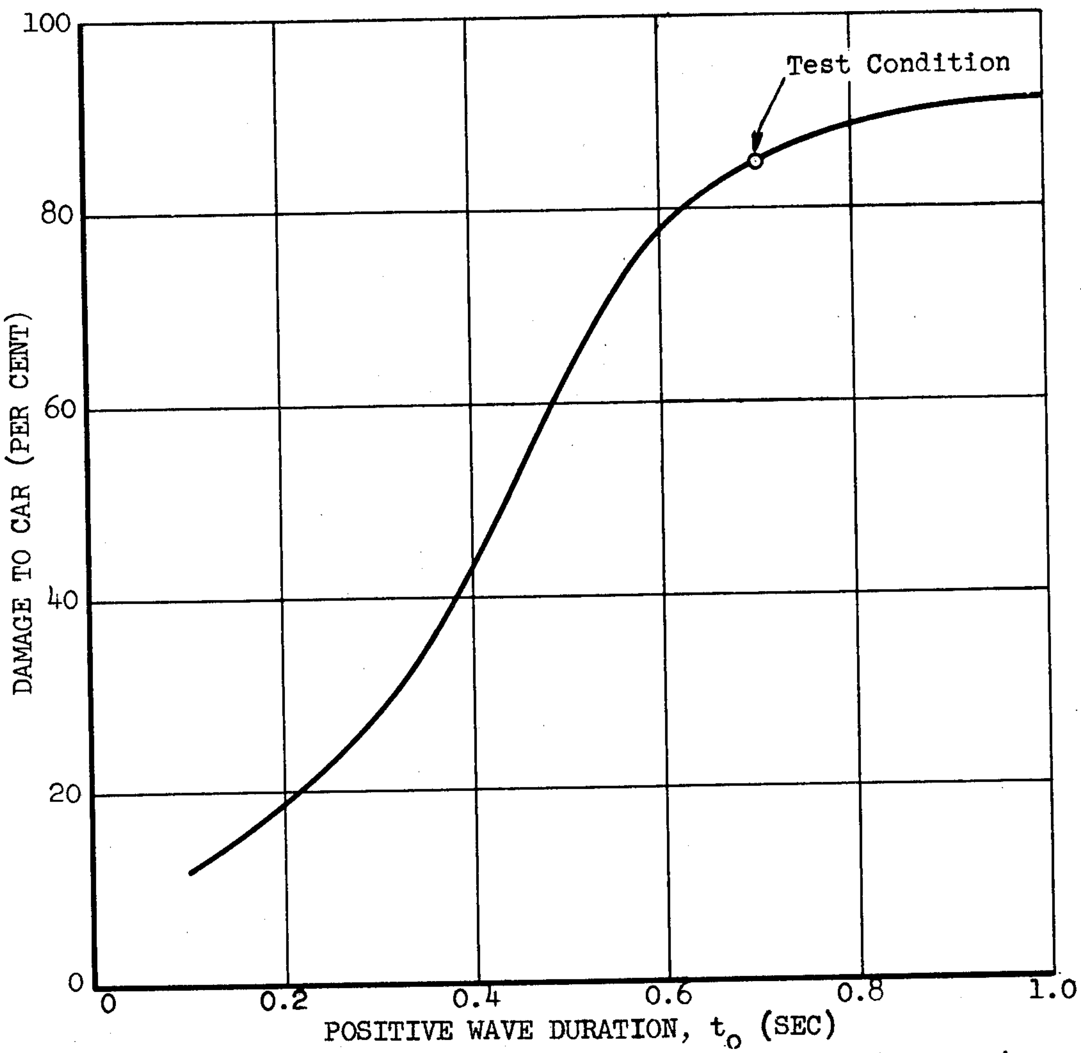

Fig. 5.8 Damage Versus Duration, Boxcar 3.6f (7.5 psi)

[redacted]

CHAPTER 6

CONCLUSIONS

The following conclusions have been reached as a result of the analysis of the test data presented in this report.

1. Railroad equipment of the types tested (with the possible exception of the diesel locomotive) will be severely damaged,1/ if not totally destroyed, when located within about 2500 ft of ground zero under Shot 10 conditions (precursor region).

2. Boxcars of the types tested will be severely damaged at overpressures in excess of about 7.5 psi in the Mach region where the duration is not substantially less than that of Shot 10. A marked decrease in damage can be expected to occur between about 7.5 and 6 psi. At pressures of about 2 psi, negligible damage will occur.

3. A diesel locomotive of the type tested will sustain only minor damage at an overpressure of about 6 psi in the Mach region where the duration is not substantially less than that of Shot 10.

4. The plywood boxcars of the type tested are the most susceptible to blast damage. The cars of standard wooden construction and steel construction (i.e., steel roof and side panels) rank in order of decreasing vulnerability, the steel car being considerably less vulnerable on the basis of this test. The trucks and underframes of the cars proved to be salvable in many instances, even though the car body was totally demolished. Thus, in cases of emergency the possibility exists that even heavily damaged cars could be utilized as flatcars.

1/ It should be kept in mind that the concept of damage used here refers to the particular method of evaluation presented in section 5.3.

[redacted]

5. Overturning does not appear to be a significant contributing factor in physical damage of boxcars. In every case where cars loaded in the lower portion and empty boxcars of the same type were at the same ground range, the over-all damage[2] was identical, even though in some cases the loaded cars remained upright, whereas the empty ones overturned.

