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Rationale for Wind-Borne Missile Criteria for DOE Facilities

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September 1999

Lawrence Livermore National Laboratory

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Rationale for Wind-Borne Missile Criteria for DOE Facilities

By

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Prepared for
Hazards Mitigation Center
Lawrence Livermore National Laboratory

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FOREWORD

This report is the culmination of more than 20 years of research by the author and colleagues at Texas Tech University. One of the first missiles studied was a 13.5-ft diameter by 20 ft long steel tank that was transported by the Lubbock tornado of 1970. News reports stated that the huge tank had flown through the air for more than 5 miles. Careful study by Texas Tech University personnel showed that the tank actually rolled and tumbled the stated distance and never rose more than a few feet above ground. The incident points to the need for very careful study of tornado missiles in the field. To date, Texas Tech University researchers through the Institute for Disaster Research have studied damage and documented missiles in more than 70 windstorm events, including hurricanes, tornadoes and high winds.

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The author wishes to acknowledge the contributions of faculty and graduate students, who over the years performed the analyses and impact tests described in this report. Dr. Robert Bailey and Dr. Milton Smith designed and constructed the tornado missile cannon. Brad White performed impact tests on a number of CMU block walls; Peng- Hsiang Luan made estimates of missile speeds in tornadoes by means of trajectory simulations and Blair Nevins conducted impact tests and contributed to the development of the recommended DOE missile barrier criteria.

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EXECUTIVE SUMMARY

High winds tend to pick up and transport various objects and debris, which are referred to as wind-borne missiles or tornado missiles, depending on the type of storm. Missiles cause damage by perforating the building envelope or by collapsing structural elements such as walls, columns or frames. The primary objectives of this study are as follows:

1. to provide a basis for wind-borne or tornado missile criteria for the design and evaluation of DOE facilities, and
2. to provide guidelines for the design and evaluation of impact-resistant missile barriers for DOE facilities

The first objective is accomplished through a synthesis of information from windstorm damage documentation experience and computer simulation of missile trajectories. The second objective is accomplished by reviewing the literature, which describes various missile impact tests, and by conducting a series of impact tests at a Texas Tech University facility to fill in missing information.

Damage documentation files at Texas Tech University (TTU) contain data collected from more than 70 windstorm events over the last 25 years. Tornadoes tend to pick up and transport missiles more readily than other windstorms because of their high wind speeds and unique vertical wind speed component. Tornado missiles are addressed, and then criteria for missiles appropriate to other storms are inferred.

The DOE design criterion (DOE -STD- 1020-94) includes tornado wind speeds up to and including Fujita Scale Category F4. Tornadoes rated F2, F3 and F4 that had documented missile data were identified in the TTU damage documentation. The missiles were classified into three categories: Lightweight missiles that are lifted and transported by the winds, medium-weight missiles that are accelerated horizontally as they fall to the ground, from some height above ground and large heavy missiles that roll and tumble along the ground. These classes of missiles are represented by a 2x4 timber (15 lb), a 3-in. dia. steel pipe (75 lb) and an automobile (3000 lb), respectively.

The TTU tornado missile trajectory simulation software was used to estimate the speed, maximum height, and distance traveled by the missiles. The details of the trajectory simulation program are presented in this report along with supporting data for validation. The recommended missile impact speeds in DOE STD 1020-94 were deduced from the trajectory calculations (see Table 1.1 for missile impact criteria).

The literature was reviewed to identify missile impact tests that have been conducted in the past. Most tests conducted prior to about 1985 involved the missile spectrum specified by the US Nuclear Regulatory Commission for design of nuclear power plant facilities. The missiles and impact speeds were very much larger than those in the DOE criteria. Tests were conducted at TTU to fill in information missing from the literature. Tests were conducted to define threshold impact speeds for perforation and backface scabbing. Wall configurations to meet the defined impact criteria were then built and tested. Recommended wall sections are presented that will meet the impact criteria in DOE 1020-94 (see Section 4.7). These include walls constructed of reinforced concrete, clay brick and concrete masonry.

1. INTRODUCTION

1.1 Wind and Tornado Missiles

High winds tend to pick up and transport various objects and debris, which are referred to as wind-borne missiles, or simply tornado missiles. Tornado missiles tend to be larger, achieve higher velocities, and travel greater distances than missiles generated by hurricanes and other extreme winds. Wind-borne missiles present a major threat of injury or death to persons caught in the open during a storm. In addition, missiles cause physical damage to buildings and facilities.

In non-tornadic winds (thunderstorm outflows, downslope winds, and hurricanes), there is no significant vertical component to the wind velocity. Objects propelled horizontally by the wind may experience some uplift, but generally are falling under the influence of gravity. Gravity forces are partially overcome by the upward wind velocity component in tornadic winds. Lightweight missiles such as sheet metal or pieces of wood sometimes are carried to great heights before finally falling to the ground.

Wind-borne missiles range in size from roof gravel to large objects such as railroad cars or storage tanks. Bailey (1984) categorized missiles as small, medium or heavy. The small missile category includes roof gravel, tree branches and pieces of lumber. Small diameter pipes, steel roof joists and small beams comprise typical missiles in the medium category. Utility poles, large diameter pipes, automobiles, railroad cars, and storage tanks fit into the heavyweight missile class. The heavyweight missiles are found only in damage of very intense tornadoes. The types of missiles depend on the damage caused by the windstorm. Damage to residences produce numerous timber missiles, while damage to commercial or industrial facilities tends to produce heavier and more rigid missiles. Construction sites provide a prime source of both medium and heavy missiles.

1.2 Objectives and Scope of Study

Wind-borne missiles are a potential damage mechanism in windstorms. Protection against wind-borne missiles should be a component of all wind-resistant designs. This report is the culmination of years of study of the effects of wind-borne missiles. The findings and recommendations are based on observations of missiles in post-storm damage investigations, computer simulations of missile trajectories, and tests of the impact resistance of various construction materials. Although the study is primarily directed to the design and evaluation of Department of Energy (DOE) facilities, much of the information is applicable to other wind-resistant buildings and structures.

In the DOE context, a facility can be divided into structures, systems, or components (SSCs) according to DOE-STD-1021-93 (DOE 1993). A *Structure* is an element, or collection of elements, that provides support or enclosure such as a building, freestanding tank, basin, or stack. A *system* is a collection of components assembled to perform a function, such as piping, cable trays, conduits, or HVAC installations. A *component* is an item of equipment, such as a pump, valve or relay, or an element of a larger array, such as a length of pipe, elbow, or reducer. Unlike earthquakes, wind forces in general only affect structures. However, wind-borne missiles are capable of damaging structures, systems, and components.

The objectives of this study are as follows:

1. to provide a basis for wind-borne missile criteria used in the design and evaluation of SSCs in DOE facilities, and
2. to provide guidelines for design and evaluation of impact-resistant missile barriers for SSCs in DOE facilities.

The first objective is accomplished through synthesis of information from windstorm damage documentation experience and computer simulation of missile trajectories. Data files of more than 70 windstorm events documented by personnel at Texas Tech University were consulted in the course of this study. Damage documentation alone does not give the complete story of missile behavior. One can observe the original location and impact point of a missile, but the maximum velocity and maximum height attained by the missiles are unknown. Occasionally, a movie film or video of a tornado in action will show trajectories of missiles, but these events are rare. Computer simulation is about the only tool available to predict the trajectories of postulated tornado missiles. Although computer simulations of missile trajectories cannot tell the exact story, they indicate general trends in the behavior of missiles that are adequate for design purposes. Indications of missile velocity, height above ground, and distance traveled can be obtained from a missile trajectory simulation model.

The second objective of the study is accomplished by reviewing literature which describes various missile impact tests and by conducting impact tests at Texas Tech University to fill in missing information. This report describes the Texas Tech University tests.

1.3 DOE Approach to Natural Phenomena Hazards

DOE Order 5480.28 establishes DOE policies and requirements for natural phenomena hazard (NPH) mitigation for DOE sites and facilities using a graded approach. The graded approach is one in which SSCs are placed into performance categories such that the required level of analysis, documentation, and actions are commensurate with following factors:

1. the relative importance to safety, safeguards, the environment and security,
2. the expected magnitude of any hazard involved,
3. the programmatic mission of a facility,
4. the particular characteristics of the SSCs, and
5. the cost and replaceability of the SSCs.

SSCs comprising a DOE facility are assigned to appropriate performance categories utilizing the approach described in DOE (1993). The design and evaluation criteria for natural phenomena hazards are specified in DOE STD 1020-94 (DOE 1994). A Natural Phenomena Hazard panel developed the design and evaluation approach, which is consistent with DOE Order 5480.28. Components of the design and evaluation approach include:

1. Natural Phenomena Hazard Probability (NPH) assessment from which loads are derived,
2. Design and evaluation procedures for each performance category with which to evaluate SSC response to the NPH loads, and
3. Standards to assess whether or not the computed response is acceptable.

Natural Phenomena Hazards Addressed in DOE STD 1020-94 includes earthquakes, winds, tornadoes and floods. Missiles are a part of the wind and tornado criteria.

Wind hazard models for 25 DOE sites have been published (Coats and Murray, 1985). A wind hazard exceedance model gives probability versus wind speed for a particular site. The model addresses those windstorms that are likely to affect the site, which may include straight winds, hurricanes, or tornadoes. A uniform treatment of wind loads generally follows the procedures of ASCE 7-88 (ASCE 1990).

The DOE STD 1020-94 establishes the level of wind hazard probability for each of the four performance categories, which in turn, establishes the appropriate wind speed for design and evaluation of SSCs. Missile criteria consistent with the design and evaluation wind speeds also are specified in the DOE STD 1020-94. The material presented herein provides a rationale for the wind-borne missile criteria specified in DOE STD 1020-94.

Table 1.1 summarizes the wind-borne missile criteria for design and evaluation of DOE SSCs. Performance Categories 1 and 2 consider only the effects of straight winds and hurricanes, whereas Performance Categories 3 and 4 also consider tornadoes, if they are deemed a viable threat at the site. Wind-borne missile criteria are specified for Performance in Categories 3 and 4 for straight winds, hurricanes or tornadoes, depending on which storms are applicable at a particular site.

Table 1.1 Summary of Minimum Wind Design Criteria for DOE SSCs

(from DOE STD 1020-94)

	Performance Category	[1]	[2]	[3]	[4]
Wind	Hazard Annual Probability of Exceedance	$2x10^{-2}$	$2x10^{-2}$	$1x10^{-3}$	$1x10^{-4}$
	Importance Factor *	1.00	1.07	1.00	1.00
	Missile Criteria	NA	NA	2"x4" timber plank 15 lb @ 50 mph (horiz.); max. height 30 ft.	2"x4" timber plank 15 lb @ 50 mph (horiz.); max. height 50 ft.
Tornado	Hazard Annual Probability of Exceedance	NA	NA	$2x10^{-5}$	$2x10^{-6}$
	Importance Factor *	NA	NA	1.00	1.00
	APC	NA	NA	40 Psf @ 20 Psf/sec	125 Psf @ 50 Psf/sec
	Missile Criteria	NA	NA	2"x4" timber plank 15 lb @ 100 mph (horiz.); max. height 150 ft.; 70 mph (vert.) 3 in. dia. Std. Steel Pipe 75 lb @ 50 mph (horiz.); max. height 75 ft. 35 mph (vert.)	2"x4" timber plank 15 lb @ 150 mph (horiz.); max. height 200 ft.; 100 mph (vert.) 3 in. dia. Std. Steel Pipe 75 lb @ 75 mph (horiz.); max. height 100 ft. 50 mph (vert.) 3000 lb automobile @ 25 mph, rolls and tumbles

* *See ASCE 7, Table 5*

1.4 Background

Appropriate levels of hazard probabilities for DOE SSCs are derived from precedents established by governmental agencies or by established industrial practices. For hazardous facilities, the practices have evolved from those adopted for nuclear power plant design.

The general design criteria for nuclear power plants are established in Title 10, CFR, Part 50, Appendix A. General Criterion 2 states:

> Structures, systems and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquake, tornadoes, hurricanes, flood, tsunami and seiches without loss of capability to perform their safety function. The design basis shall reflect the following:
> 1. Appropriate considerations of the most severe natural phenomena that have been historically reported for the site and surrounding area with sufficient margin for limited accuracy, quantity and the period of time in which the historical data have been accumulated,
> 2. Appropriate combinations of the effect of normal and accidental conditions of the effects of natural phenomena, and
> 3. The importance of the safety function to be performed.

Ravindra et al. (1993) traces the evolution of tornado design practice for nuclear power plants. In order to meet the Title 10 CFR criteria, the Atomic Energy Commission (AEC) established criteria based on an annual tornado hazard probability of $1x10^{-7}$ per year. The rationale for the 10^{-7} value has been lost over the years. Old records suggest it was predicated on the assumption of 2000 operating nuclear power plants in the U. S. by the year 2000 A.D., an assumption which has not been realized.

A study referred to as WASH 1300 was performed by Markee, et al. (1974) to establish the tornado hazard on a probabilistic basis at the $1x10^{-7}$ probability level. The study incorporated several layers of conservatism. Nevertheless, WASH-1300 became the basis for Reg. Guide 1.76 (USNRC 1974), which forms the design basis for protection of nuclear power plants against tornadoes (see Table 1.2).

Reg. Guide 1.76 does not specify tornado missile criteria. Standard Review Plan (SRP) 3.5.1.4 (USNRC 1975) provides acceptance criteria for identification of appropriate design missiles and their impact speeds for nuclear power plants. The acceptance criteria were established after a number of topical studies on tornado missiles were submitted by various A/E firms engaged in nuclear power plant design. The missile impact speeds are expressed as a function of the design basis for tornado wind speed. Table 1.3 lists the missiles that were acceptable in June 1975. Later, in 1977, the Nuclear Regulatory Commission (agency that replaced the old AEC) adopted alternative missile criteria consisting of two sets of design missiles denoted Spectrum I and Spectrum II. Spectrum I missiles consisted of a rigid slug and a 2x4 timber plank. Spectrum II consisted of another list of planks, pipes, poles, and automobiles. A minimum acceptable barrier thickness for damage protection against tornado-generated missiles is listed in SRP Section 3.5.3.

The damage to a nuclear power plant by tornado missiles is a very low probability event because a sequence of events must take place in order for a missile to cause an unacceptable accident. Probabilistic risk assessment (PRA) studies for extreme winds have been published for the Indian Point, Limerick, Millstone, Seabrook and Zion nuclear plants. In addition, extreme wind studies have been conducted for six plants as part of the TAP A-45 abbreviated PRA project. Results of the full-blown PRAs are summarized in Table 1.4.

Table 1.2 Tornado Design Criteria for Nuclear Power Plants

(Reg. Guide 1.76 (AEC 1974))

Region	Maximum Wind Speed [a] (mph)	Rotational Wind Speed (mph)	Translational Wind Speed (mph)		Radius of Maximum Rotational Wind Speed (ft.)	Pressure Drop (psi)	Rate of Pressure Drop (psi/sec)
			Maximum	Minimum			
I	360	290	70	5	150	3.0	2.0
II	300	240	60	5	150	2.25	1.2
III	240	190	50	5	150	1.5	0.6

[a] *The maximum wind speed is the sum of the rotational speed component and the maximum translational speed component*

Tornado Intensity Regions

Table 1.3 Tornado Missile Criteria for Nuclear Power Plants ***(NRC 1975)***

Missile	Weight (lbs)	Nominal Dimensions (in.)	Missile Velocity (mph)		
			I	II	III
A. Wood Plank	115	4 x 12 x 144	288	240	192
B. 3-in. dia. Sch 40 Pipe	78	3-in. dia x 120	144	120	96
C. 1-in. dia. Steel Rod	9	1-in. dia x 36	216	180	144
D. 6-in. dia. Sch 40 Pipe	285	6-in. dia x 180	144	120	96
E. 12-in. dia. Sch 40 Pipe	750	12-in. dia x 180	144	120	96
F. Utility Pole	1125	13.5-in. dia x 420	144	120	96
G. Automobile	4000	196 x 80 x 50	72	60	48

Missiles A-E are considered at all elevations;
Missiles F-G are considered up to 30 ft. above ground

The extreme wind studies for the TAP A-45 project were not full-scope PRAs, but the analysis procedure was similar. Plants included in the study were Arkansas Nuclear-One, Cooper, Point Beach, Quad Cities, St. Lucie and Turkey Point. In all six cases studied, the estimated core damage frequency was below 1×10^{-8} per year when tornado missiles were part of the damage sequence.

The point of this discussion on NRC tornado missile criteria for nuclear power plants is that the regulatory authority adopted a very conservative approach back in the late 1960s and has not substantially reduced it in the last 25 years. The missile criteria adopted in DOE STD 1020-94 for design and evaluation of DOE SSCs are significantly different from the NRC criteria for nuclear power plants. The DOE criteria are different because:

1. missiles are selected from actual field observations,
2. level of risk is different from nuclear power plants and
3. design tornado wind speeds are significantly lower than those in NRC criteria.

In the next section, field observations of missiles are reviewed in order to validate the tornado missile specified in DOE design and the evaluation criteria for SSCs. Section 3 describes the methodology and results of tornado missile trajectory simulation. This information is used to set missile impact speeds and maximum height above ground. Section 4 describes impact tests and recommends appropriate barriers to resist the specified missile impact criteria.

Table 1.4 Summary of Results of Probabilistic Risk Assessments for Selected Nuclear Power Plants

(Tornado Missile)

Plant	Results
Indian Point	Core damage frequently due to tornado missile for each of two units was estimated to be less than $1x10^{-7}$ per year
Limerick	Systems analysis were performed and it was found that the contribution of tornado-initiated accidents to core damage frequency is less than $1x10^{-9}$ per year, including missile-caused accidents
Millstone Unit 3	Using the results from Twisdale (1981), the frequency of tornado missile-induced core melt accident sequence was estimated at less than $1x10^{-7}$ per year
Seabrook	Core damage frequency due to tornado missiles was estimated at $3.4x10^{-10}$ per year
Zion	Based on results of tornado risk analysis reported in Twisdale (1981), the probability of tornado missiles striking and scabbing the walls of the Zion plant structure was estimated at $2 x10^{-6}$ per year. The probability of damaging certain equipment, thereby leading to core damage was estimated to be around $12 x10^{-8}$ per year. The core damage probability was judged to be acceptably small; tornadoes and tornado missiles were not considered to be significant risk contributors.

2. MISSILE CLASSES BASED ON FIELD OBSERVATIONS

The best available information on the kinds of missiles picked up and transported by extreme windstorms comes from field observations of windstorm damage. The damage documentation files at Texas Tech University contain data collected from more than 70 windstorm events over the last 25 years. Although most of the studies did not have missile documentation as a primary objective, significant amounts of data relating to missiles were collected.

Tornadoes tend to pick up and transport missiles more readily than other windstorms because the wind speeds are higher and tornadoes have a strong vertical wind component in the vortex. The behaviors of tornado missiles are treated first because more information is available. The behavior of missiles in non-tornadic storms is deduced from the results of the tornado missile studies.

The objective of this study is to determine the most probable missiles found in tornado damage paths as a function of tornado intensity. The Fujita Scale is used to rate tornado intensity. The identified missiles are then used in trajectory calculations as described in Chapter 3 of this report to determine missile speed, maximum height and distance traveled. These studies provide the data necessary to establish tornado missile impact criteria for the design and evaluation of DOE facilities (SSCs).

The amount of information on missiles that can be obtained from the field is limited. The impact point is known. Sometimes it is possible to determine the point of origin of the missile, but nothing is known about the trajectory the missile followed as it was transported by the winds. The size and weight of a missile can be measured in the field, but very little information of this type is available. The material and size of missiles can be estimated from good quality, low-level aerial photos of the damage path. The Missile material is identified; the weight is then estimated by assuming a unit weight for the material. An approximate scale of aerial photo is determined from objects of known size. This procedure is not precise, but it gives general characteristics of the missiles found in tornado damage paths.

2.1 Approach

The following approach is taken in this study:

1. Express the design tornado wind speeds for each DOE site in terms of the Fujita-Scale categories.
2. Identify those tornadoes from the Texas Tech University Damage files that contain missile data and determine their Fujita-Scale rating.
3. Identify the sources and types of missiles visible in aerial photos and estimate mean size and weight.
4. Count the number of individual missiles visible in aerial photos and estimate mean size and weight.
5. Determine a statistical distribution of missiles counted in Step (4)
6. Group missiles into various classes.
7. Identify a representative missile for each class.

2.2 Fujita Scale

Because it is impossible to obtain direct anemometer measurements of wind speeds in a tornado, indirect methods are relied upon to estimate tornado wind speeds. Several methods have been successfully used, including evaluation of structural damage, photogrammatic analysis of tornado movies, and analysis of cycloidal ground marks.

The most widely accepted method is the Fujita-Scale. Wind speeds are estimated from the appearance of damage. A Fujita Scale category is assigned to the tornado based on the worst damage observed in the path. Each category is related to range of wind speed. Table 2.1 describes the damage associated with each Fujita Scale category.

Table 2.1 Fujita- Scale Classification of Tornadoes
(Fujita 1971)

F-Scale	Wind Speed* (mph)	Damage Description
(F0) **Light Damage**	40 - 72	Some Damage to chimneys or TV antennae; breaks branches off trees; pushes over shallow-rooted trees; old trees with hollow insides break of fall; sign boards damaged.
(F1) **Moderate Damage**	73 - 112	Peel surface off roofs; windows broken; trailer houses pushed or overturned; trees on soft ground uprooted; some trees snapped; moving autos pushed off the road.
(F2) **Considerable Damage**	113 - 157	Roof torn off frame houses leaving strong upright wall standing; weak structure or outbuildings demolished; trailer houses demolished; railroad boxcars pushed over; large trees snapped or uprooted; light object missiles generated; cars blow off highway; block structures and walls badly damaged.
(F3) **Severe Damage**	158 - 206	Roofs and some walls torn off well-constructed frame houses; some rural buildings completely demolished or flattened; trains overturned; steel framed-hanger warehouse structures torn; cars lifted off the ground and may roll some distance; most trees in a forest uprooted, snapped, or leveled; block structures often leveled.
(F4) **Devastating Damage**	207 - 260	Well-constructed frame houses leveled, leaving piles of debris; structure with weak foundation lifted, torn, and blown off some distance; trees debarked by small flying debris; sandy soil eroded and gravel flies in high winds; cars thrown some distance or rolled considerable distance, finally to disintegrate; large missiles generated.
(F5) **Incredible Damage**	261 - 318	Strong frame houses lifted clear off foundation and carried some considerable distance to disintegrate; steel-reinforced concrete structures badly damaged; automobile-sized missiles carried a distance of 100 yards or more; trees debarked completely; incredible phenomena can occur

*Fujita Scale wind speed is fastest one-quarter mile wind speed at 10m in open terrain.

Table 2.2 lists those DOE sites that have tornado design criteria. The design wind speeds are given (in terms of fastest-one-quarter mile wind speeds) for Performance Categories PC3 and PC4. The corresponding Fujita Scale class is also listed in the table for each site. The design tornado wind speeds range from F1 to F4.

Table 2.2 Tornado Design Wind Speed at DOE Sites

DOE Site	PC3		PC4	
	Wind Speed*	F-Scale	Wind Speed*	F-Scale
Kansas City, MO	144	F3	198	F4
Mound Lab, OH	136	F2	188	F4
Pantex, TX	132	F2	182	F3
Argonne-East, IL	146	F3	196	F4
Brookhaven, NY	95	F1	145	F3
Princeton, NJ	103	F2	150	F3
FMPL, OH	139	F2	192	F4
Oak Ridge, TN	113	F2	173	F3
Paducah, KY	144	F3	198	F4
Portsmouth, OH	110	F2	166	F3
ETEC, CA	95	F1	111	F2
Savannah River, SC	137	F2	192	F4

* *Fastest-mile one-quarter mile wind speeds (mph)*

2.3 Tornado Missile Data

Table 2.3 lists the tornadoes for which missile data are available from the TTU archives along with the Fujita Scale rating of each storm.

Table 2.3
Tornadoes with Documented Missile Data

Tornado	Year	Fujita-Scale
Burnett, TX	1973	F2
Hubbard, TX	1973	F2
Monahans, TX	1977	F2
Grand Island, NE	1980	F2
Plainview, TX	1972	F3
Grand Island, NE	1980	F3
Kalamazoo, MI	1980	F3
Altus AFB, OK	1982	F3
Sweetwater, TX	1986	F3
West Memphis, AR	1987	F3
Louisville, KY	1974	F4
McComb, MS	1975	F4
Omaha, NE	1975	F4
Bossier City, LA	1978	F4
Cheyenne, WY	1979	F4
Wichita Falls, TX	1979	F4
Grand Island, NE	1980	F4
Huntsville, AL	1989	F4
Plainfield, IL	1990	F4
Lancaster, TX	1994	F4
Lubbock, TX	1970	F5
Xenia, OH	1974	F5
Brandenberg, KY	1974	F5
Birmingham, AL	1977	F5

2.3 Missile Observations

2.3.1 General Views of Damage

Figure 2.1 shows an aerial view of tornado damage caused by the Wichita Falls, Texas, tornado (F4). The source of missiles in this case was damaged or destroyed residential roofs. The vast majority of pieces are 2x4 and 2x6 rafters, joists, or prefabricated truss chords.

Figure 2.2, also from Wichita Falls, shows missiles and debris from the destruction of a shopping mall a half block away. Steel roof joists, steel angles, timber planks, a broken utility pole and sheet metal can be seen in the photo. Figure 2.3 shows an inside courtyard of McNeil Junior High School in Wichita Falls. Light-weight steel channels, angles, chunks of lightweight roofing material, insulation board and tree limbs can be seen in the photo.

Figure 2.4 is a view of a heavily damaged commercial building in Bossier City, Louisiana (F4). One can see pieces of the poured in place light weight gypsum roofing, pieces of metal roof deck, plastic pipe (round white objects), pieces of plywood, and steel angle shapes.

Figure 2.5 is an aerial view of damage from the Wichita Falls, Texas, tornado of 1979 (F4). The source of the missiles is destruction of a large apartment complex. Roofing material and plywood deck have been removed, leaving the prefabricated trusses unsupported on their top chords. The trusses tend to fall over like dominos when this happens. Some trusses have broken into pieces, providing timber plank missiles.

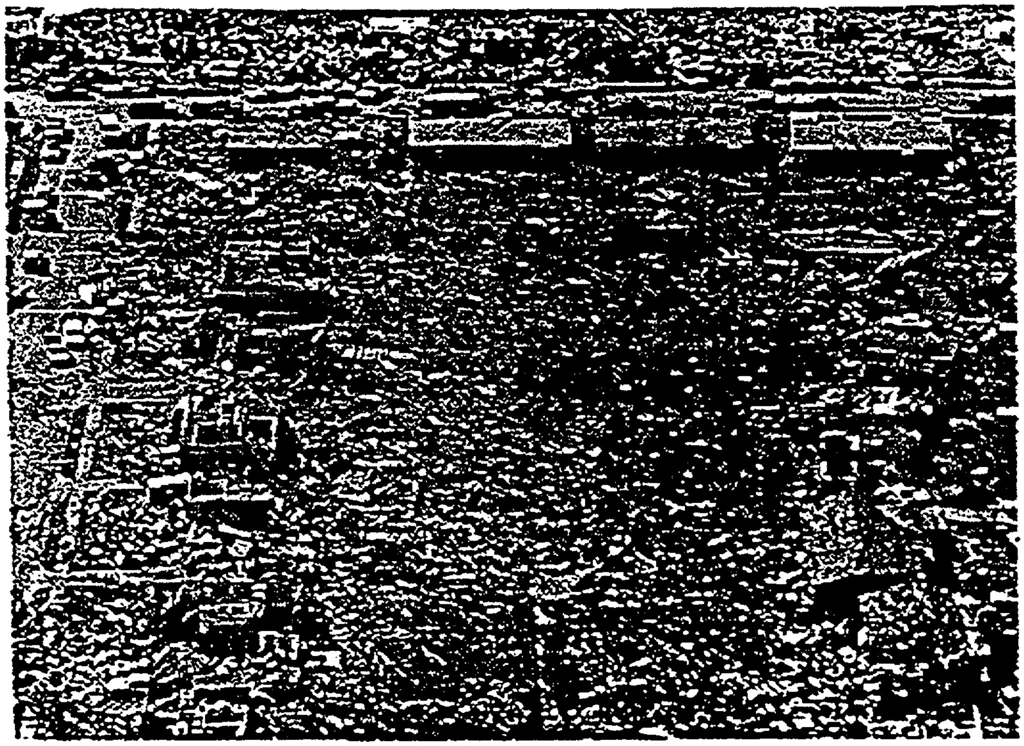


FIGURE 2.1 AERIAL VIEW OF DAMAGE CAUSED BY WICHITA FALLS TORNADO (F4, 1979)

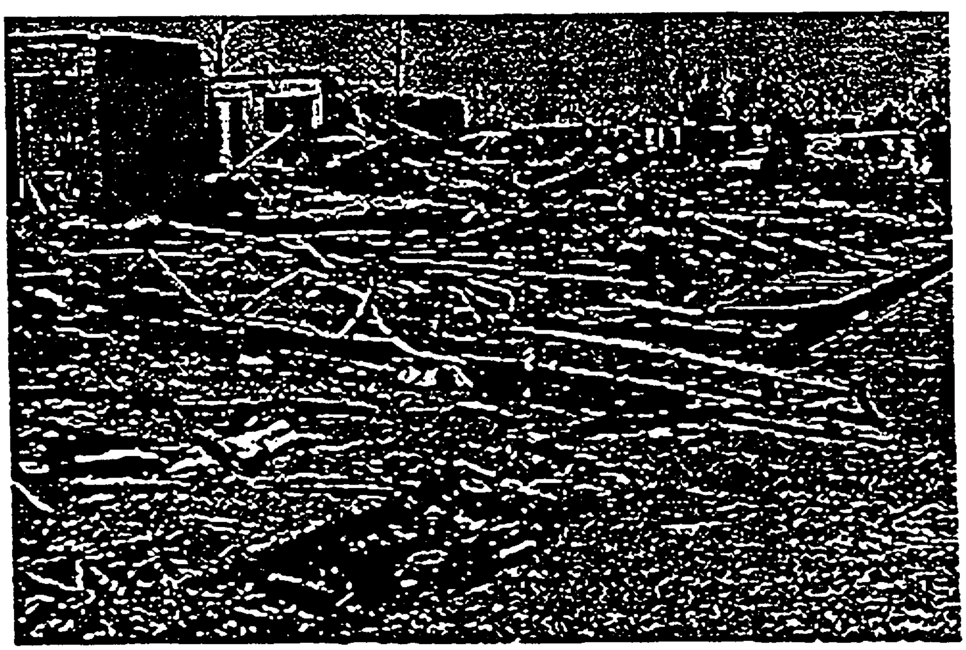


FIGURE 2.2 MISSILES AND DEBRIS FROM DAMAGED SHOPPING CENTER CAUSED BY WICHITA FALLS, TEXAS TORNADO (F4, 1979)

FIGURE 2.3 COURTYARD at MCNEILL JUNIOR HIGH, WICHITA FALLS, TEXAS (F4, 1979)

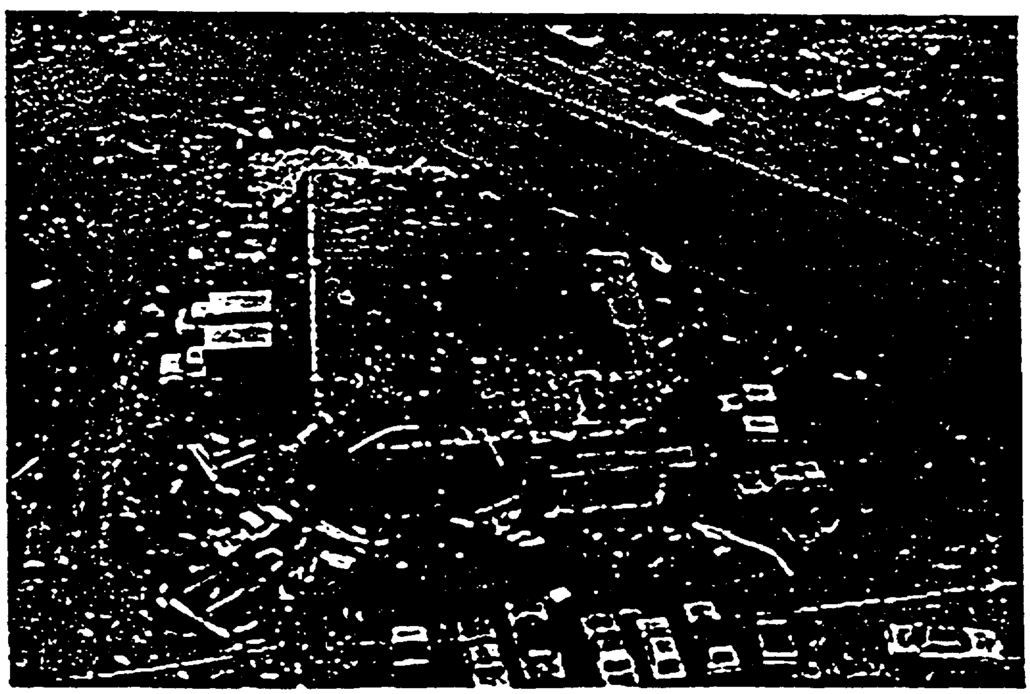


FIGURE 2.4 HEAVILY DAMAGED COMMERCIAL BUILDING IN BOISSIER CITY, LOUISIANA (F4, 1978)

FIGURE 2.5 AERIAL VIEW OF APARTMENT COMPLEX DAMAGE IN WICHITA FALLS, TEXAS (F4, 1979)

2.3.2 Examples of Individual Missiles

A number of examples of individual missiles are shown to give a sense of the types that are picked up and transported.

Wood Planks

Wood planks are the most common missiles found in residential damage. Figure 2.6 in Hubbard, Texas (F2): 2x4 wood planks perforated 36 in. into the ground. Figure 2.7 in Bossier City, Louisiana (F4): a 2x4 wood plank extended between the ceiling channel and the window frame. The roof may have been lifted slightly during the storm to allow the missile to slip between the two window components. Figure 2.8 in Wichita Falls, Texas (F4): a timber plank penetrated a mansard roof. Figure 2.9 in Cheyenne,

FIGURE 2.6 TIMBER PLANKS (2X4 PENETRTE 3-ft GROUND IN HUBBARD, TEXAS (F2, 1973)

FIGURE 2.7 A 2X4 TIMBER PLANK SLICES BETWEEN CEILING CHANNEL AND WINDOW FRAME IN BOISSIER CITY, LOUSIANA (F5, 1978)

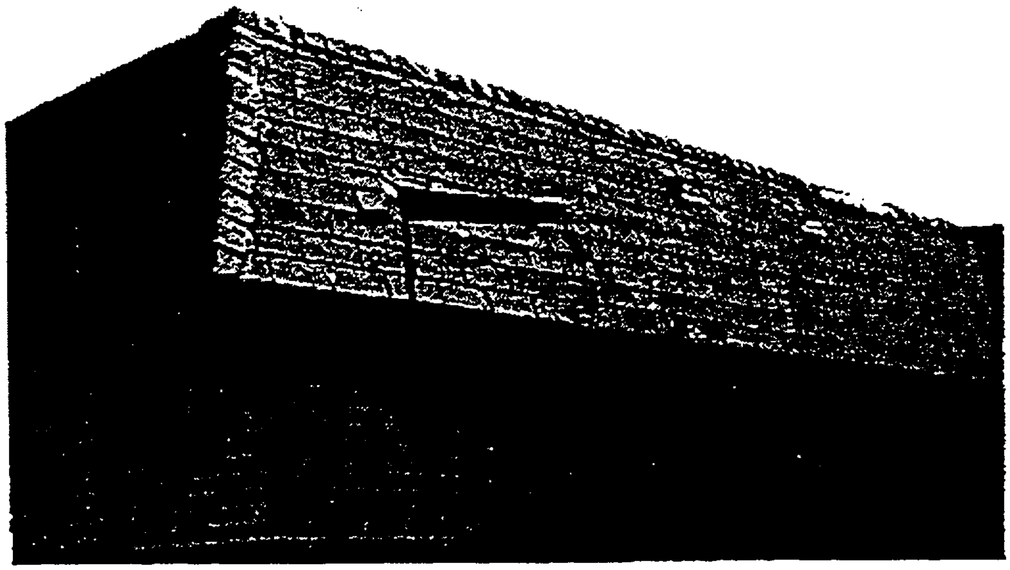


FIGURE 2.8 TIMBER PLANK PENETRATES MANSARD ROOF IN WICHITA FALLS, TEXAS (F4, 1979)

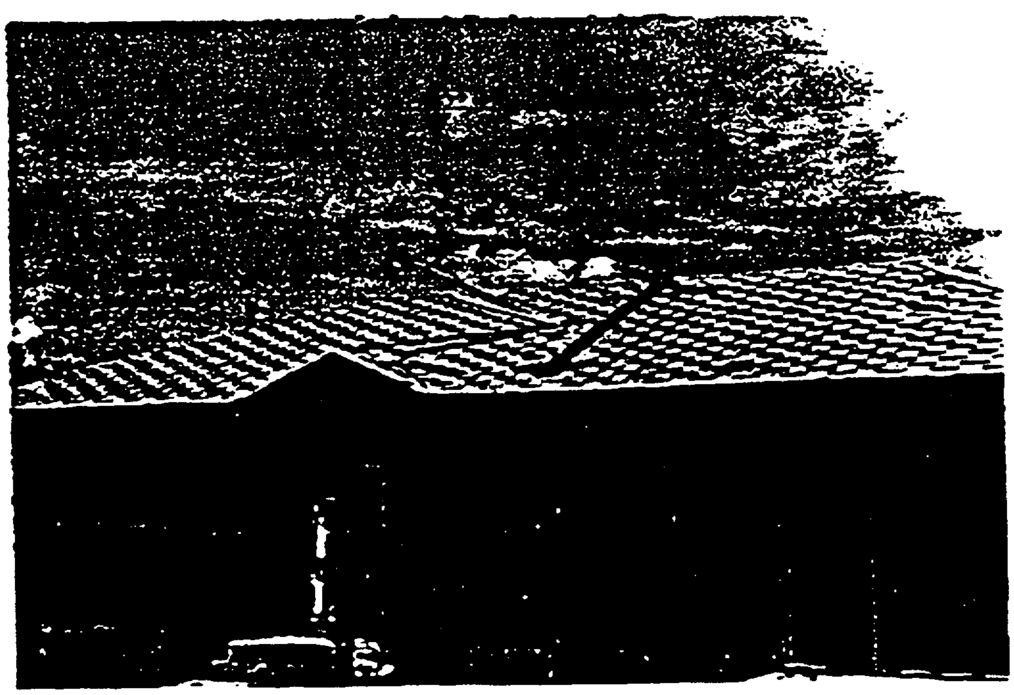


FIGURE 2.9 TIMBER PLANKS PENETRATE RESIDENTIAL ROOF IN CHEYENNE, WYOMING (F4, 1979)

Wyoming (F3); several timber planks penetrated the roof of a residence. The one nearest the eave in is a 1x6 wood board. Figure 2.10 in Altus, Oklahoma, AFB. (F3); a 2x6 timber sliced through an unreinforced concrete block wall in.

Other Debris

Figure 2.11 shows assorted debris generated by the Altus, Oklahoma, AFB tornado. In addition to various pieces of wood, a section of a utility pole, a roof exhaust vent, and pieces of sheet metal can be seen in the photo. The weight of the broken utility pole is estimated at 110 lbs.

A piece of plywood sliced through the rear fender of an automobile in Figure 2.12. Other Debris, including sheet metal, aluminum angles, and pieces of timber, can be seen in the photo. Again, various pieces of debris have collected against the school bus shown in Figure 2.13 (Bossier City, Louisiana, F4). Pieces of plywood, a metal door made from a steel plate, a broken piece of furniture, sheet metal, and pieces of wood are visible in the photo.

Poles and Pipe

Poles and pipe are often found in the rubble, but they are not as common as the previously examined timber planks. A steel pole along with some timber planks and pieces of plywood are seen in Figure 2.14 (Omaha, Nebraska, F4). The documentation narrative did not indicate how far the pole had traveled. Another light pole was observed in Omaha, Nebraska (F4) (Figure 2.15). The anchor bolts appear to have been sheared off. A two-in. diameter steel pipe penetrated the wall of this residence in Plainview, Texas (F3) as shown in Figure 2.16. Figure 2.17 shows a 3-in. dia. steel pipe

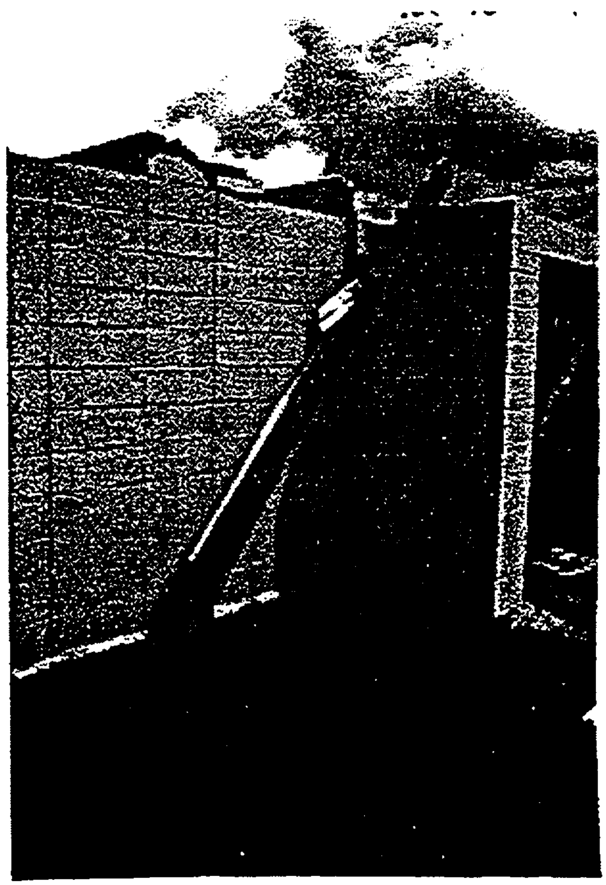


FIGURE 2.10 A 2X6 TIMBER PLANK SLICES THROUGH UNREINFORCED CONCRETE BLOCK WALL AT ALTUS AFB, OKLOHOMA (F3, 1982)

FIGURE 2.11 VARIOUS DEBRIS FOUND IN THE ALTUS, OKLOHAMA AFB TORNADO (F3, 1982)

FIGURE 2.12 A PIECE OF ½-in.THICK PLYWOOD SLICES THROUGH REAR FENDER OF AUTOMOBILE IN ALTUS, OKLAHOMA AFB (F3, 1982)