6. Thermal damage associated with blasts capable of demolishing equipment of the type tested is negligible.

7. A comparison of pretest predictions with the test results, wherever applicable, indicates the following:

   a. Within the region of conventional Mach reflection, the load causing overturning of an essentially rigid box-like structure can be predicted with relatively good accuracy. Equation 3.6 yields a simple criterion for determining whether or not overturning will occur.

   b. In connection with the response analysis, a drag coefficient of 1.0 for box-like shapes appears to be a realistic value.

   c. It is not realistic to associate damage to boxcar roof and side panels with elastic yield displacements of these components, as was done in the pretest work. If it is reasonable to treat these components as simple beams, then failure apparently does not occur until at least five or six yield displacements have been reached.

In summation, the following can be said with respect to the test objectives of specific interest to the Air Force (see Chapter 1):

1. The test objective dealing with the prediction of damage to railroad rolling stock has been fulfilled to the extent that might reasonably have been expected from the test setup.

2/ Possible exceptions to this as a general conclusion might occur in those cases where the present damage concept is invalid (e.g., where overturning constitutes significant damage in itself) and/or where cargo lends greater rigidity to the car body than did the sandbag loading employed in the test. The latter condition could well invalidate any correlation made in this report between damage to empty and damage to loaded cars. However, in those cases where the cargo does not afford greater rigidity to the car body than the sandbag loading, this conclusion probably need not be restricted with respect to the height of the cargo in the car.

[redacted]

2. The test objective dealing with the correlation between car damage and mode of response has been fulfilled to the extent that conclusion 5 above is generally applicable.

3. The test objective dealing with the determination of car damage resulting from the thermal pulse associated with the bomb has been fulfilled.

4. The test objective dealing with the accumulation of data for the vulnerability classification system established by the Directorate of Intelligence, Hq., USAF, has not been specifically considered in this report. However, the data obtained, especially in the form of damage versus distance plots (Fig. 5.5), can doubtless be incorporated by this agency into its system.

5. The test objective dealing with the experimental determination of blast loading data on boxcars has not been fulfilled because of the lack of success in obtaining usable pressure-time data. However, relatively good agreement has been obtained between predicted and measured response of the boxcars in the region of conventional Mach reflection. Since these predictions were based on the loading schemes described in Chapter 3, it can be expected that their application will yield reasonably accurate results when applied to the response problem.

The test was also designed to yield information applicable to certain specific needs of the Transportation Corps. Based upon this information, further work involving theoretical considerations and shock tube studies is being conducted under separate contract as a responsibility of the Transportation Corps. With respect to the Transportation Corps objectives listed in Chapter 1, the following may be said:

1. The objective dealing with the determination of blast and thermal damage to our own railroad marshaling yards and rolling stock has been partially fulfilled within the limitations of the test in that the portion relating to damage of rolling stock has already been completed. The remainder of this objective will be attained by completion of the work mentioned above.

2. The objective dealing with the determination of effort and time required to restore service and replace damaged equipment will depend on the additional work for its eventual fulfillment. It is believed, however, that bases for such estimates, which must ultimately rely on the judgment and experience of qualified Transportation

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Corps personnel, have been established through observations made following the test (see Chapter 4).

3. The objective dealing with the collection of damage data which can be used in formulating dispersion criteria for calculating risk formulae has not been specifically considered in this report, and probably cannot be fulfilled on the basis of this test alone. This is a task which will require the application of statistical methods whose accuracy will be increased with the number of tests performed. It is believed that the additional work indicated above will enhance the results of the present test in this respect.

4. The test objective dealing with the verification or modification of existing damage criteria, as found in TM 23-200, Capabilities of Atomic Weapons, has not been specifically considered in this report. However, TM 23-200 has been modified to reflect the criteria established by the project as of the writing of this report.

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APPENDIX A

COMMENTS ON DESIGN OF RAILROAD CARS TO REDUCE BLAST DAMAGE

The Transportation Corps has expressed interest in determining the desirability of design modifications of railroad cars in order to increase their resistance to blast damage. A comprehensive study of this problem is, of course, beyond the intended scope of this project, and no such attempt is made herein. Nevertheless, it is believed that the test results are applicable to at least one aspect of the design problem. It should be kept in mind, however, that the following discussion is not in the least an exhaustive treatment of even this one aspect and, in fact, no positive conclusions are reached.

A rather obvious and theoretically desirable design modification would be one in which the running gear is connected in a positive fashion to the underframe. The purpose of so doing would be to increase the resistance of the car to overturning inasmuch as the test results indicate that, with present designs, the car body can overturn independently of the trucks. The trucks comprise about one-third of the tare of an average (empty) wooden boxcar and, from static considerations, would result in an increase in overturning force (applied at mid-cab height) of about 60 per cent if they acted as an integral part of the car. If the car is considered to be carrying cargo comparable to test conditions, the effect of the truck weight is to increase the static overturning force by only about 17 per cent.

In the event that the degree of damage is influenced strongly by whether or not the car remains upright, the effect of attaching the trucks could prove significant under certain restricted conditions. However, according to the damage concept employed in this report, whether or not the car overturns appears to influence the over-all damage only slightly. Indeed, if the car overturns and carries the running gear with it, the possible additional damage to these components due to ground impact might well result in greater over-all damage to the car. The additional difficulties which might be encountered in repair techniques resulting from this type of modification need also to be considered.

Thus, the results of this test clearly do not show any obvious decrease in blast vulnerability to be gained from attaching the trucks to the underframe in a positive fashion.

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