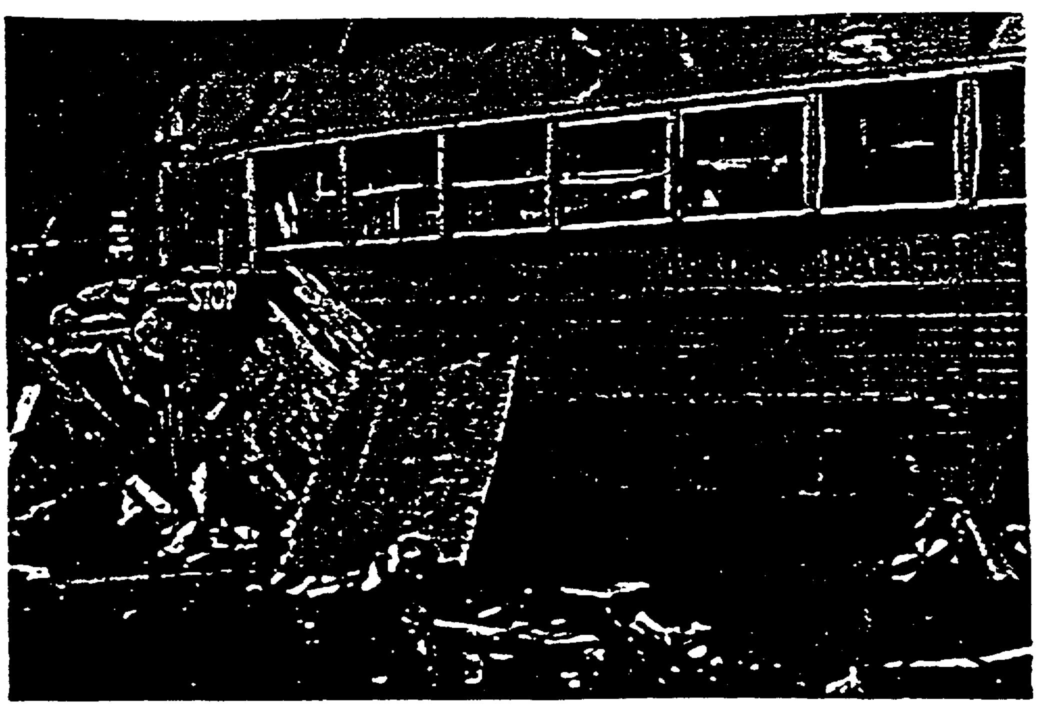


FIGURE 2.13 VARIOUS PIECES OF DEBRIS HAVE COLLECTED AGAINST SCHOOL BUS IN BOSSIER CITY, (F5, 1978)

FIGURE 2.14 STEEL LIGHT POLE WAS RIPPED FROM ITS FOUNDATION IN OMAHA, NEBRASKA (F4, 1975)

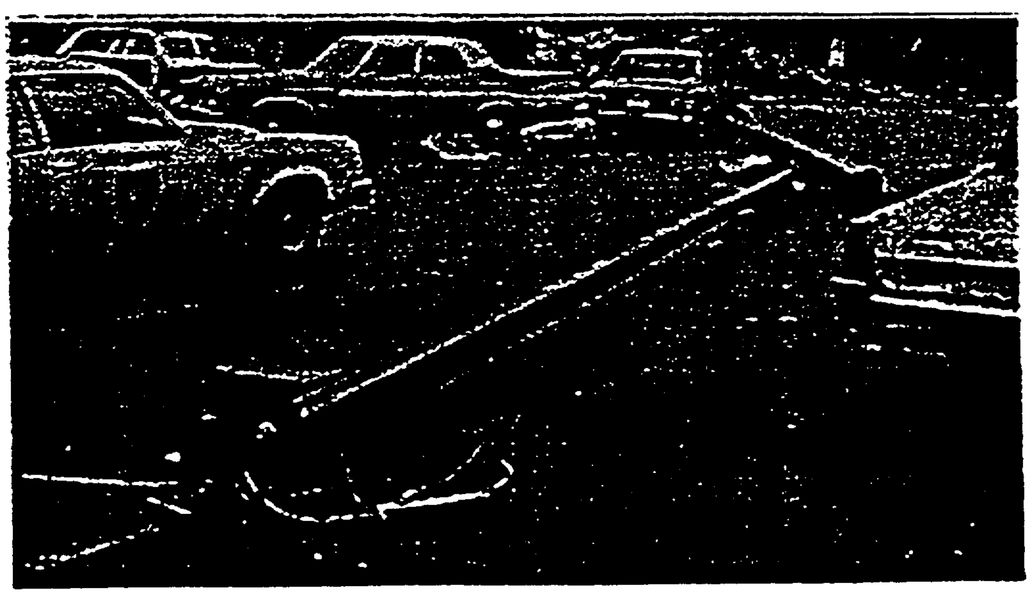


FIGURE 2.15 ANCHOR BOLTS OF THIS LIGHT POLE HAVE SHEARED OFF, OMAHA, NEBRASKA (F4, 1975)

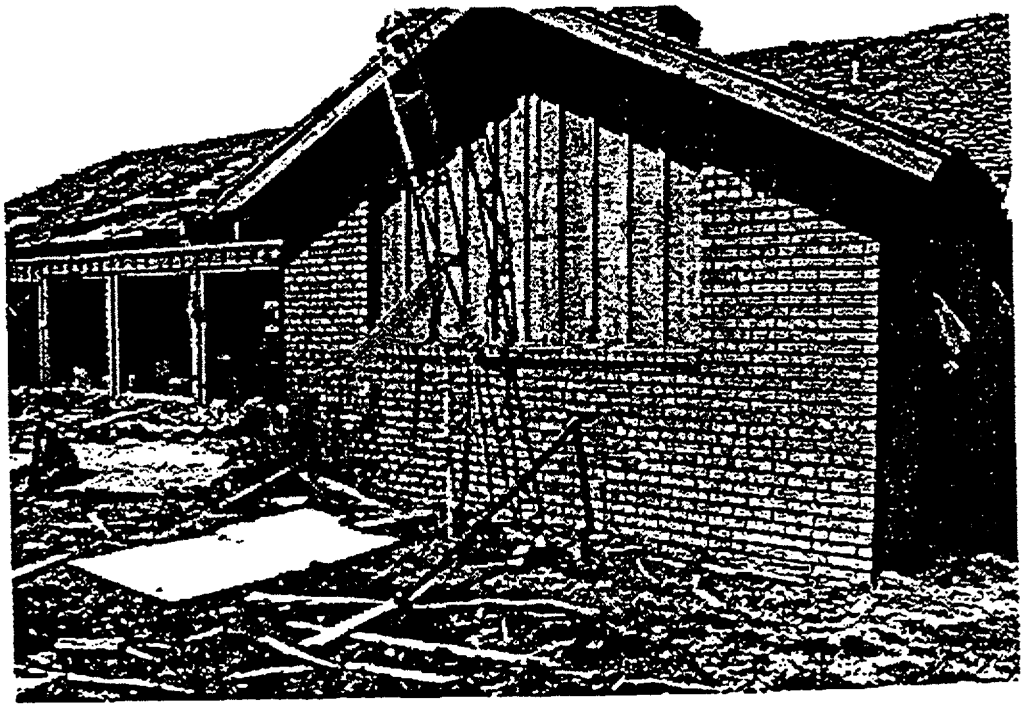


FIGURE 2.16 A 2-in. dia. PIPE PENETRATED RESIDENTIAL WALL IN PLAINVIEW, TEXAS (F3, 1973)

FIGURE 2.17 THIS 3-in. dia. STEEL PIPE (APPROXIMATELY 75 lb) WAS TRANSPORTED BY THE SWEETWATER, TEXAS TORNADO (F3, 1986)

approximately 10 ft. long. This pipe is estimated to weigh 75 lbs. A 2-in. dia. pipe (or electrical conduit) penetrated the ground in Figure 2.18 (Hubbard, Texas, F2).

Automobiles

Automobiles are frequently rolled and tumbled by tornadic winds. The van shown in Figure 2.19 (Omaha, Nebraska, F4) was reported in the media to have flown over a five-story hospital. The van had been parked on one side of the building before the storm and was found on the opposite side of the building after the storm. Careful examination of the ground surrounding the hospital revealed parts and pieces (including a license plate) of the van that provided evidence it had rolled and tumbled around the building, not flown over it.

Figure 2.20 shows an automobile that was slammed against a steel pole. The point where the automobile struck the pole suggests that the automobile was rolling and tumbling along the ground at the time of impact.

Incredible Missiles

Heavy missiles include standard steel sections and concrete masonry bond beams. The wide flange steel beam shown in Figure 2.21 is 24 ft long and weighs 720 lbs. It penetrated 8-ft into the ground. The missile and five others were observed in Bossier City, Louisiana (F4) (additional discussion found in section 3.7.1). The steel wide flange is one of the largest missiles ever observed in a tornado damage path. The missile traveled approximately 450 ft before penetrating into the relatively soft ground.

FIGURE 2.19 A VAN ROLLED AND TUMBLED AROUND HOSPITAL IN OMAHA, NEBRASKA TORNADO (F4, 1975)

FIGURE 2.20 AN AUTOMOBILE THAT WAS SLAMMED AGAINST A STEEL POLE IN BOSSIER CITY, LOUISIANA (F5, 1978)

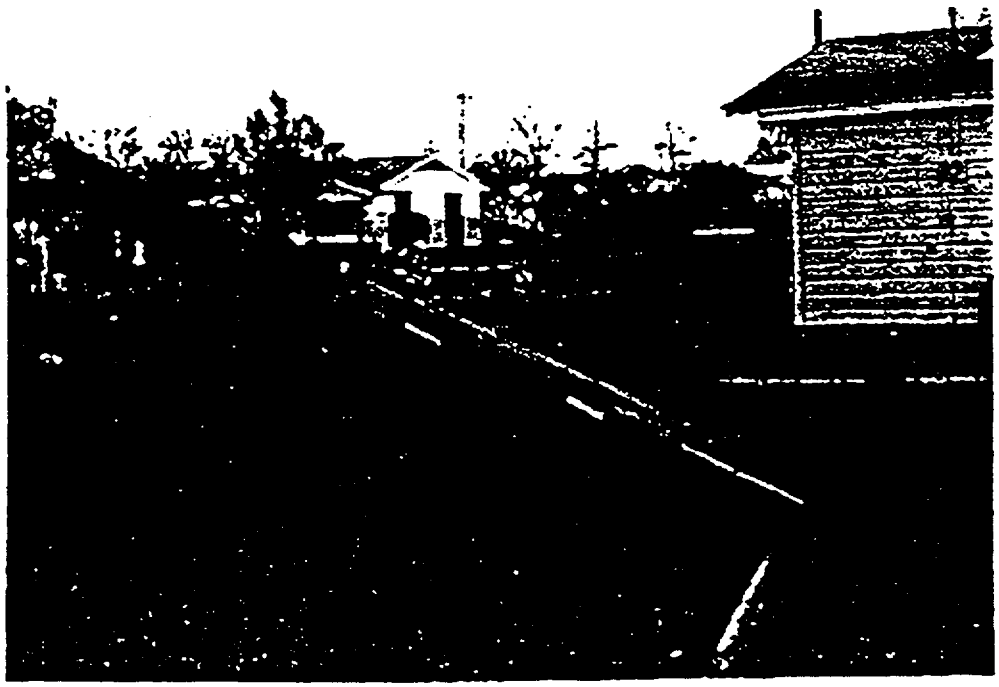


FIGURE 2.21 STEEL WIDE-FLANGE BEAM TRANSPORTED 450-ft FROM ORIGINAL LOCATION IN BOSSIER CITY, LOUISIANA (F5, 1978)

A bond beam was uplifted from the top of a wall and became airborne when the roof of a building was uplifted by the Altus AFB, Oklahoma, tornado (F3) (see Figure 2.22). Roof joists were anchored into the bond beam, but there was no vertical reinforcement in the wall to prevent the bond beam from being lifting with the roof.

2.4 Distribution of Timber Missiles

Field studies of tornado damage indicate that a majority of the missiles originate from the roofs of timber residences and light commercial structures. In all the tornadoes surveyed, pieces of wood plank constituted an overwhelming majority of the missiles observed. The reason for this is that the sources of these missiles are building roofs, which experience higher wind loading than any of the other building components. The wood plank missile itself has a relatively aerodynamically high flight parameter, which enables it to be easily transported by the tornado winds.

A quantitative assessment of the wood plank missile was carried out for three selected tornadoes: Hubbard, Texas in 1973 rated F2, Sweetwater, Texas in 1986 rated F3, and Wichita Falls, Texas in 1979 rated F4. The goal of this investigation was to determine the relative prevalence of the various sizes of wood plank missiles and hence validate or reject a 2x4 wood plank as a design basis missile.

Figures 2.23, 2.24, and 2.25 contain the aerial photos taken at the three tornado events. Individual pieces of timber plank were identified in the photos. Dimensions were estimated by scaling features of known dimensions on the photographs. The missile width was estimated from its relative size in the aerial photo. The missile thickness was assumed based on the type of structures in the aerial photo. Tables A-1, A-2, and A-3 in

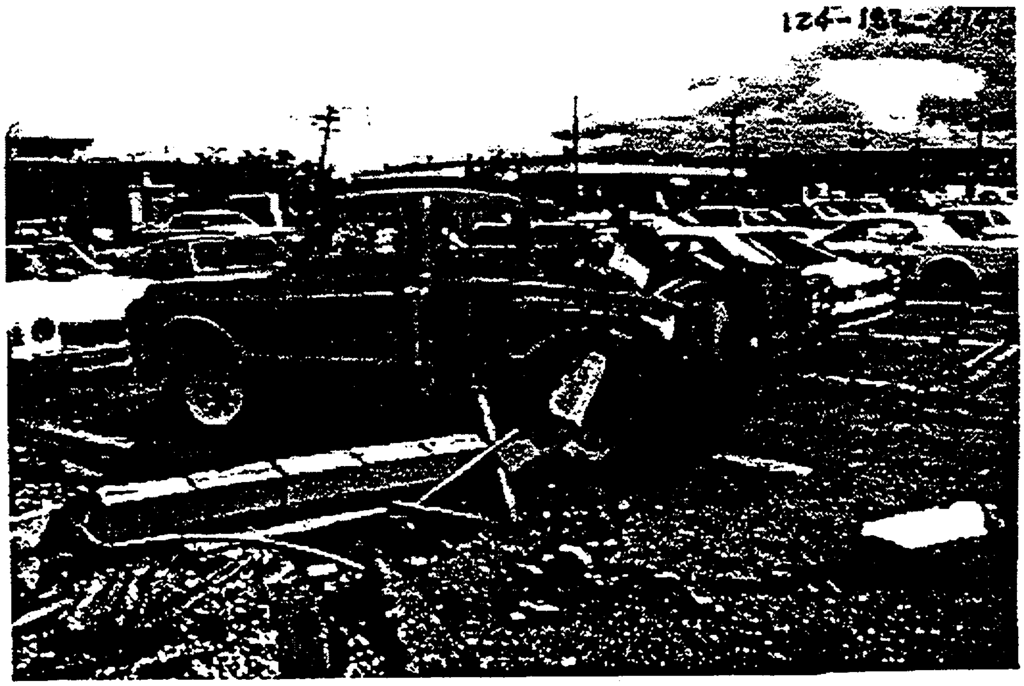


FIGURE 2.22 A BOND BEAM WAS LIFTED FROM THE TOP OF A CONCRETE BLOCK WALL IN ALTUS AFB, OKLAHOMA TORNADO (F4, 1982)

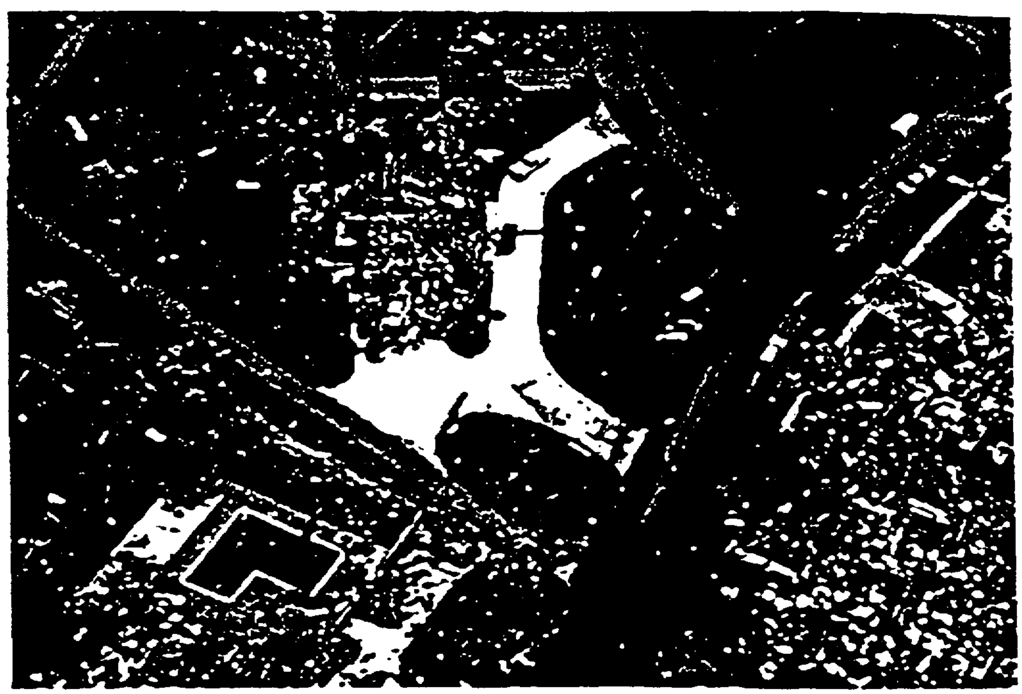


FIGURE 2.23 AERIAL VIEW OF HUBBARD, TEXAS TORNADO DAMAGE PATH (F2, 1973)

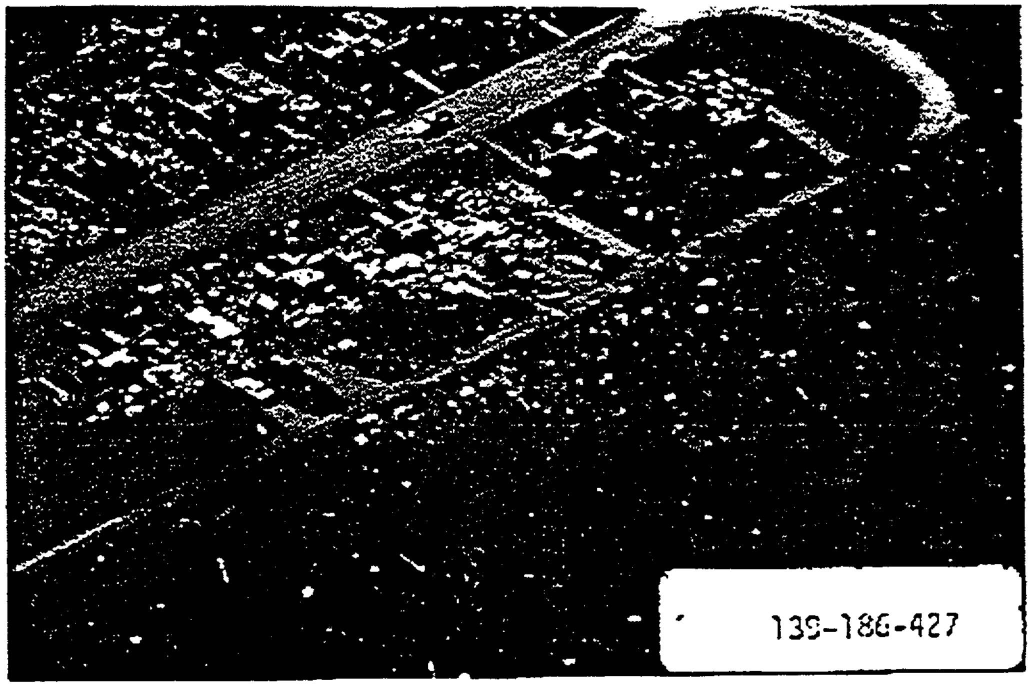


FIGURE 2.24 AERIAL VIEW OF SWEETWATER, TEXAS TORNADO DAMAGE PATH (F3, 1986)

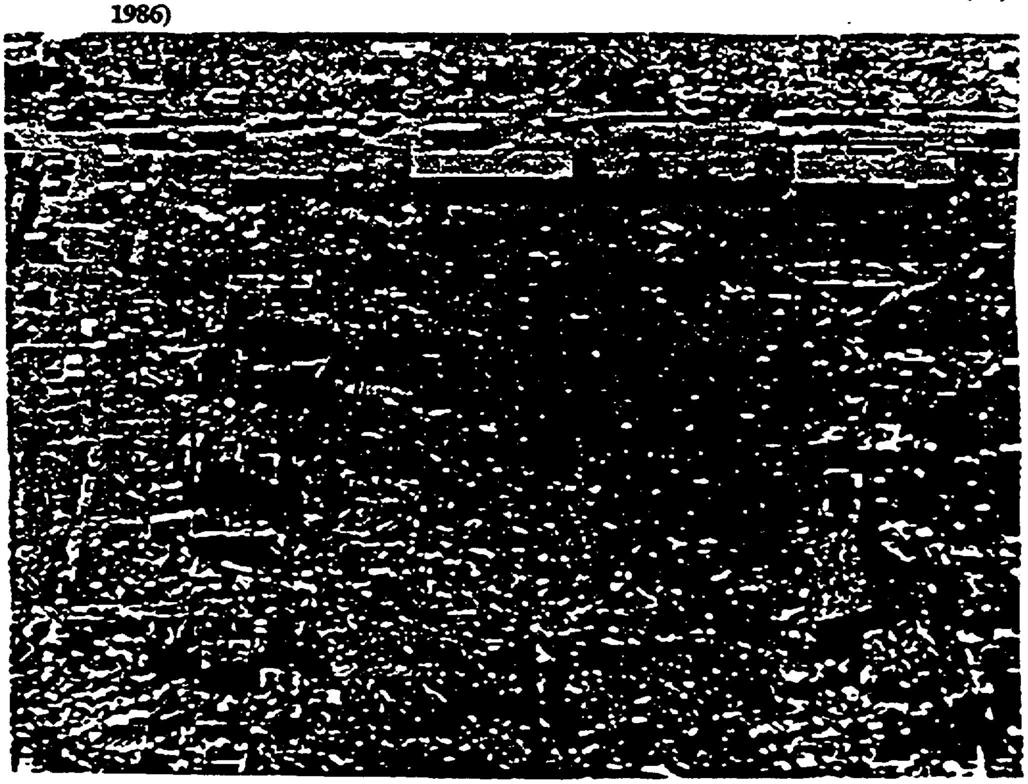


FIGURE 2.25 AERIAL VIEW OF WICHITA FALLS, TEXAS TORNADO DAMAGE PATH (F4, 1979)

Appendix A. tabulate the estimated sizes of the wood plank missiles and their weights for Hubbard, Texas, Sweetwater, Texas and Wichita Falls, Texas respectively. Mean lengths, and sample sizes from the three aerial photos are summarized in Table 2.4.

Table 2.4 Data Summary for Wood Missiles

Tornado	Sample Size	Mean Length of Wood Missile(ft)	Mean Weight of Wood Missile(lb)
Hubbard, Tx (F2)	70	5.44	7.74
Sweetwater, TX (F3)	88	6.20	8.32
Wichita falls, TX (F4)	143	6.94	9.20

The DOE missile criteria for SSCs (Table 1.1) specifies 2x4 timber missile which weighs 15 lb. This implies that for the mean weights of all observed missiles to correspond to the 2x4 wood missile, the observed mean weights corresponding to the observed mean lengths of 5.44 ft, 6.20 ft, and 6.94 ft, should be, respectively: 6.80 lb, 7.75 lb, and 8.68 lb for the three tornadoes. The unit weight assumed by the DOE criteria is 34.3 lb per cu. ft. It only remains to show that the observed mean weights of 7.74 lb, 8.32 lb, and 9.20 lb, respectively for the three tornadoes, are not significantly different from the corresponding 2x4weights.

The 95% confidence limits on the observed mean weights were calculated using the usual formula for the large samples and unknown standard deviation:

$$\bar{x} \pm t_{\alpha/2} \left(\frac{s}{\sqrt{n}} \right)$$

where

x= sample mean

s= sample standard deviation

n = sample size

$t_{\alpha/2}$= confidence limit at the α percent level

Significance tests on the mean weights were also carried out to test:

1) H_o: μ= 6.80   2) H_o: μ= 7.75   3) H_o: μ= 8.68

H_1: $\mu \neq 6.80$ H_1: $\mu \neq 6.80$ H_1: $\mu \neq 6.80$

where

Ho = null hypothesis

H_1 = alternate hypothesis

The results are tabulated in Table 2.5. It can be seen from Table 2.8 that the weights for the 2x4 missile fall within the 95% confidence bounds.

Table 2.5. Confidence Limits and significance Test Results

Tornado	Observed Mean Missile Weight(lb)	95% Confidence Limit LCL UCL	Mean wt. of 2x2 Missile (lb)	Mean wt. of 2x4 Missile (lb)	Mean wt. of 2x6 Missile (lb)	P-value for Test of Significance
Hubbard, TX (F2)	7.74	6.76 8.74	3.40	6.80	10.20	0.07
Sweetwater TX (F3)	8.32	7.35 9.29	3.88	7.75	11.63	0.26
Wichita Falls, TX (F4)	9.20	8.51 9.88	4.34	8.68	13.01	0.14

At the significance level $\alpha = 0.05$, the test of significance leads us not to reject the H_o hypothesis in each case; i.e., we have no evidence to say that the mean weights of all the missiles are not the same as those corresponding to the mean weights of 2x4 missiles. Use of the 2x4 wood missile as the design basis missile is therefore validated.

2.5.1 Other Missiles

The observation presented in section 2.3 indicates objects and debris other then timber missiles that can be treated as two distinct classes of tornado missiles. These missiles are heavier than the timber plank and do not fly as readily as the planks.

One class of missiles is represented by the 3-in. diameter schedule to steel pipe. The pipe represents TV antenna poles, electrical conduits, clothlines posts, fence posts, steel roof joints, water and gasoline pipes and small rolled steel sections. These item do not occur frequently enough to conduct an exercise similar to the one for the timber planks. The 3-in. pipe weighing 75 lb was chosen based on experience and judgement to represent the close missiles. A pipe was chosen because it is easier to replicate impact test than with other non-circular shapes.

The third close of tornado missiles included automobiles, light trucks, vans, buses, trailers, track dumpsters and storage tanks. Many automobiles are observed upside down or on their sides, suggesting a rolling, tumbling mode of transport. The argument for the tumbling mode of transport is reinforced by the relatively low flight parameter for these shapes. Based on observations and judgement, a 3000 lb automobile is representative of this class of missiles.

2.6 Missiles that Did Not Fly

Some missiles do not fly because their aerodynamic flight parameter, C_DA/W (where C_D is an aerodynamic drag coefficient, A is the cross sectional area normal to the relative wind direction, and W is the missile weight), is small. The loose items lying on the ground in Figure 2.26 were not picked up and transported, even though some have relatively large flight parameters. The wind speed increases as the tornado approaches, but the potential missiles are pushed along and collect against buildings, trees or automobiles, as in shown in Figures 2.12 and 2.13.

Heavy missiles in the USNRC missile spectrum (6-in. diameter steel pipe, 12-in. diameter steel pipe and utility poles) might fly in the 360 mph USNRC design basis tornado, but they are rarely observed in tornadoes rated F3 or F4. The steel beam in Figure 2.21 was an exception. It along with five others, flew in a F4 tornado wind speed reached approximately 100 mph and then were suddenly released. This action gives each missile an impulse load, causing it to accelerate rapidly.

There are other reasons why missiles do not fly in an intense tornado. The highest wind speed in a tornado occupies only a small part of the damage path area (see Figure 3.5). Thus even though an intense tornado passes over a potential heavy missile, it may not release because it does not experience winds of sufficient intensity to release and transport the missile. Racks of pipe of various sizes were passed over by the Washita, Oklahoma tornado (F3) and were not picked up and transported. The Brandenberg, Kentucky, tornado (F5) (1974) passed over a rack of utility poles by they did not fly. Several were blown off the rack, but remained on the ground. In the same storm, 2x4 in lumber pieces were picked up from stacks in a lumber yard and transported several miles.

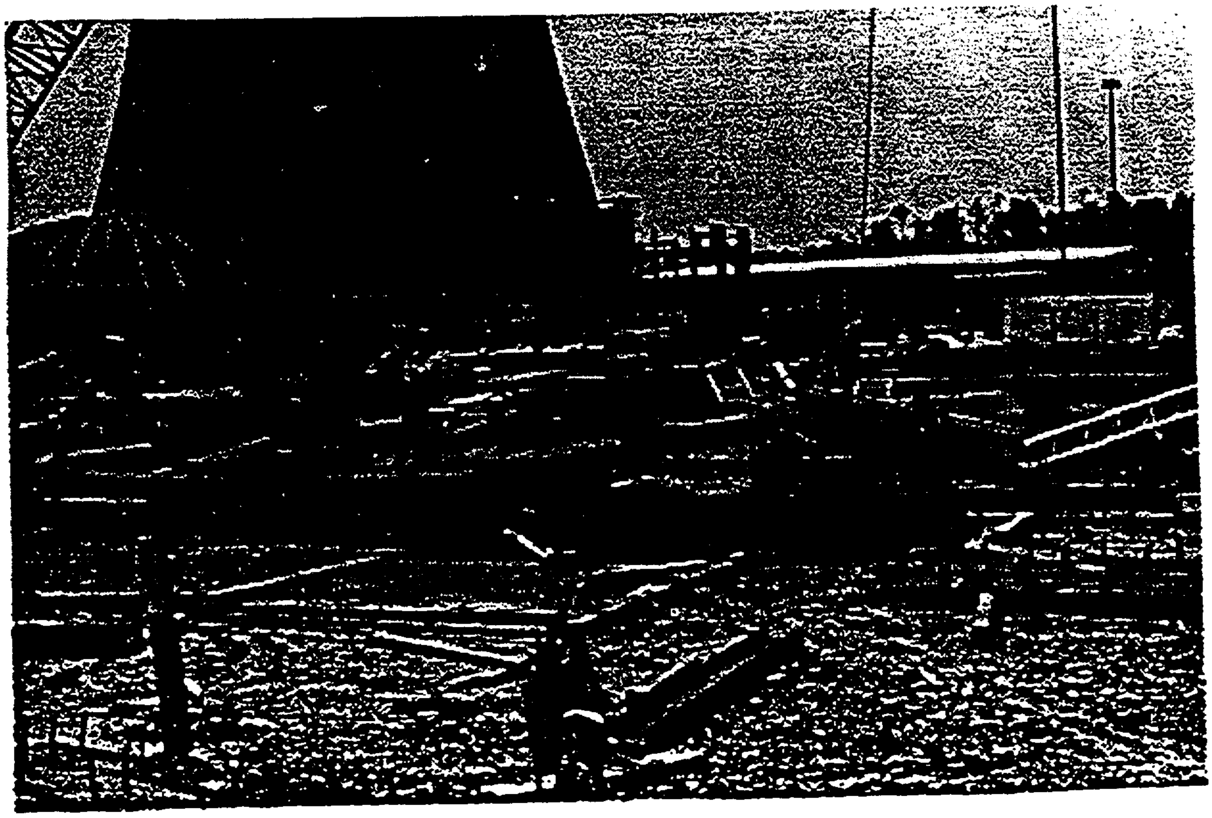


FIGURE 2.26 LOOSE OBJECTS LYING ON THE GROUND ARE NOT PICKED UP BY TORNADO WINDS, GRAND GULF, MISSISSIPPI (F3, 1978)

2.7 Recommended Missiles

2.7.1 Tornado Missiles

Many different missiles have been observed in field investigations of tornado damage. The missiles that have been observed in F2, F3, and F4 tornadoes fit into three categories that can be represented by:

- 2x4 timber plank
- 3-in. diameter steel pipe
- Automobile

The 2x4-timber missile represents the many pieces of wood from damaged or destroyed structures. In addition wood plank represents other light to medium weight objects such as plastic pipe, electrical conduit, and small diameter pipes. The 3-in. steel pipe represents a class of missiles observed in the field, including TV antenna, clotheslines posts, large direction feve? Posts, open ? steel joints? Electrical conduit and small steel rolled sections. The automobile is representation of other objects that roll and tumble in the mid ? trash dumpster, light trailer and storage tanks.

A survey of timber missiles observed in three tornadoes, rated F2, F3 and F4, suggest mean weights of 6.70, 7.75, and 8.68 for the 2x4 missile. Significance tests show that the mean weights of all missiles in each storm are not significantly different than the 2x4 missile weights. Thus, it is appropriate to use the 2x4 as a design missile. Because of other objects represented by the 2x4 classification, with a weight greater than the mean weight of the 2x4. Hence, a weight of 15 pound is recommended to represent the 2x4-missile classification.

The 3-in. diameter pipe represents a class of missiles that are not lifted significantly by the winds, but can be accelerated horizontally as they fall to the ground from their initial elevation due to gravity. Objects by the 3-in. diameter pipe missile can be represented by a 75-pound weight.

Missiles represented by the automobile roll and tumble along the ground. There is no field evidence to support their being lifted to high elevations. Stories of flying automobiles and trucks are sometimes printed in the news media, but in cases investigated by Texas Tech University personnel, there was no scientific evidence to support these claims. The mass of automobile missiles will produce a structural response failure of wall panels and columns upon impact.

Thus, from field observations, the following design missiles are recommended for tornado design of SSCs in the PC3 and PC4 categories:

2x4 Timber weighing 15 lb

3-in. Diameter Schedule 40 steel pipe-weighing 75 lbs

Automobile weighing 3000 lbs

The impact speeds of the recommended missiles are obtained in Chapter 3.

2.7.2 High Wind Missiles

Straight winds and hurricane winds are less intense than tornado winds. In addition, straight wind and hurricane winds do not have the strong vertical component observed in tornadoes. Missiles observed in straight wind and hurricane damage are in the class represented by the 2x4 timber. Typical damage includes broken window glass, perforation of metal panel walls and stud walls with various wood, aluminum and vinyl cladding. Thus, the 2x4-timber missile is selected for high wind design criteria. The recommended impact speeds are obtained in Chapter 3.

3. COMPUTER SIMULATION OF TORNADO MISSILE TRAJECTORIES

3.1 Introduction

Before the missile speeds can be defined and before impact resistance of various materials used in construction can be evaluated, information is needed on the flight trajectories of missiles that are transported by tornadoes. In addition to identifying the types and sizes of missiles, information is needed on the speed and height achieved by the missiles as they are transported by the tornado winds. Their means of injection into the tornado and simulation of the missile trajectories are needed for design or evaluation of SSCs.

As with the determination of most tornado characteristics, direct measurements are difficult, if not impossible. Damage investigation following a destructive tornado reveals the origin and final location of a missile, but determining its trajectory from the field observations is almost impossible. Occasionally, a rolling or tumbling automobile or trash dumpster will leave evidence of its path by marks on the ground, but if the object becomes airborne, its speed and trajectory cannot be determined in the field.

Motion pictures of tornadoes sometimes show large pieces of debris being transported by the tornado winds. Hoecker (1960) tracked sheets of plywood which were picked up by the Dallas tornado of 1957. Through photogrammetric analysis techniques, he was able to deduce velocities achieved by pieces of plywood. Hoecker used the calculated missile speeds to estimate wind speeds in the Dallas tornado. Photogrammetric analyses have not produced sufficient data for establishing tornado missile design criteria to date. For this reason, researchers resorted to tornado missile trajectory simulations to obtain the needed information. This chapter describes a study conducted at Texas Tech University.

3.2 Objectives

The primary objective of this study is to estimate the probable speed achieved by the two tornado missiles (2x4 timber plank and 3-in. diameter steel pipe) identified in Chapter 2 for design and evaluation of DOE SSCs in tornadoes of various intensities. The estimates include the horizontal speeds and the vertical speeds of the missile, which are of interest in designing walls and roofs, respectively. The maximum height above ground that the missile reaches also is of interest. Missile speeds and trajectories are estimated by means of computer simulation of the tornado-missile interaction in the wind field.

A tornado missile trajectory simulation code developed at the Institute for Disaster Research is used for trajectory calculations. Tornadoes of various intensities are passed over an array of missiles that are uniformly spaced across the tornado path. A trajectory calculation is made for each missile in the path. At each time step, the missile's position in space, its speed and its acceleration are calculated by the numerical technique. Depending upon the location within the tornado path, some missiles are transported, while others remain stationary. The tornado wind speeds must reach certain minimum value before the missile is released from its restraint in a building or structure. Tornado intensities are expressed in terms of the Fujita Scale (Fujita, 1971). Statistical analyses of the computer-generated data on missile speeds associated with various probability levels.

The scope of this study is limited to the timber plank and steel pipe missiles, although the method is applicable to other objects. As shown in Chapter 2, objects representative of medium weight missiles are by far the most common ones found in damage to residential and commercial construction.

3.3 Requirements for Missile Trajectory Simulation

There are two basic requirements for tornado missile trajectory simulation:

1. the transport of a tornado missile is a random event that depends on a number of factors, and
2. each parameter affecting tornado missile transport has a range of values that affects the trajectory outcome.

Random factors that affect the transport of a missile include:

1. characteristics of the tornado wind field,
2. location of missile within tornado path,
3. degree to which missile is restrained, and
4. physical characteristics of the missile.

Characteristics of a tornado wind field that affect missile transports are maximum wind speed, variation of wind speed within the tornado wind field (assumed wind field model), radius of maximum wind speed, and transnational wind speed. Wind speed varies across the width of a tornado path. Most tornado wind field models including the one used in this study assume that the maximum wind speed occurs at some distance from the tornado path centerline (radius of maximum wind speed). From this point, the wind speed decays with increasing distance from the centerline. The edge of the tornado path is defined at the 75-mph wind speed boundary.

A missile becomes airborne more readily if it is restrained as the tornado approaches and then suddenly releases when the wind speed reaches a certain value. Wind forces overcome the restraint and the missile is released for transport by the winds. Because the release wind speed for planks and pipes are typically greater than 75 mph, all missiles distributed across the tornado path will not be transported by the winds.

The physical characteristics of missiles that affect their tendency to fly include shape, surface area, and weight. Aerodynamic drag on the missile produces the wind forces that cause it to translate and lift. Medium weight missiles have a relatively large surface area-to-weight ratio, which allows them to be transported more easily than heavyweight missiles.

Parameters that affect tornado missile transport includes tornado wind speed, translational wind speed, initial height of missile above ground and the missile release wind speed. Each of these parameters affects the missile speed and its trajectory.

3.4 Literature Review

There have been numerous attempts to simulate tornado missile trajectories and thus obtain information on maximum speeds achieved by certain types of missiles as well as the heights above ground attained by them.

Studies of tornado missiles in the late 1960s and early 1970s were attempts to establish criteria for the design of nuclear power plants. Most missiles considered were in the heavyweight category (large diameter pipes, utility poles, automobiles), although missiles in the medium-weight category (timber planks, pipes and rods) also were included in the studies. Missile trajectory simulations were performed by Bates and

Swanson (1967), Paddleford (1967), Lee (1973), Burdette at al., (1974) and Beeth and Hobbs (1975).

The missiles were treated as particles (three-dimensional model). Hoecker's (1960) analysis of the Dallas tornado of 1957 was used to define the tornado wind field models. Different assumptions were made on injection mechanism and initial position of the missiles relative to the tornado path. A variety of values of drag and lift coefficients were assumed. As a result of the different assumptions, a wide range of maximum missiles impact speeds were calculated, depending on the particular set of missile and wind field parameters assumed.

Redmann et al. (1976) introduced a six-degree-of-freedom (rigid) model for missile trajectory calculations. While the model has distinct advantages over the particle model in that it is possible to account for lift forces independently of drag forces, the model is more complex and requires additional aerodynamic coefficients (Castello, 1976). Drag, lift and rotation coefficients as a function of missile orientation in space (pitch, yaw and roll) were determined from the wind tunnel tests (Redmann, et al., 1976).

While a six-degree-of-freedom model has the potential of more accurately predicting actual missile motion, Costello (1976) speculated that given knowledge of the wind field and aerodynamic coefficients, it might be that rotations about one or two axes will not significantly affect the trajectory. This would certainly seem to be a reasonable conjecture concerning rotation of a slender body about its long axis.

Iotti (1975) presented a novel approach to the tornado missile problem based on deterministic calculations of tornado missile trajectories using a particle model. By uniformly placing a large number of identical missiles in a volume surrounding the tornado center and calculating their trajectories, he determined a probability distribution of missile speeds, which turned out to be nearly normal. Using the missile distribution and the tornado strike probability, he was able to estimate the total probability of a given missile having a velocity larger than some value V_m.

While the basic concept of Iotti is valid, several improvements have been made in recent years. Since 1976, better wind field models have been proposed, more accurate drag and lift coefficients have been obtained, and the concept of minimum wind speed to release a missile from its restrained position has been introduced. This latter concept suggests a different arrangement of the missiles in the tornado path prior to running the trajectory calculations and a slightly different approach to probabilistic assessment. The factors mentioned above are discussed in greater detail in subsequent sections of this document.

Monte Carlo simulation of the tornado missile events is an alternative approach to the missile problem. The basic premise of Monte Carlo simulation is that certain parameters affecting a process are repeatedly selected at random until an adequate sample is obtained for statistical analysis. Johnson and Abbot (1977) performed a Monte Carlo simulation of tornado missiles on the Piligrium 2 Nuclear Power Plant site. The tornado trajectories were calculated using a particle model and deterministic methods. The approach modeled the plant and identified specific impact points on the roof and walls.

The most sophisticated code for Monte Carlo simulation of tornado generated missiles is the TORMIS code by Twisdale and Dunn (1981). The missile targets are modeled so that missile impact points can be visualized. The approach provides excellent estimates of the uncertainties in the model. The two limitations of the code are that site specific studies must be performed (as opposed to generic studies) and the degree of sophistication of the model may not be justified in light of available wind and missile data. The approach presented in this study is an alternative to Monte Carlo simulation.

3.5 Factors Affecting Missile Trajectories

Tornado generated missile trajectories are determined by computer calculations. The deterministic solution of a tornado missile trajectory involves

1. a tornado wind field model
2. dynamic equations,
3. an aerodynamic flight parameter, and
4. a means of injection. Each item discussed in the paragraphs below.

3.5.1 Tornado Wind Field Model

Tornado wind field models can be grouped into two general categories:

1. meteorological models, and
2. engineering models.

Meteorological models attempt to satisfy thermodynamic and hydrodynamic balances associated with tornado dynamics. The objective of an engineering model is to represent the tornado wind field in a simplistic manner that bounds the magnitudes of the various wind components (Lewellen, 1976). The discussion presented herein is restricted to engineering models.

Early wind field models used for tornado missile trajectory studies were based on Hoecker's (1960) analysis of the Dallas tornado of April 2, 1957. The wind field model was determined from photogrammetric analyses of movies of the tornado. Bates and Swanson (1967) first used the Hoecker windfiled model to calculate tornado missile trajectories. Other researchers (Lee, 1973 and Burdette et al., 1974) used slightly modified forms of the Bates and Swanson wind field model.

Beeth and Hobbs (1975) and Simiu and Cordes (1976) simplified the wind field model to a combined Rankine vortex for the assumption of tangential wind speed. Simple linear relationship for radial and vertical wind speed components as a function of the tangential wind speed were assumed which did not satisfy continuity of flow.

Fujita (1978) presented wind field models that represent two types of tornadoes observed in the field. The models are based on photogrammetric analysis of tornado movie films, on ground marks left by tornadoes, and on damage patterns observed in post-storm investigations. Fluid mechanics equations of motion and continuity are satisfied and scaling to adjust tornado size and intensity is consistent and has a physical basis. DBT-77 (Design Basis Tornado based on 1977 technology) represents a typical single vortex tornado. DBT-78 represents a multiple-vortex tornado in that it has several small satellite vortices rotating around the center of the parent vortex. The satellite vortices were thought, at one time, to be a principal damaging mechanism (see e.g. Fujita, 1970). They were used to explain cases where one house would have been completely destroyed, while the one next door would have been virtually untouched, even though they were both in the tornado's path.

Studies since the early 1970's (see e.g. Minor et al., 1977) point out that satellite vortices are very unstable and tend to dissipate over rough terrain (as in a suburban area). Most authorities no longer believe they are a significant factor in tornado damage.

Hence, they are not considered a significant factor in propelling tornado missiles. For this reason and others, the DBT-77 model is selected as the wind field model for the trajectory calculations in this study. The model has the following advantage over other models used in previous work:

1. Fluid mechanics equations of continuity are satisfied,
2. Flow patterns are consistent with the spatial distribution of flow observed in photogrammetric analysis of tornado movies,
3. The model accounts for the presence of a boundary layer within a few hundred feet of ground, and
4. A minimum number of parameters must be assumed to obtain a complete description of the model.

Details of the Fujita DBT-77 tornado wind field model are given in Appendix D.

3.5.2 Dynamic Equations

The dynamic motion of tornado missiles can be modeled with three or six degrees of freedom. For reasons discussed in Section 3.3, a three degree-of-freedom model is selected for this study.

Equation of motion of the missile when subjected to the forces of the wind is well known. The equation can be formulated in either a polar or rectangular coordinate system. A rectangular system is used herein. The drag force acting on the missile is

$$F = 0.5 \rho V_r^2 C_D A \tag{1}$$

where

ρ is mass density of air, slug/ft^3,

C_D is a drag coefficient,

V_r is the magnitude of the wind vector relative to the missile, ft/sec, and

A is a specified surface area of the missile, ft^2.

Using Newton's second Law of motion, this force is divided by the mass of the missile to obtain the acceleration.

$$a = F/m = 0.5\left(\rho/m\right)V_r^2 C_D A \tag{2}$$

Replacing ρ/m with γ/W the equation reduces to

$$a = 0.5\gamma V_r^2 \left(C_D A/W\right) \tag{3}$$

where

m is the mass of missile, slugs

is the weight of the missile, and

γ is the density of air, lb/ft^3

C_DA/W is called the flight parameter, ft^2/lb.

Recognizing that acceleration is the second derivative of displacement with respect to time, the initial value problem is described by a set of ordinary differential equations which can be solved by integrating forward in time from prescribed initial conditions until the missile impacts the ground or reaches some other prescribed initial condition. A numerical technique is described later for solving the equations of motion.

3.5.3 Aerodynamic Flight Parameter

It follows from Equation (3) that for a given flow field and initial conditions, the motion of the missile depends only upon the value of the parameter C_DA/W. Values of C_D are determined in wind tunnel tests. The values tend to be a function of Reynolds number, depending on the shape of the missile.

According to Simiu and Cordes (1976), Equation (3) is a reasonable model if, during motion, the missile either maintains a constant or almost constant attitude relative to the relative wind velocity vector or has a tumbling motion such that some mean value of C_DA can be used with no significant error. Furthermore, for a body to maintain a constant attitude, the resultant aerodynamic force would have to be applied exactly at the center of mass of the body, which is highly unlikely, given the turbulence and wind velocity gradients in a tornado. Since no stabilizing effect is produced by the flow of air past a bluff body, the assumption that tornado missiles tumble during their flight appears to be reasonable. The assumption of a tumbling mode is used in this work.

Simiu and Cordes (1976) accounted for random tumbling by assuming that an equivalent value of the product of C_DA is given by the expression as follows:

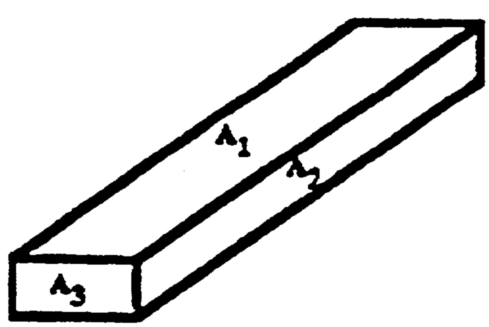
$$C_DA = c(C_{D1}A_1 + C_{D2}A_2 + C_{D3} A_3) \quad (4)$$

in which $C_{Di}A_i$ (I=1,2,3) are products of the projected areas corresponding to the principal axes of the body, and the corresponding static drag coefficients. The area A is specified as the largest projected surface area of the missile. In Equation (4), c is a weighting coefficient assumed to be 0.50 for timber planks, rods, pipes and poles. Table 3.1 lists the flight parameters for the 2x4 timber plank and 3 in. dia. steel pipe.

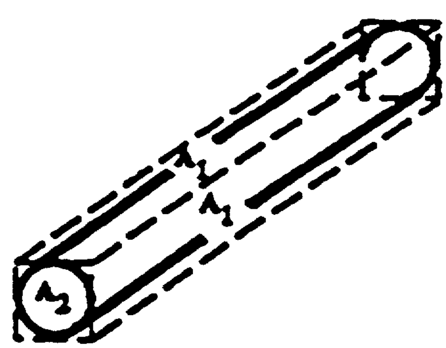
Table 3.1 Tornado Missile Flight Parameters

Missile Type	Missile Dimensions (in.)	Missile Weight (lb./ft)	Drag Coefficients and Areas				
			C_{D1} (A_1)	C_{D2} (A_2)	C_{D3} (A_3)	C_D A* ($ft.^2$)	C_D A/W ($ft.^2$/lb.)
(2x4) Timber Plank	1 5/8 x 3 5/8 x 144	1.25	2.00 (1.63)	2.00 (1.63)	2.00 (0.04)	5.29	0.352
3-in. dia. Steel Pipe	3 ½-in. dia. x 120	7.58	0.70 (2.92)	2.00 (0.07)	0.70 (2.92)	2.11	0.028

* *A is the largest projected surface area*



Timber Plank



Steel Pipe

3.5.4 Means of Injection

Bates and Swanson (1967) introduced the idea of three possible ways for a missile to be injected into the tornado wind field as given below:

1. Explosive injection caused be a suddenly-imposed pressure differential,
2. Aerodynamic injection where the shape of an object produces lift in the horizontal air flow while the object is restrained for some brief period of time, and
3. Ramp injection where the object achieves a horizontal speed and then is deflected upward.

These mechanisms have been incorporated in trajectory calculations in various ways. Lee (1973) assumed that missiles are initially lifted off the ground by a vertical lift force caused by both the horizontal and vertical components of the tornado wind. He assumed that the effective lift force only acts for a brief period of time, and thus produces an impulsive force. Although the pipe and plank missiles are not airfoils in the strictest sense, their shapes when combined with random tumbling appear to sustain a limited force produced by the horizontal flow of air. The upward component of the tornado wind alone is not large enough to overcome the pull of gravity and allow light and medium weight missiles to be carried to great heights as observed in available tornado movies. Some lift produced by the horizontal wind component is required for sustained flight.

Most tornado missiles studies simply place the missile at some location in the tornado path and suddenly release it to the wind field. When a missile is released in this fashion, the aerodynamic drag force produces a sudden acceleration and the missile is displaced from its initial position. The problem with this approach is that it does not consider the circumstances under which the missile is released.

Potential missiles are either attached, loosely attached, or unattached to SSCs. The wind speed at which a missile is released from its attachment is called the missile release wind speed. As a tornado translates along its path, the location of a potential missile experiences wind speed of varying magnitude and direction. When the tornado wind speed reaches the missile release wind speed, the missile is free to be transported by the wind. The direction that the missile will move depends on the direction of the tornado wind speed vector at the instant of release.

The missile release wind speed greatly affects the path taken by the missile and determines if the missile will move at all. If the tornado wind speed is less than the minimum missile release speed, the missile will remain stationary. If the missile releases at a small wind speed, the drag force on the missile will be small and hence the initial acceleration will be small and the missile may not travel very far before failing to the ground. The wind speed at which a missile will release generally can be calculated, if its form of attachment and its material properties are known.

The wind speeds at which the 2x4 plank and 3-in. diameter pipe release are estimated at 100 and 150 mph, respectively. The timber plank is representative of a class of missiles that result from the destruction of timber residences, trailers or commercial buildings. The wind speed that produces destruction to the extent that individual pieces of timber are released from the roof or wall structures is estimated to be about 100 mph (Minor et al., 1977). The 3-in. diameter pipe is representative of a class of missiles including small pipe columns, electrical conduit, fence posts, and TV antennas. These items are generally more securely attached than the timber missiles. Hence, they have a larger estimated release wind speed than the timber planks.

The initial height of a missile above ground affects the magnitude of the vertical and horizontal wind component acting on the missile. A plank or pipe missile lying on the ground will not be picked up because the vertical and horizontal wind components approach zero at ground level. Missiles located at some elevation above ground will be picked up and transported by the tornado wind. However, as the initial missile height is decreased, a level is reached where it will not be transported. The vertical and horizontal components of wind are not able to sustain the missile in the wind field. If released, it will fall to the ground. The vertical and horizontal components of the tornado wind increases with the height in the DBT-77 model up to the top of the boundary level (several hundred feet). Thus, the higher the initial missile position, the larger the force trying to lift the missile. In the case of the 2x4 plank and 3 in. diameter pipe missiles, the source of these missiles is assumed to be buildings from one to three stories high. Their initial heights are likely to range from 12 to 52 ft above ground.

3.6 Formulation of IDR Tornado Missile Trajectory Code

A computer program developed at the Institute for Disaster Research (IDR), Texas Tech University (Luan, 1987), calculates the time-history response of missiles generated by an assumed tornado wind field model. The program also predicts values of maximum height achieved by the missiles. Details of the IDR tornado missile trajectory code are described below.

3.6.1 Equations of Motion

The equations of motion used in the code are based on a rectangular coordinate system. The radial, tangential and vertical wind components, U, V, W, respectively, are converted to rectangular coordinates by the following transformation equations:

$$V_x = U\cos\theta - V\sin\theta$$

$$V_y = U\sin\theta - V\cos\theta \qquad (5)$$

$$V_z = W$$

where V_x and V_y are the horizontal wind speeds in the x and y directions, respectively. V_z is the vertical wind speed in the z direction and θ is the angle that a line joining the tornado center and the missile position makes with the x-axis. The translational velocity of the tornado is added vectorially to the wind velocity components.

Recall from Section 3.5 that the dynamic equation of missile motion is based on the aerodynamic drag force produced by the wind. Equation (3) is the dynamic missile acceleration equation. Let P_f represent the aerodynamic flight parameter, C_DA/W. Recognizing that

$$a = (a^2_x + a^2_y + a^2_z)^{1/2} \qquad (6)$$

and $$V_r = (V^2_{rx} + V^2_{ry} + V^2_{rz})^{1/2} \qquad (7)$$

the x, y, and z components of acceleration can be expressed as follows:

$$a_x = 0.5\,\gamma P_f V_{rx} V_r$$

$$a_y = 0.5\,\gamma P_f V_{ry} V_r \qquad (8)$$

$$a_z = 0.5\,\gamma P_f V_{rz} V_r$$

where V_r is the wind velocity vector relative to the missile. As such as given below:

$$V_{rx} = V_x - V_{mx} \quad (9)$$

$$V_{ry} = V_y - V_{my}$$

$$V_{rz} = V_z - V_{mz}$$

where V_{rx}, V_{ry} and V_{rz} are the components of the relative wind velocity vector and V_{mx}, V_{my} and V_{mz} are the components of the missile velocity vector. In the z direction, the effect of gravity and lift produced by the horizontal wind component must be taken into account in the acceleration term. Thus, the expression for acceleration in the z direction is as follows:

$$a_z = 0.5\,\gamma\,P_f\,V_{rz}\,V_r - g + 0.5\,\gamma\,P_{fz}\,V_{rz}\,V^2_{rxy} \quad (10)$$

where g is gravity acceleration, 32.2 ft/sec^2

$$V^2_{rxy} = V^2_{rx} - V^2_{ry} \quad (11)$$

3.6.2 Numerical Solution

The IDR computer code uses an iterative scheme to numerically solve for the missile propagation along its trajectory. It is assumed that the acceleration over a time step, dt, varies linearly as shown below:

$$a_{i+1} = K\,dt + a_i \quad (12)$$

where dt represents the time interval between steps i and i+1, and K is a constant which is initially assumed to be as follows:

$$K = (a_i - a_{i-1})\,/\,dt \quad (13)$$

Then, based on this assumption, a new velocity and position of the missile at step i+1 are evaluated by the following equations:

$$V_{Mi+1} = 0.5(a_i + a_{i+1})\,dt + V_{Mi} \quad (14)$$

$$R_{Mi+1} = 0.5(V_i + V_{i+1})\,dt + R_{Mi} \quad (15)$$

where R_M is the position of the missile with respect to the origin of the coordinate axes. Once the new position and velocity of the missile are known, the acceleration of the missile is calculated using Equation (8). Using these new values of the acceleration components, the process is repeated until the accelerations from the previous iteration are within some specified tolerance, e. The above steps are repeated for each time increment dt. The value for dt is typically 0.1 sec.

3.6.3 Computer Code

A computer code is used to calculate trajectories and velocities of tornado-generated missiles. The computer code is written in BASIC language to numerically solve the equations formulated previously in this section. The program calculates the missile position, velocity, and acceleration as a function of time.

The input data required for the program are tornado wind field characteristics, missile flight parameter, and the initial location of the missile. Three tornado parameters are required as input. These are maximum tangential wind speed, radius of maximum wind speed and the translational speed of the tornado. The initial parameters of the missile include the initial coordinates relative to the origin of the coordinate system, and the missile release wind speed.

The tornado starts at the origin of the coordinate system shown in Figure 3.1. The initial position of the missile is specified relative to the coordinate system (R_{mx}, R_{my}, R_{mz}). The initial value of R_{mx} is arbitrary. It should be larger than the radius of damaging winds to assure that wind speed is less than release value. The tornado

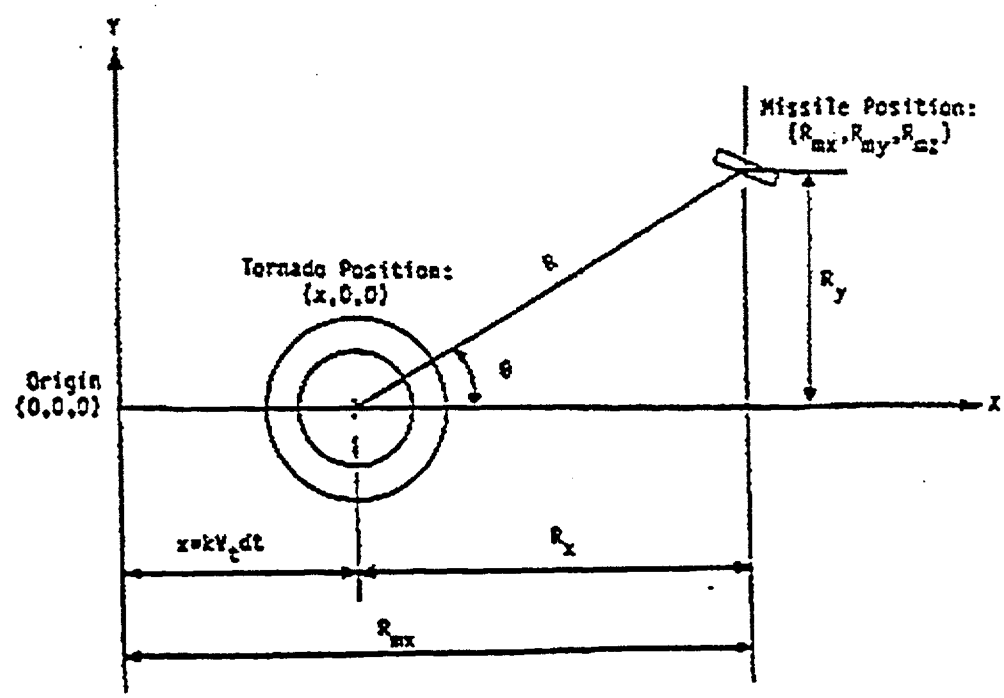


FIGURE 3.1 SPATIAL RELATIONSHIP BETWEEN TORNADO AND MISSILE

marches along the x-axis. Its position at any time step is given below:

$$x = k\ V_t\ dt$$

where

k is the number of steps from t equals zero,

V_t is translational speed of the tornado, ft/sec, and

dt is the time step, sec.

The distance from the tornado position to the missile is R and the angle measured from the tornado path is θ (see Figure 3.1). The parameters R and θ determine the magnitude and direction of the wind components acting on the missile. The wind velocity vector at the missile location is obtained from a subroutine called WINDVEL, which models DBT-77. The tornado moves along the x-axes, moving forward with each time step until the horizontal component of wind speed at the missile reaches the missile release speed, at which time the missile is released from its restraint. The tornado continues to move along the x-axis and the missile responds to the tornado winds according to the dynamic equation of motion. The calculations are terminated when the missile strikes the ground. Tornado position, tornado wind speed, missile speed, acceleration and position are recorded at each time step after release. The maximum horizontal speed, maximum vertical speed and maximum height above ground achieved by the missile also are recorded.

3.7 Validation of IDR Computer Code

The IDR computer code for tornado missile trajectories has been used since its first development in 1975. Two instances are cited in this section for the purpose of validating the code. The first case is an attempt to produce the trajectories of six heavy weight missiles, whose behavior was observed in the field. The second case is a comparison of results of trajectory calculations with the model published by Simiu and Cordes (1976).

3.7.1 Bossier City, Louisiana Tornado

In December 1978 a violent tornado struck Bossier City, Louisiana. Six W14x30 wide-flange steel beams, weighing up to 700 lbs each, were picked up and transported from the roof of Meadowview Elementary school to various locations around the school. One of the six beams impacted the roof of a house located more than 1000 ft from the beam's original location. The others traveled lesser distances and in other directions. The damage at the school was carefully documented by McDonald (1981) and Fujita (1979). From a ground survey, McDonald determined the original location of each beam, its impact point, and the construction details that related to the release wind speed. The Fujita made an aerial survey of the residential damage surrounding the school. From the data collected, Fujita estimated the location of the tornado path center line, as it traveled across the school ground. In addition, he deduced the radius of maximum wind speed and estimated the maximum tangential wind speed and the translational speed of the tornado. Based on other damage to the building, Fujita estimated the maximum wind speed at the school to approximately 200 mph. The radius of maximum wind speed was only 50 ft, which is an extremely tight tornado core. The tight core contributed to the powerful forces that transported the 700 lb beam sections. The translational speed was estimated at 25 mph.

Maaleb (1980) used the IDR tornado missile trajectory code to try and reproduce the six missile trajectories. The tornado characteristics identified by Fujita were scaled to fit the DBT-77 model. The known quantities for the analyses were tornado wind field characteristics, missile shape and weight, initial location and impact points of the missiles. The unknowns were missile flight parameters and wind speed to release the missiles from their restraints. Reasonable values of both of these parameters could be estimated, but each could vary within a range of values. A number of combinations of the unknown parameters were tried until trajectories were found that began at the original missile locations and terminated in the vicinity of the observed points. Figure 3.2 shows the six trajectories that best matched the initial missile locations and the impact points (Maaleb, 1980). The IDR trajectory code was thus able to reproduce reasonable trajectories using flight parameters and missile release wind speeds that fell within a plausible range. While this is only circumstantial evidence, the results demonstrate the ability of the computer code to predict reasonable trajectories that matched observations in the field. The IDR computer code results also explained why the impact points of the six missiles were dispersed over such a wide area (see Figure 3.2).

In making trajectory calculations, a missile is located at some fixed point, and the tornado is passed along a predetermined path. The missile is restrained by its connections or anchorages until the tornadic wind speed reaches a value to overcome the restraint forces. The trajectory followed by the missile depends on where the missile is located relative to the tornado's location and the value of the wind speed at release. Of major importance is whether the missile is on the right side or the left side of the tornado's center line. Two cases are illustrated using a timber missile. In Figure 3.3, the

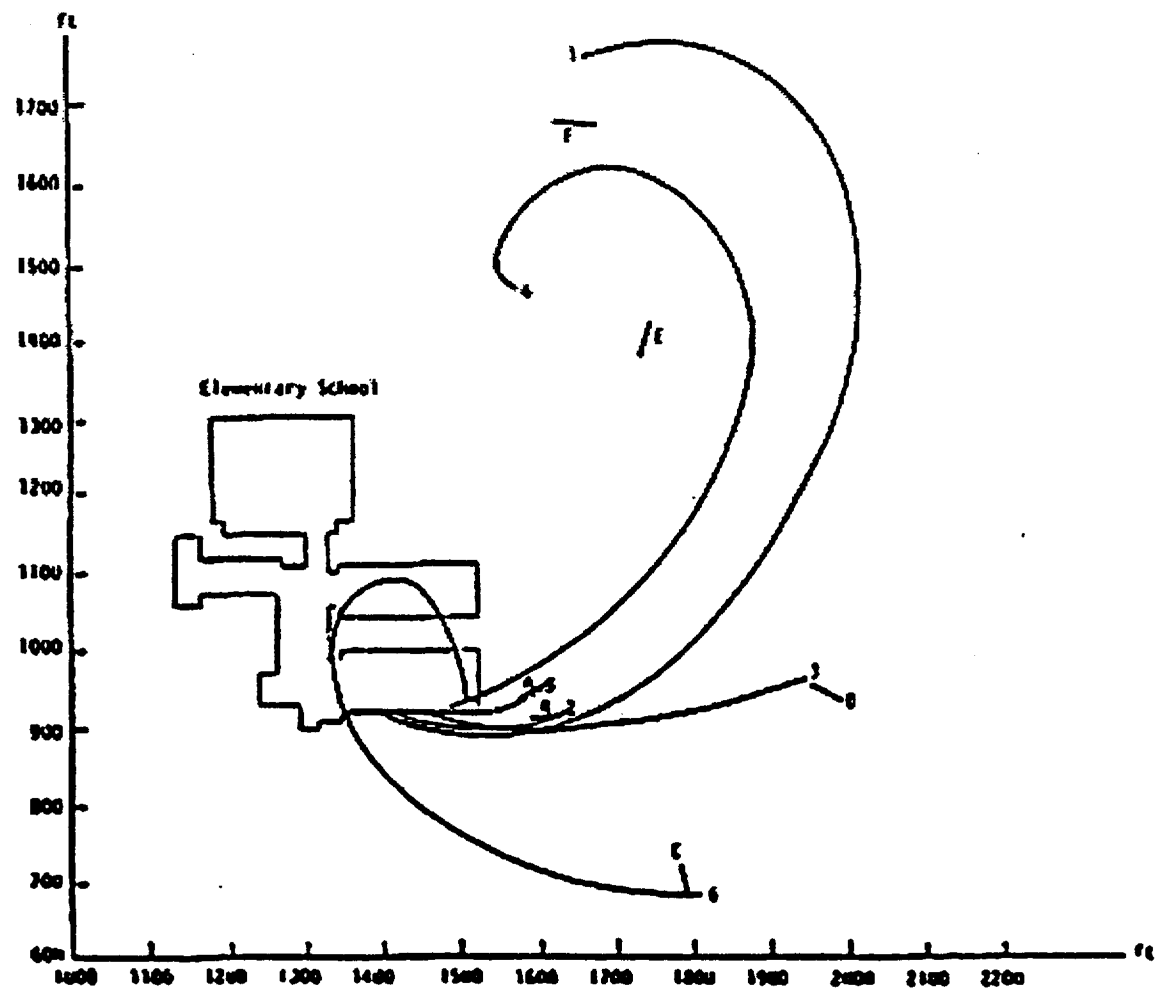


FIGURE 3.2 CALCULATED MISSLE TRAJECTORIES AND OBSERVED IMPACT POINTS (MAALEB, 1980)

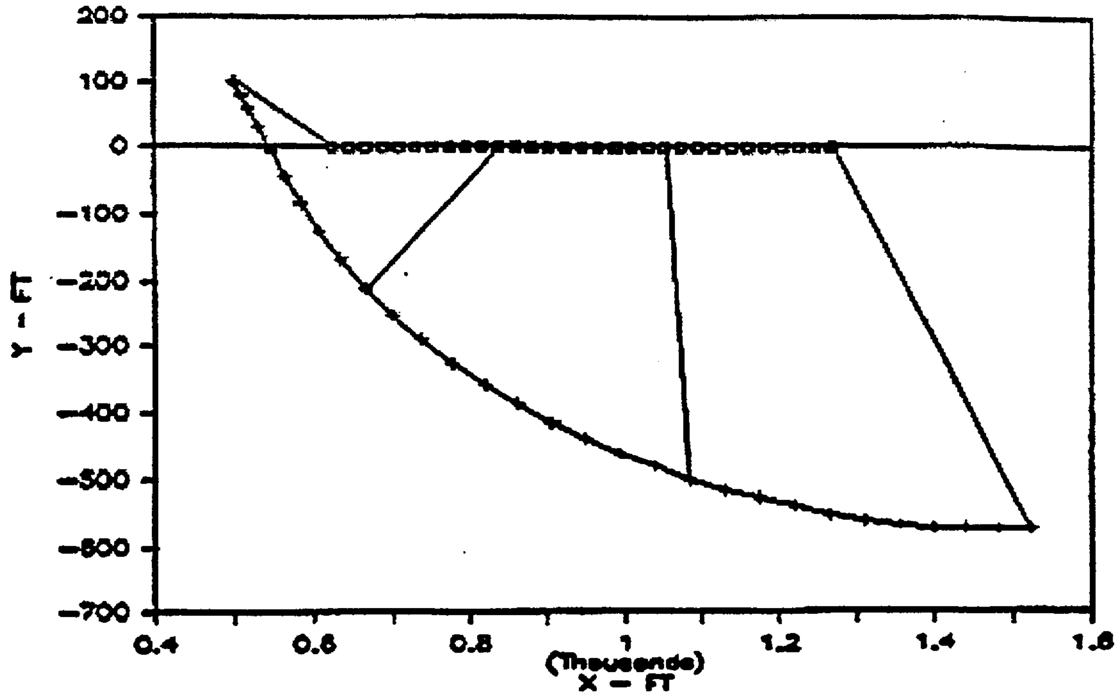
missile is initially located on the left side of the tornado path center line (looking in direction of translation). The missile does not release from its restraint until center of the tornado is past the missile. The trajectory then wraps around the back side of the tornado wind field. It crosses the center line and impacts on the right side of the tornado path. The missile in Figure 3.4 is initially located on the right side of the tornado center line and releases on the front side of the tornado wind field. The missile almost makes a loop. The net distance traveled by the missile from its point of origin to its impact point is small, compared to the first example. However, the distance traveled along the trajectory path is relatively large.

3.7.2 Comparison with NBS Trajectory Model

Simiu and Cordes (1976) published a three degree-of-freedom trajectory model (NBS model). Many features of the NBS model are similar to the IDR model, although they were developed independently. The primary differences are in the wind field models and the manner in which the missiles are released from their restraints. The two models essentially use the same dynamic equations, both assume a tumbling mode in evaluating the aerodynamic flight parameters and both use a numerical integration scheme to calculate the trajectories.

The major difference in the two methods is the wind fields. The NBS model uses a wind field that has linear relationship between radial and vertical wind components as a function of tangential wind speed. The tangential wind speed is treated as a Rankine combined vortex model. Table 3.2 Shows a comparison between results of the NBS and IDR trajectory models for the 2x4 timber plank and 3-in. diameter steel pipe. When the

F3 TORNADO



Initial Position of Timber Missile Relative to Tornado path:

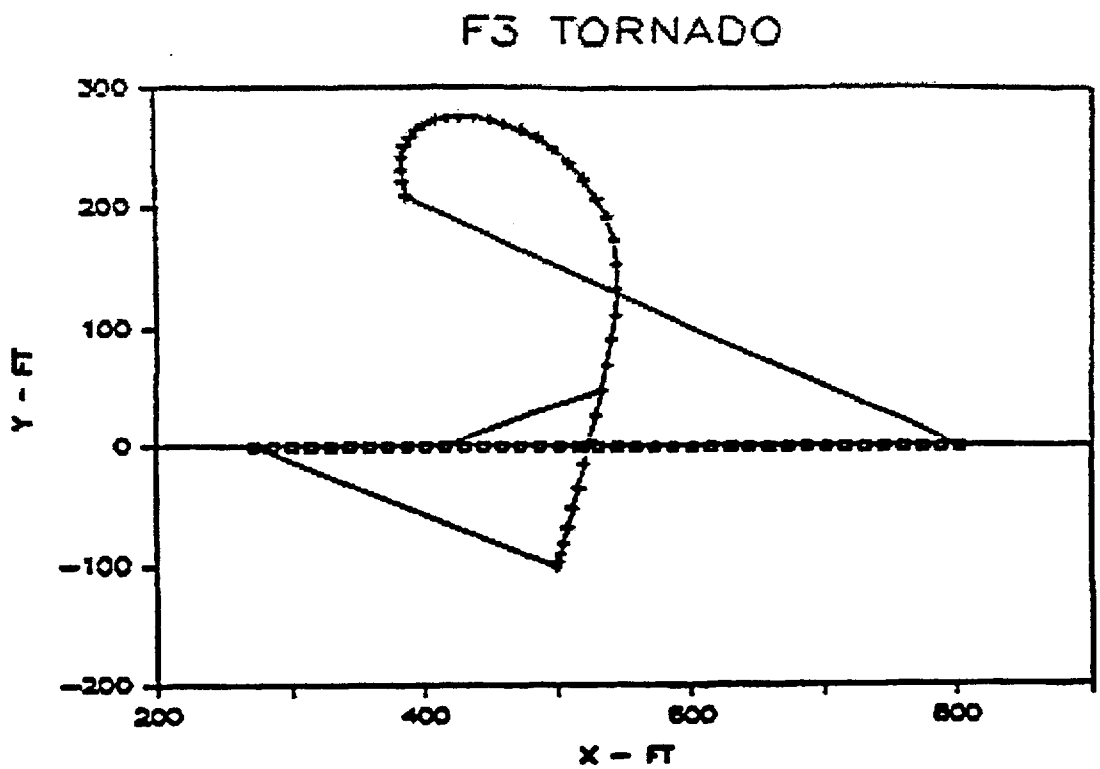
X = 500 ft, Y = 100 ft, Z = 12 ft (initial height)

Missile Release Wind Speed: 100 mph

F3 Tornado Parameters:

Maximum Tangential Speed: 148mph
Radius of Maximum Wind: 193 ft
Translational Speed: 50 mph

FIGURE 3.3 MISSILE POSITION REALTIVE TO TORNADO POSITION WHEN MISSILE IS RELEASED ON LEFT SIDE OF TORNADO PATH



Initial Position of Timber Missile Relative to Tornado path:

X = 500 ft, Y = -100 ft, Z = 12 ft (initial height)

Missile Release Wind Speed: 100 mph

F3 Tornado Parameters:

Maximum Tangential Speed: 148mph
Radius of Maximum Wind: 193 ft
Translational Speed: 50 mph

FIGURE 3.4 MISSILE POSITION REALTIVE TO TORNADO POSITION WHEN MISSILE IS RELEASED ON RIGHT SIDE OF TORNADO PATH

NBS wind field is used in the IDR model, the maximum horizontal missile speeds are almost identical. This comparison is presented as quality assurance for the IDR model.

When the DBT- 77 wind field is used in the IDR trajectory model, the maximum horizontal missile speeds are on the average 50 percent less than those predicted by the NBS model (see Table 3.2). The reason for the difference is that the DBT-77 tornado wind field only has a strong updraft (vertical wind speed) in the outer core, which extends over a limited area. The NBS tornado wind field model has a strong updraft over the entire tornado vortex diameter. As discussed in Section 1, there are good reasons to believe that DBT-77 is a valid representation of actual tornado wind flow. When used with the DBT-77 wind field, the IDR trajectory model produces estimates of missile speeds that are consistent with observations in the field. The estimated speeds were indirectly verified by Malaeb's work and agree with an independent model (NBS model) when a direct comparison is made.

3.8 Estimates of Missile Impact Speeds from Trajectory Simulations

The exercise for determining expected missile speeds in a tornado of specified Fujita Scale is described in this section. Specific missiles considered are the 2x4-timber plank and the 3-in. diameter steel pipe, although the method is applicable to any object that can be modeled as a three degree-of-freedom missile. The IDR missile code is used in the trajectory simulations.

3.8.1 Description of Method

Missiles (e.g. the 2x4 plank) are assumed to be uniformly placed across the tornado path and are available to be transported by the tornado winds. A tornado model

Table 3.2 Comparison of Maximum Horizontal Missile Speeds from NBS and IDR Models

V_{max} (mph)	V_T (mph)	Flight Parameter (ft.^{2}/lb.)	Maximum Horizontal Missile Speed (mph)		
			NBS	IDR[1]	IDR[2]
Timber Missile					
290	70	0.132	185	190	132
240	60	0.132	156	158	121
190	50	0.132	129	134	96
Pipe Missile					
290	70	0.021	117	120	76
240	60	0.021	94	98	62
190	50	0.021	23	72	41

[1] *Based on NBS wind field model*
[2] *Based on DBT-77 wind field model*

<u>Notes:</u>

Missile initial position relative to tornado path:
X = 300 ft, Y = 0, Z = 130 ft(initial height)
Tornado parameters:
V_{max}: Maximum wind speed
VT: Translational wind speed
Radius of Maximum Wind: 150 ft.

(DBT-77) of specified Fujita-Scale intensity is passed over the distributed missiles. The trajectory of each missile is calculated using the IDR missile simulation code. The maximum horizontal and vertical speeds of each missile are tabulated, along with the maximum height each missile achieves. Initial parameters of height above ground, position relative to tornado path and release wind speed are specified for each missile. Each of these parameters has an effect on the missile trajectory, the speed achieved and the height attained by the missile. Specifying the Fujita Scale, F_λ, determines the maximum wind speed and the translational speed of the tornado. Other wind velocity components are then obtained from the DBT-77 tornado wind field model.

All missiles do not release from their restraint, because in some parts of the tornado wind field the wind speed is less than the missile release wind speed. Trajectory calculations are performed for those missiles that are released. Parameters of interest from the trajectory calculations include maximum vertical missile speed and the maximum height achieved by the missile.

Certain parameters that define the tornado wind field and the missile characteristics are not uniquely defined, but vary over a range of values. The initial height of 2x4 timber plank and 3 in. diameter pipe missiles typically varies from 12 to 50 ft above ground, if the source of the missiles is destruction of one-to three-story buildings or residences. The maximum tornado wind speed in each Fujita Scale category varies over a range. Likewise, the translational speed ranges typically from 20 to 50 mph. These variations are treated in the trajectory calculations. Specific details of the calculations are presented in subsequent sections.

3.8.2 Distribution of Missiles

The number of missiles distributed across the tornado path depends on the path width. The edge of the path is defined by the boundary of 75 mph wind speeds. Because the translational velocity acts in the opposite sense of the tangential velocity on the left side of the path, separate expressions are required for wind speed on the left and right sides of the path. The variation of wind speed across the path width is illustrated in Figure 3.5. The distances from the center of the tornado to the left and right edge (75 mph wind speed), respectively, are:

$$R_L = V_{Lmax} R_{max}/75 \qquad (17)$$

and

$$R_R = V_{Rmax} R_{max}/75 \qquad (18)$$

The damage path width is:

$$W = R_L + R_R \qquad (19)$$

$$= (R_{max}/75)(V_{Lmax} + V_{Rmax})$$

where

R_{max} is the radius of maximum tangential wind speed, ft

V_{Lmax}, V_{Rmax} are maximum wind speeds on the left and right side of the tornado path,respectively, mph

The difference between V_{rmax} and V_{lmax} is the translational speed, V_t.

The missiles are arbitrarily spaced 10 ft apart across the tornado path as illustrated in Figure 3.5. A 10-ft spacing was selected to give a sufficiently large sample for the statistical calculations without requiring an excessive number of trajectory calculations. If the wind to cause the missiles to release from their restraint is greater than 75 mph,

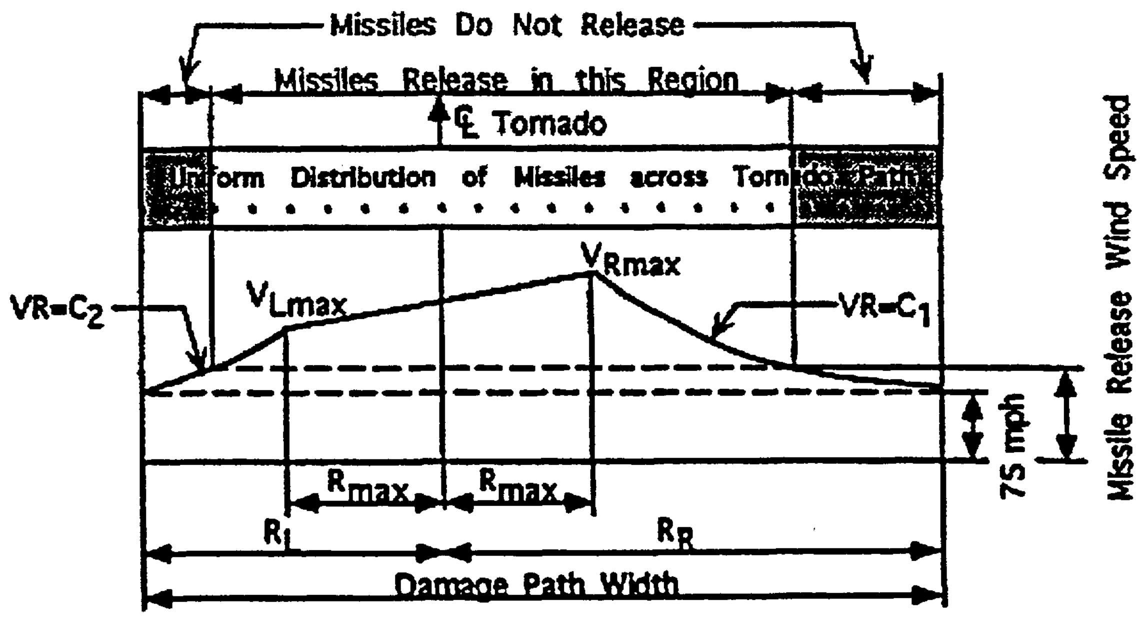


FIGURE 3.5 VARIATION OF WIND SPEED ACROSS TORNADO PATH. MISSILES RELEASE AT WIND SPEEDS GREATER THAN MISSILE RELEASE WIND SPEED

there will be a strip along each side of the path where missiles are not released (see Fig, 3.5). Table 3.3 lists the number of missiles distributed across the path of each Fujita Scale tornado.

3.8.3 Sample Trajectory Calculations

Flight trajectories and the conditional probability distributions are presented in this section for the 2x4-timber plank in an F3 tornado and the 3-in. diameter pipe in an F5 tornado. Final results consider both missiles in F2 through F5 tornadoes.

2x4 Timber Plank

A study is first performed to identify critical values of initial height and tornado translational speed. Table 3.4 summarizes the results of the study to determine the effect of initial height on the maximum horizontal and vertical missile speeds achieved. Sets of trajectory calculations were run with the initial missile height at 12 and 50 ft above ground. Translatioanal velocity and missile release wind speed were 50 and 100 mph, respectively. Missiles released at locations between 420 ft on the left to 980 ft on the right side of the F3 tornado path. The results for missiles located 420 ft on the right side of the path center are listed in Table 3.4. Speeds achieved by the remaining missiles on the right side are not significant. The table shows that missiles released at 12 ft achieve a higher maximum horizontal speed than those that are released at 50 ft above ground. At first glance, this may appear to be an anomaly, because wind speeds in tornadoes tend to increase with height. However, to understand the situation, one must remember that the tornado approaches the missile and the missile releases from its restraint when the wind

Table 3.3 Number of Missiles Distributed across Path of Each F-Scale Tornado

Tornado F-Scale	Mean Wind Speed* (mph)	Radius of Maximum Wind Speed (ft.)	Damage Path Width (ft.)	Number of Distributed Missiles**
F2	135	298	940	95
F3	182	416	1760	177
F4	234	548	2970	298
F5	290	690	4620	463

* *See Appendix C for details of the F-Scale tornadoes as modeled by DBT-77*
** *Missiles are uniformly spaced 10 ft apart across damage path*

speed reaches 100 mph. Because the wind speed is higher at 50 ft than at 12 ft above ground, the missile at 50 ft releases at a larger distance from the tornado center than the one at 12 ft. Because the wind speeds tend to increase with distance from center up to the radius of maximum wind speed, the missile at 12 ft height is initially affected by a higher wind speed gradient than the one at 50 ft and, hence, achieves a higher horizontal speed along its trajectory.

To further illustrate the effect of initial height on maximum horizontal speed achieved by a missile, trajectory calculations were made for missiles located 420 ft left of the tornado center and placed at 12, 20, 30, 40 and 50 ft above ground. As noted previously, the highest maximum horizontal speed was reached when the missile was released at 12 ft (see Table 3.4). The maximum speed reached by a missile was not significantly affected by initial height. The maximum height reached by a missile was not significantly affected by initial height of the missile. Trajectory calculations that allow the translational speed of the tornado to vary from 20 to 50 mph revealed that the 50 mph translational speed produces highest missile speeds.

These parameters are then used in the set of trajectory calculations that form the basis for the statistical analyses. A summary of the calculation results is given in Appendix A. Figure 3.6 shows a typical plot of horizontal and vertical missile speed and the height of the missile speed and height of the 2x4 timber as a function of time. Time equals zero at the instant a missile is released. The missile tends to reach its maximum horizontal speed at about the time it reaches maximum height. A positive value of vertical speed means an upward velocity component.

Table 3.4 Results of Trajectory Calculations
(2"x4" Timber Plank in F3 Tornado)

Initial Position Y (ft)	Initial Position Z (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
420	12	181	36	200
210	12	153	41	256
0	12	132	40	259
-210	12	129	37	211
-420	12	120	29	63
420	50	137	38	214
210	50	130	38	242
0	50	125	33	185
-210	50	104	28	97
-420	50	101	27	95
420	12	181	36	200
420	20	156	37	221
420	30	145	38	223
420	40	138	38	220
420	50	137	38	214

Missile Release Wind Speed: 100 mph
Translational Speed: 50 mph

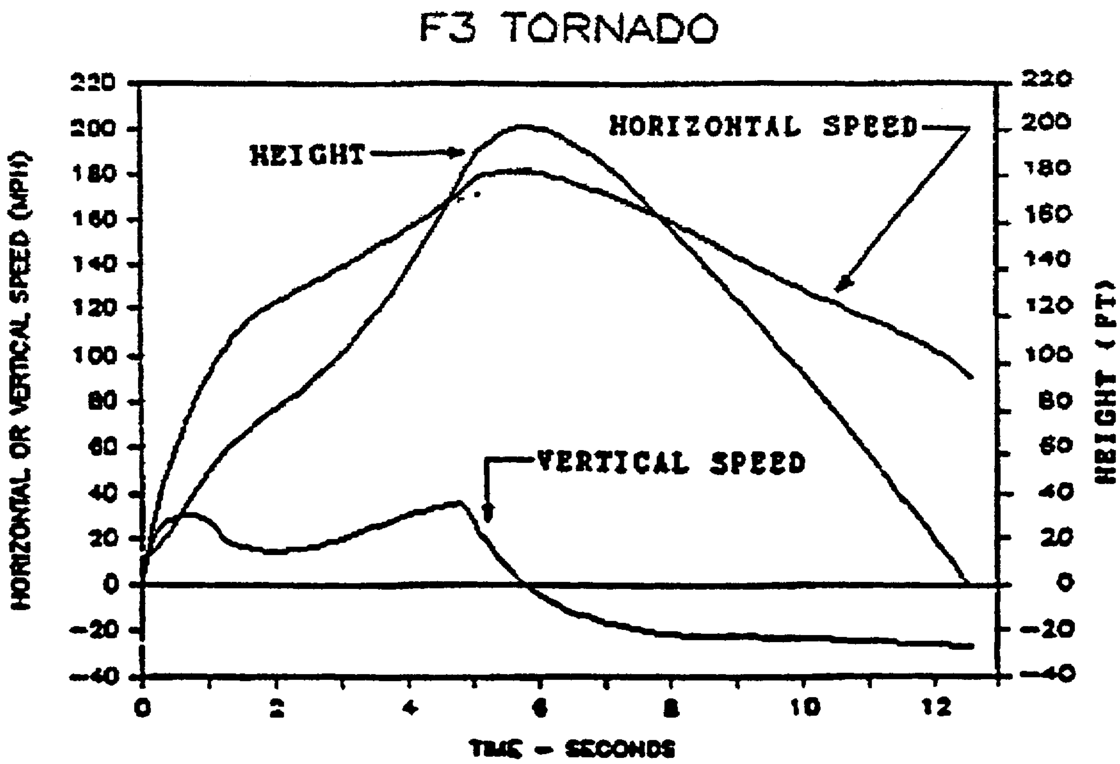


FIGURE 3.6 HORIZONTAL AND VERTICAL MISSILE SPEEDS AND HEIGHT VERSUS TIME FOR 2X4 TIMBER MISSILE

The horizontal trajectories of five missiles at various locations across the path are shown in Figure 3.7. The timber plank missiles tend to follow the tangential winds around the center of the tornado. Missiles that originate on the left side of the path end up on the right side. Those initially located on the right side of the path do not travel as far as the ones on the left side.

A total of 141 out of 177 missiles were released in the tornado winds. A release frequency histogram of the maximum horizontal 2x4 timber missile speeds is shown in Table 3.5. Of the missiles that released (at 100 mph wind speed), all of them achieved a speed in the range between 102 mph and 181mph.

From Appendix A, the mean impact speed for the 141, 2x4 timber missile that released in an F3 tornado was 129 mph with a standard deviation of 18 mph. From Table 3.5, 77 percent of the released missiles achieved a maximum horizontal impact speed less than 140 mph. One of the 141missile achieved a maximum impact of 181 mph (Trajectory No. 1 in Appendix A). The missile reached a maximum height of 200 ft above ground after being released 12 ft above ground level. The maximum vertical speed of 36 mph was achieved at impact with the ground. Another missile (Trajectory, No. 35 in Appendix A) achieved a maximum height of 275 ft above ground and reached a vertical impact speed of 44 mph at impact with the ground.

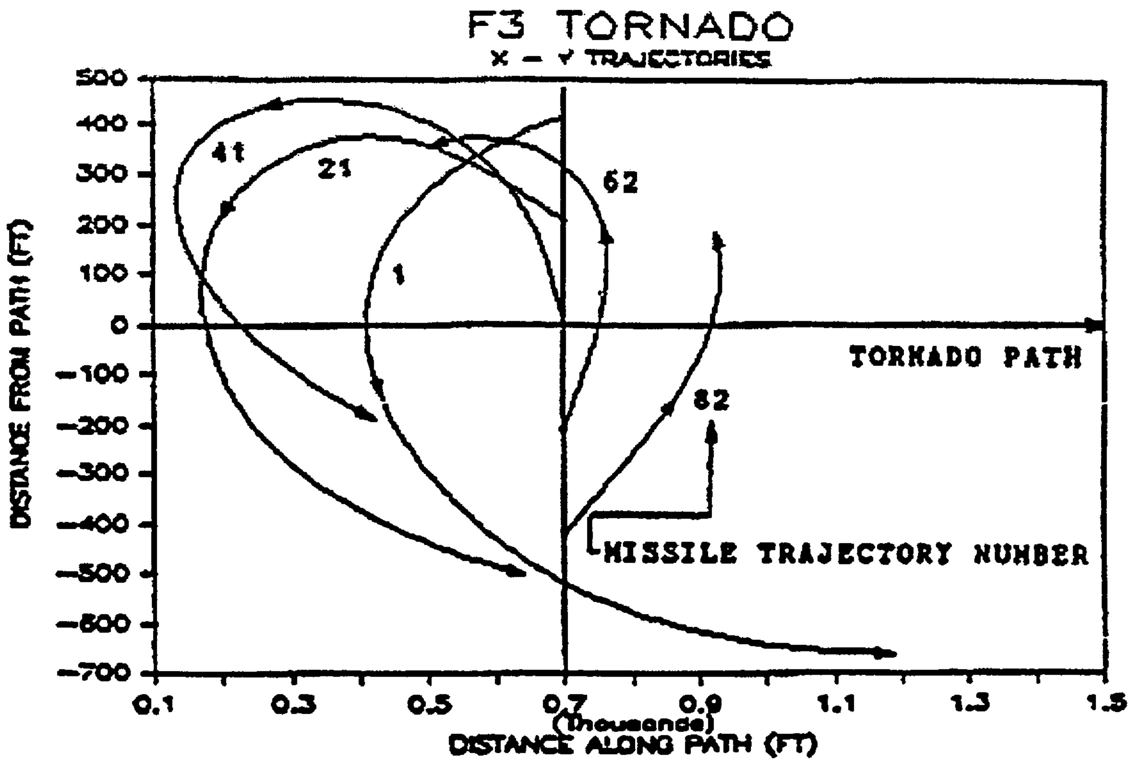


FIGURE 3.7 TYPICAL TRAJECTORIES OF 2X4 TIMBER MISSILES LOCATED AT VARIOUS DISTANCES FROM F3 TORNADO PATH CENTERLINE

Table 3.5 Frequency Histogram of 2x4 (15 lb) Timber Missile That Released in F3 Tornado

Missile Speed (mph)	No. of Missiles Released	Percent released (%)	Cumulative Percent (%)
100-109	21	15	15
110-119	34	24	39
120-129	23	16	55
130-139	31	22	77
140-149	9	6	83
150-159	12	9	92
160-169	7	5	97
170-179	3	2	99
180-189	1	1	1.0
Total	141	1.0	

u = 129 mph

s = 18 mph

3-Inch Diameter Steel Pipe

As a second example, calculations are presented for the 3-in. diameter steel pipe missile in an F5 tornado. The procedure is exactly the same as for the 2x4 timber plank. Table 3.6 summarizes the results of the study to determine the effect of initial height on maximum horizontal and vertical missile speed achieved by the pipe. Again, a set of missile trajectory calculations were run with the initial missile height at 12 and 50 ft above ground. Translational speed of the tornado and missile release wind speed were 50 and 150 mph, respectively. Missiles released at locations between 920 ft on the left side to 1630 ft on the right side of F5 the path. Results for missiles located 690 ft on either side of the tornado path are listed in Table 3.6. Speeds achieved by the remaining missiles that released are not significant.

In the case of the pipe, those missiles that released at 50 ft above ground achieved higher speeds than those released at 12 ft. The reason is that the pipe basically falls to the ground without experiencing very much lift. Falling from 50 ft rather than 12 ft gives the horizontal components of the wind more time to act on the pipe and accelerate to a higher speed. At 12 ft initial height, neither the horizontal nor vertical speed has time to develop.

The largest horizontal missile speed in Table 3.6 is developed by the missile located 690 ft left of the tornado path center line at an initial height of 50 ft. The lower part of Table 3.6 illustrates the effect of increasing the initial height from 12 to 50 ft. Both horizontal and vertical missile speeds increase with increasing initial height.

The maximum vertical missile speeds of the pipes are more sensitive to initial height than those of the 2x4 plank. The 50-mph tornado translational speed produces higher missile speeds than those at lower values. These parameters are used in the set of trajectory calculations that form the basis for the statistical analyses. A summary of the pipe missile calculations are given in Appendix B.

Figure 3.8 shows a typical plot of horizontal and vertical missile speed and height of the 3-in. dia. pipe missile as a function of time after release. A comparison of Figures 3.7 and 3.8 clearly shows the difference between the trajectories of the 2x4 plank and the 3-in. dia. pipe missiles.

The horizontal trajectories of five pipe missiles distributed across the path are shown in Figure 3.9. Missile on the left side of the path tend to move in the opposite direction of the tornado travel. The ones on the right side of the path tend to move across the path and slightly forward.

A total of 256 out of 463 missiles were released in the tornado winds. A release frequency histogram of the maximum horizontal pipe missile speeds is shown in Table 3.7. Of the missiles released (at 150 mph wind speed), the maximum horizontal speeds ranged from 65 to 87 mph

From Appendix B, the mean impact speed for the 256 pipe missile that released in an F5 tornado was 78 mph with a standard deviation of 6 mph. From Table 3.7, 48 percent of the released pipe missile achieved a maximum horizontal speed greater than or equal to 80 mph. The fastest of the 256 missiles that released, reached a top speed of 87 mph (Trajectory, No. 140, Appendix B). The high missile speeds are attributed to the 150 mph release speed. The resulting wind forces suddenly applied to the missile at

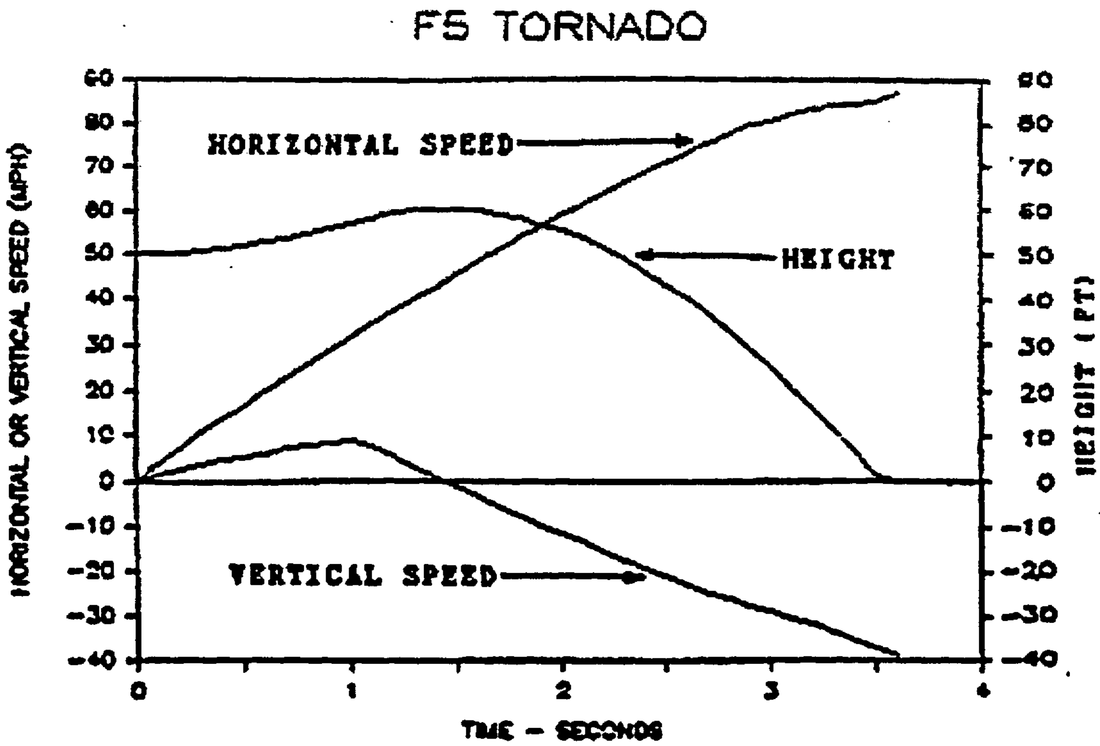


FIGURE 3.8 HORIZONTAL AND VERTICAL MISSILE SPEEDS AND HEIGHT VERSUS TIME FOR 3-in. dia. STEEL PIPE MISSILE

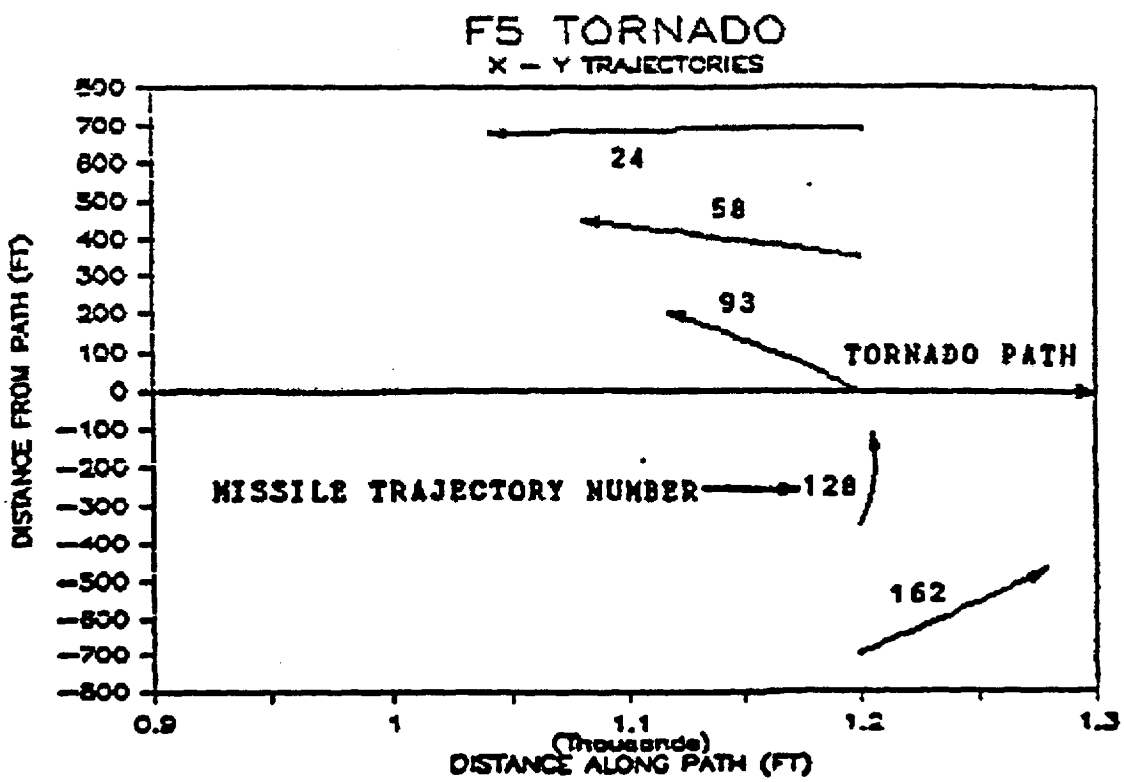


FIGURE 3.9 TYPICAL TRAJECTORIES OF 3-in. dia. STEEL PIPE MISSILES LOCATED AT VARIOUS DISTANCES FROM F5 TORNADO PATH CENTERLINE

release results in a very rapid acceleration. The pipe missiles typically were lifted from 8 to 11 ft above their release elevation. Upon falling to the ground they reached a maximum vertical speed of 40 mph at impact with the ground.

Table 3.6 Results of Trajectory Calculations for 3 in. dia. Steel Pipe in F5 Tornado

Initial Position Y (ft)	Initial Position Z (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
690	12	71	26	24
350	12	69	27	26
0	12	70	26	23
-350	12	68	27	25
-690	12	67	25	23
690	50	87	39	60
350	50	84	38	61
0	50	85	40	60
-350	50	80	39	60
-690	50	75	40	59
690	12	71	26	24
690	20	73	29	31
690	30	77	32	41
690	40	81	35	50
690	50	87	39	60

Missile Release Wind Speed: 150 mph
Translational Speed: 50 mph

Table 3.7 **Frequency Histogram of 3-in. Diameter Steel Pipe Missile that released in an F5 Tornado**

Missile Speed (mph)	No. of Missiles Released	Percent Released (%)	Cumulative Percent Released (%)
65-69	35	14	14
70-74	54	21	35
75-79	44	17	52
80-84	86	34	86
85-89	37	14	1.0
Total	256		

3.8.4 Rational for Impact Speed Recommendations

The probability of the 2x4 timber missile achieving an impact speed of 181 mph in an F3 tornado is very small. Factors affecting the probability of a missile achieving some threshold impact speed are given below:

1. Probability of wind speed to release and accelerate the missile,
2. Probability that missile will release, and
3. Probability that a missile is at some critical location to be released and accelerated.

Because of these reasons, it is entirely too conservative to select the maximum possible impact speed for design purposes.

Missile barriers are discussed in detail in Chapter 4. The Minimum wall configuration to stop a 15 lb 2x4 timber missile is an 8-in. CMU wall with #4 rebar grouted in each vertical cell. This wall will stop the missile at any impact speed, large or small. At impact speeds below about 135 mph, the wall stops the missile with no damage to the wall and minimum damage to the missile. At impact speeds greater than 135 mph, the wall is not damaged, but missile splinters into many small pieces. Thus, the same minimum wall configuration is adequate for all predicted impact speeds of the 2x4 timber missiles. The recommended missile criteria for both PC3 and PC4 SSCs is 2x4 timber missile (15 lb.) at 100 mph impact speeds at any height up to 200 ft above ground.

The probability of the 3-in. diameter steel pipe missile achieving an impact speed of 87 mph in an F5 tornado is significantly smaller than the 2x4 timber missile reaching 181 mph in an F3 tornado. Unlike the timber missile, the steel pipe does not shatter into splinters. The mass of the wall barrier must be larger for the high speed impacts than required for smaller impact speeds.

Because the design tornado wind speed for PC4 SCC's is an F4 rather than an F5 tornado, the recommended design impact speed for PC4 is a 3-in. diameter steel pipe (75 lb) at 75mph. The design wind speed for PC3 SSCs is an F3 tornado. The F3 tornado is not nearly as wide as the F5 (see Table 3.3). The number of pipe missiles distributed in an F3 tornado is much less and the maximum impact speed is somewhat less. The recommended missile impact speed is 50 mph for PC3 SSCs. The pipe missile is elevated by the wind about 10 ft in an F5 tornado (see Appendix B). If a missile is released at 50 ft, it falls as it accelerates horizontally. By the time the pipe reaches a speed of 75 mph in a F4 tornado, its height above ground is 30 ft or less. Likewise, by the time a pipe reaches 50 mph in an F3 tornado its height above ground is 30 ft or less. Thus, the recommended maximum height of the 3-in. diameter pipe is 30 ft and 50 ft for PC3 and PC4 SSCs, respectively.

4. TORNADO MISSILE IMPACT CRITERIA

4.1 Introduction

As discussed earlier, missiles transported by a tornado can vary in size and weight. Upon impact, a missile can spall, scab, penetrate or perforate a wall or roof structure as illustrated in Figure 4.1. Impact test data have been published on light and heavyweight missiles. Beason, Lynn and Minor (1976) tested lightweight missiles in the form or roof gravel impacting in window glass. Heavyweight missile impact tests were conducted by Vassallo (1975) Stephenson (1975) tested one 74 lb, 3-in. diameter steel pipe among his other tests. No other test data on 3-in. diameter pipe impacts was available, thus leaving a large gap in test data for this projectile and suggesting the need for further impacting testing.

Information gathered from impact tests reported herein will benefit engineers and contractors in the design and/or evaluation of SSCs required to resist tornado-generated missiles. The data will enable engineers to optimize their designs and avoid over design of SSCs. In evaluating existing SSCs, designers will be able to determine safe areas for occupant protection and sensitive materials during a tornado event. Finally, recommendations are prescribed that establish minimum barrier standards for impact of both the 2x4 timber plank and the 3-in. diameter steel pipe. These standards satisfy DOE STD 1020-94 impact criteria.

The objectives of this experimental study are as follows:

1. Impact clay brick, concrete masonry, and reinforced concrete wall sections with 3-in. diameter steel pipe at various impact speeds

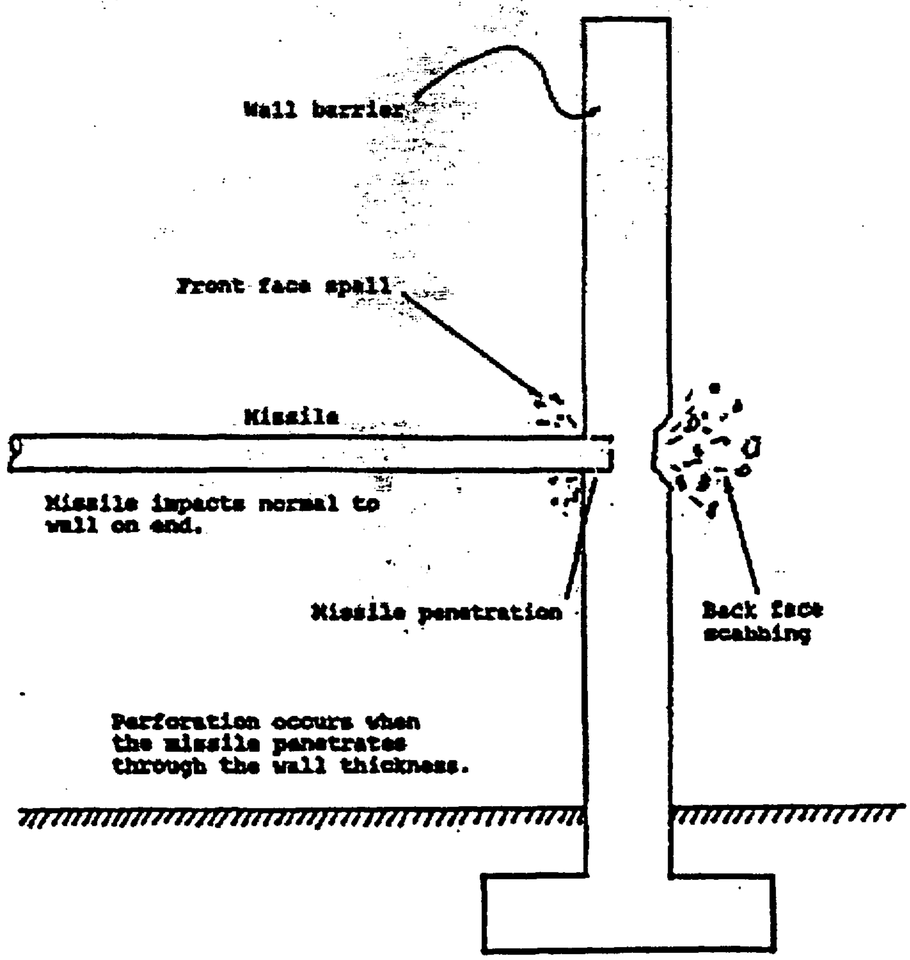


FIGURE 4.1 MISSILE IMPACT NOMENCLATURE

2. examine the effect of different rebar patterns in concrete barriers
3. identify specific wall and roof barriers that are capable of safely resisting impact of missiles specified in DOE 1020-94.

To accomplish these objectives, twelve test specimens of various configurations were constructed in accordance with industry standards. Each was impacted by a steel pipe shot from an air-actuated cannon at a specified impact speed. Damage was identified as hairline cracks, penetration, front face spall, back face scabbing, or perforation. These data are then used with existing 15 lb 2x4 in. impact test data to formulate a complete set of medium weight missile impact standards.

The scope of this study is limited to testing barriers required to meet criteria specified in DOE STD 1020-94. A review and assimilation of test results for the 15 lb 2x4 in. timber plank missile is included, but the study mainly concentrates on the impact resistance of clay brick masonry, concrete masonry, and reinforced concrete barriers to the steel pipe missile. Neither the wind forces necessary to pick up and transport a steel pipe, nor the probability of such a missile event is addressed in this study. For SSCs classified PC4, the 3000 lb automobile traveling at an impact speed of 25 mph requires structural response calculations that are also beyond the scope of these project (see, for example, McDonald and Zang , 1993).

Subsequent chapters contain the following information: Section 4.2 reviews previous research relating to missile impact, while Section 4.3 explains design of the experiment. Section 4.4 describes the test faciity, and Section 4.5 focuses on the laboratory procedures and test panel construction. Section 4.6 presents the data from each test and examines the results of these experiments. A summary of results and a minimum impact criteria chart for the 2x4 plank and steel pipe missiles are given in Section 4.7. Finally, Section 4.8 provides the conclusion and recommendations.

4.2 Review of Previous Research

The impact of lightweight and heavyweight missiles has been studied previously. Lightweight missiles typically damage window glass. Heavyweight projectiles are tested for design of nuclear power plants. Impact tests of medium weight missiles are treated in this report.

4.2.1 Previous Research on 2x4 Timber Plank Impacts

Bailey (1984) conducted tests on typical residential walls using 15 lb, 2x4 timber missiles. These tests were conducted in the Tornado Missile Impact Facility at Texas Tech University. In his research, Bailey tested barriers made of stucco, lapboard, plywood, masonite, concrete masonry, and clay brick masonry, which characterize typical residential exterior walls as defined in *Architectural Graphic Standards* (1981). Table 4.1 shows that most walls tested were perforated at about 50 mph except the clay brick veneer wall was able to resist perforation of the 2x4 timber missile at speeds up to 120 mph.

White (1986) continued Bailey's research by testing a more extensive set of concrete masonry unit (CMU) walls for resistance to the 15lb, 2x4 timber plank. The CMU walls varied in thickness and amount of reinforcement. The walls that were reinforced and grouted provided substantial impact resistance. Most tests were conducted with the impact normal to the wall surface. A few tests shot provided impact at oblique angles to the wall. The normal impact turned out to be worst case. Most tests were conducted with a blunt-ended missile; others had a sharp, pointed end. The 2x4 missiles with pointed ends perforated the unreinforced CMU walls more easily than the blunt-ended ones, but it made little difference on the walls that were grouted. The results of White's impact tests are summarized in Table 4.2.

A series of unpublished impact tests on reinforced concrete panels were conducted at Texas Tech University in 1989 (Table 4.3 summarizes the results). Concrete compressive strength was a nominal 4000 psi. Rebar was Grade 40. All panels were cured for at least 28 days. The panels were impacted normal to the surface, on end by a blunt ended 2x4 timber missile weighing 15 lbs. The 4-in. thick unreinforced test panel was impacted at 122 mph. The missile did not penetrate the concrete, but a vertical crack propagated through the panel thickness. The 2x4 timber missile was reduced to splinters. Number three rebar (3/8-in. diameter) was added to the second 4-in. thick test panel. It experienced no damage when impacted at 121 mph. A second shot at 147 mph on the same panel produced hairline cracks on the back face. The missiles were splintered. A 6-in. panel with similar reinforcement experienced no damage from the impact of the 2x4 timber plank. From these and other tests with similar results it was concluded that 4-in. reinforced concrete slab with a minimum reinforcement of # 3 rebar at 6-in. on center each way in center of slab is sufficient to stop the 15 lb, 2x4 timber missile at impact speeds expected in tornado winds.

Table 4.1 Impact Speed to Perforate Typical Residential Wall Panels
(Bailey, 1984), (2x4 - 15 lb. Timber Missile)

Panel Description	Perforation Velocity (mph)
Masonite Siding	54
Insulation Board / Masonite Siding	54
Plywood (1/2 in.) / Masonite Siding	52
Plywood (1/2 in.)	52
Plywood (3/4 in.)	53
Stucco Wall	53
Lapboard Siding	53
Insulation Board / Lapboard Siding	52
Brick Veneer	122

All barriers constructed on a 2x4 stud frame.

Table 4.2 **Impact Speed to Perforate CMU Walls**
(White, 1986), (2x4 - 15 lb. Timber Missile)

Barrier Description	Perforation Velocity (mph)
8-in. Wall	
Grout and #4 rebar in every cell	> 130
Grout only in every cell, no rebar*	>130
Grout and #4 rebar in every other cell **	65
Unreinforced **	60
12-in. Wall	
Grout and #4 rebar in every cell	> 130
Grout only in every cell, no rebar *	>130
Grout and #4 rebar in every other cell **	70
Horizontal Joint Reinforcement only**	70
Unreinforced **	65

* *Although walls were not perforated, they suffered severe cracking*
** *Impact point was on cells which were not reinforced and grouted*

Table 4.3 **Tornado Missile Impact Tests on Reinforced Concrete Panels**
(Texas Tech University, 1989), (2x4 - 15 lb. Timber Missile)

Barrier Description	Impact Velocity (mph)	Results
4-in. thick. rReinforced concrete panel; #3 reinforcing bars spaced 6-in. o.c. each way and placed in the middle of the panel - Test#1	121	No damage; the 2x4 timber plank was reduced to splinters.
4-in. thick. reinforced concrete panel; #3 reinforcing bars spaced 6-in. o.c. each way and placed in the middle of the panel - Test#2	147	Hairline cracks on the back face; the 2x4 timber plank was reduced to splinters.
4-in. thick. unreinforced concrete panel;	122	No penetration, but a 0.24-in. vertical crack propagated through the panel; the 2x4 timber missile was reduced to splinters.
6-in. thick. reinforced concrete panel; #3 reinforcing bars spaced 6-in. o.c. each way and placed in the middle of the panel.	140	No damage; the 2x4 timber missile was reduced to splinters.

4.2.2 Previous Research on 3-in. Diameter Steel Pipe Impacts

A single impact test using a 3-in. diameter Schedule 40 steel pipe missile weighing 75 lbs was conducted by Stevenson (1975). The 12-in. thick reinforced concrete test panel was struck by the pipe at a speed of 142 mph. Damage to the panel consisted of a 4.6 in. penetration crater at the impact point and hairline cracks on the back face. Although this test gave an indication of the impact resistance of reinforced concrete walls to steel pipe impacts, more data are needed on reinforced concrete panels with smaller thicknesses, along with concrete masonry and clay brick masonry walls. Also, pipe impact speeds slower than in Stevenson's test were needed to establish wall barrier design criteria in accordance with minimum missile criteria specified in DOE STD 1020-94.

4.2.3 Impact Equations

Two emperical equations have been proposed for predicting the impact resistance of concrete panels to tornado generated missiles. The equations are commonly known as the Rotz equation and ***Modified NDRC*** Equation. Vassolla (1975), conducted impact tests using medium and heavyweight missiles. The tests involved 8-in. diameter timber utility poles, 8 in. diameter steel pipes, and solid steel slugs impacting on 9-ft by 9-ft reinforced concrete panels. The panels were 12, 18, or 24 in. thick. These impact tests yielded data on both local damage and structural response effects on the panels. Local damage turned out to be the dominant damage factor for these missiles.

Rotz (1975) used data from the Vassolla tests to develop an empirical equation for determining the thickness of reinforced concrete slabs required to prevent back face scabbing from the impact of steel pipe missiles. The equation is:

$$T_{bs} = 5.44 * W^{0.4} * V_s^{0.65} / (f^1c^{0.5} * D^{0..2}) \qquad (1)$$

where:

T_{bs} = thickness of concrete at threshold of back face scabbing, in.

W = missile weight, lb

D = missile diameter,in.

V_s = missile impact speed fps

f^1_c = concrete compressive strength (psi)

Although Rotz developed this equation from 8-in. diameter steel pipe impact tests, he suggests that the equation is valid for other pipe diameters.

The Rotz equation has limitations. Because the equation is not non-dimensional, it can theoretically apply only to the slab thickness and missiles tested in Vassallo's research. Additional tests that could confirm the applicability of the Rotz equation to other missiles, impact speeds and slab thickness did not exist prior to the present study. Despite these limitations, the Rotz equation has potential application to 3-in. diameter pipes and reinforced concrete barriers.

The National Defense Research Committee (NDRC) formula, which was originally based on ballistic missile tests, was later modified by Kennedy (1975) to be applicable for tornado generated missiles. The modified formula is follows:

$$t_s / D = 7.91 (X / D) - 5.06 (X / D)^2 \qquad \text{for } t^s / D < 3 \qquad (2)$$

or

$$t_s / D = 2.12 + 1.36 (X / D) \qquad \text{for } t^s / D > 3 \qquad (3)$$

where:

t_s = thickness for threshold of back face scabbing in.

D = missile diameter in.

X = depth of penetration in.

X is found from the following formula:

$$G (X / D) = (KND^{0.02} W (V / 1000)^{1.8}) / D^3 \qquad (4)$$

where:

V = missile velocity fps

$$G (X / D) = (X / 2D)^2 \qquad \text{for } X / D \leq 2.0 \qquad \text{or} \qquad (5)$$

$$G (X / D) = (X / D-1) \qquad \text{for } X / D > 2.0 \qquad (6)$$

N = shape factor of 0.72 for blunt-ended missiles

W = weight of missiles lb

$K = 180 / (f'_c)^{0.5}$

f'_c = compressive strength of concrete psi

Figure 4.2 compares the threshold of back face scabbing thickness of reinforced concrete barriers as predicted by the Rotz equation and the modified NDRC equation for 3-in. diameter steel pipes. The results from the two equations are similar, although the Modified NDRC equation predicts a slightly larger (more conservative) concrete thickness for 3-in. diameter pipes impacting at the same speed. The Rotz equation was used to estimate test barrier thickness in the design of experiments for the research reported herein.

Both the Rotz and the modified NDRC equations give reasonable predictions of concrete wall and roof panel thickness for protection against 3-in. diameter steel pipe impacts. The results are conservative when compared to impact test results.

4.3 Design of Experiment

The primary objective of the Texas Tech University test was is to identify wall and roof panels that are capable of resisting impact by 3-in. diameter steel pipe as specified in DOE STD 1020-94. In addition, several rebar patterns were considered for their effect on impact resistance. To accomplish these objectives, a series of reinforced concrete and masonry panels were designed, constructed, and tested. Design of the test program is described in this section.

Several variables influenced the design of the reinforced concrete and masonry test panels. DOE STD 1020-94 specifies that panels must resist the impact of 3-in. diameter steel pipe at speeds of 35, 50, or 75 mph. The different impact speeds translate into different impact loads which, in turn, affect panel thickness and strength requirements. Concrete, masonry and steel strengths, as well as the percent of steel and its arrangement within the panel, are all parameters that affect panel impact resistance. The missile impact angle (normal or oblique) also affects the damage inflicted on the test panel.

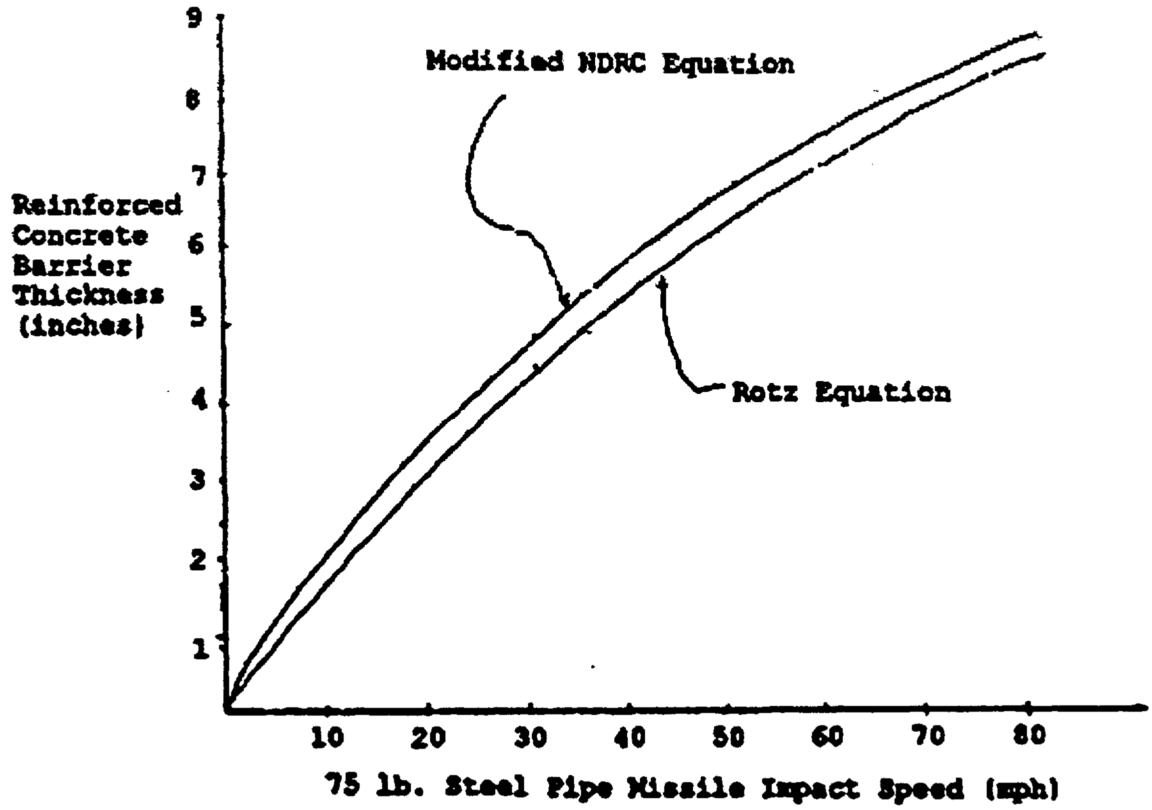


FIGURE 4.2 COMPARISON OF ROTZ AND MODIFIED NDRC EQUATIONS FOR THRESHOLD OF BACK FACE SCABBING

Test panel designs were targeted to be close to the threshold of failure, but should not fail. Failure is define as the threshold impact velocity to produce back face scabbing rather than perforation. Back face scabbing dislodges pieces of the panel that become missiles capable of injuring people or damaging objects or equipment inside the building. Material strengths of the panels were held constant to minimize the number of variables in the tests. The strength characteristics are similar to those found in typical building construction.

The concrete panels were reinforced with close to the minimum percentage of steel allowed by the American Concrete Institute (ACI) 318-89 Building Code Requirements. Concrete panels containing approximately 0.50%, steel are determined as shown in Appendix E. Providing the same percentage of steel in each test specimen allowed for panel consistency and comparability. In addition, the minimum amount of steel reinforcement represents the minimum strength case. This case was chosen so that minimum criteria for impact resistant barriers could be identified.

Masonry panels were reinforced according to current industry standards. Previous impact tests on masonry walls also influenced the amount of reinforcement in the wall panels.

All test panels were impacted with a blunt-ended missile striking on end, normal to the wall. During a tornado event, the wind transports missiles by random tumbling; the missiles rarely strike on end and normal to the wall. Normal impact is considered the worst case.

Each test panel was assigned an identification symbol. The first part identifies the panel construction. CR stands for reinforced concrete construction and CMU represents concrete masonry construction CBM and CBCMU refer to clay brick masonry and clay brick/concrete masonry unit construction, respectively. The second part of the test panel symbol identifies slab thickness and panel number. For example, CR-8.1 indicates a reinforced concrete slab 8-in. thick and is the first with these characteristics. The following paragraphs describe the test panels.

4.3.1 Reinforced Concrete Panels

Eight reinforced concrete panels of different thicknesses were constructed to resist 3-in. diameter steel pipe impacts. Panel thicknesses were chosen to resist impact speeds of 35, 50, and 75 mph. Concrete thickness required to prevent back face scabbing were estimated using the Rotz equation. Each panel was 39-in. x 39-in. Descriptions of the eight concrete test panels are presented in Table 4.4.

Three 6-in. reinforced concrete panels were constructed to test the steel pipe impact at 35 mph. The Rotz equation predicted that a 4.98-in. thick slab was required to prevent back face scabbing. In order to assure a design that would not fail, a 6-in. thickness was selected. Three 6-in. slabs were constructed. Each had the same percentage of steel, but a different arrangement of the reinforcing bars.

Three 8-in. reinforced concrete panels were designed to resist impact of the steel pipe traveling 50 mph. The Rotz equation predicted that a 6.29-in. thickness was required to resist back face scabbing. An 8-in. panel was chosen to ensure that a failure did not occur. Arrangements of the reinforcing steel had specific objectives. In CR-8.1 and CR-8.2, the effect of 9-in. and 12-in. reinforcing spacing (each way) was examined. The effect of reinforcing near both faces of the concrete was studied in CR-8.3.

Table 4.4 Reinforced Concrete Panel Construction

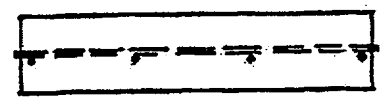
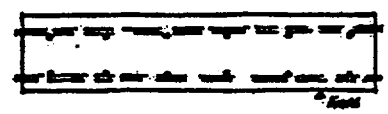
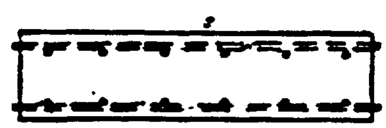
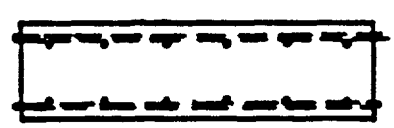
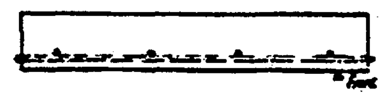
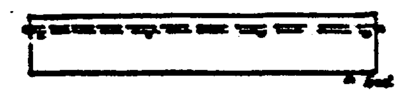
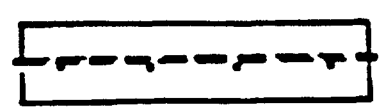
Panel Description	Panel X-Sec
<u>**CR-6.1 :**</u> *6-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 3 rebar spaced 9-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 35 mph*	
<u>**CR-6.2 :**</u> *6-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 4 rebar spaced 12-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 35 mph*	
<u>**CR-6.3 :**</u> *6-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 3 rebar spaced 6-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 35 mph*	
<u>**CR-8.1 :**</u> *8-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 4 rebar spaced 9-in o.c. each way and placed in the middle of the panel; missile impact speed: 50 mph*	

Table 4.4 Reinforced Concrete Panel Construction (*cont.*)

Panel Description	Panel X-Sec
<u>CR-8.2 :</u> *8-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 4 rebar spaced 12-in o.c. each way and placed in the middle of the panel; missile impact speed: 50 mph*	
<u>CR-8.3 :</u> *8-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 3 rebar spaced 12-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 50 mph*	
<u>CR-9.(1&2) :</u> *9-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 4 rebar spaced 6-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 75 mph*	
<u>CR-10.1 :</u> *10-in.thick. reinforced concrete, 39-in. by 39-in.; barrier is reinforced with # 4 rebar spaced 6-in o.c. each way and placed 1.50-in. from the front face; missile impact speed: 75 mph*	

The last two reinforced concrete panels were built to resist a75 mph impact speed. The Rotz equation predicted that an 8.21-in. slab was required to resist back face scabbing. Slabs with thicknesses of 9-in. and 10-in. were constructed. The 10-in. barrier was designed to further ensure satisfactory impact resistance. The rebar arrangement was the same in both panels. Each had No. 4 rebar at 6-in. o.c. each way placed 1.5-in. from each face.

4.3.2 Reinforced Masonry Panels

Four masonry wall panels were built to test impacts of the steel pipe missiles. Two panels were constructed with concrete masonry units (CMUs), while the other two consisted of a clay brick cavity wall and a clay brick/CMU combination. Reinforced masonry walls are widely used industrial applications. Unfortunately, there is no equation to estimate panel thickness to resist back face scabbing, as did the Rotz equation for reinforced concrete panels.

A schedule of the masonry wall panel construction is presented in Table 4.5. An 8-in. and a 12-in. CMU wall were built to resist the steel pipe impacting at 50 and 75 mph, respectively. Both the 8-in. and 12-in. nominal wall thicknesses are industry standards in construction. The CMU panels were 48 in. x 48 in.. All vertical cells in each wall were reinforced with # 4 rebar and filled with grout. Horizontal reinforcement consisted of truss-type joint reinforcement, which was placed at every second course.

A 9.5-in. clay brick cavity wall and a 12-in. clay brick/CMU combination wall were designd to resist the 50 mph impact of the steel pipe. The cavity wall was 52-in. high x 48-in. wide, while the combination wall was 48-in. x 48-in. The cavity wall was filled with grout and reinforced with vertical rebar. Horizontal reinforcement consisted of truss-type joint reinforcement placed at every fifth brick course. The CMU's in the combination wall were reinforced in the same way as the other two CMU walls. A single wythe of brick was mortared to the front face of the CMU wall. Horizontal truss-type joint reinforcement tied the CMU and brick wythes together; it was placed in every second CMU course.

4.4 Experimental Facility

The Tornado Missile Impact Facility (TMIF) at Texas Tech University simulates tornado generated missile impacts on wall or roof components. It contains an air-actuated cannon that can accelerate a 15 lb 2x4 timber plank or a 75 lb 3-in. diameter steel pipe up to speeds of 150 mph and 75 mph, respectively. The facility is located in the basement of the Civil Engineering Testing Laboratory in the east chamber under the structural test deck. Plan and elevation views of the TMIF are shown in Figures 4.3 and 4.4. The test chamber is 60 ft long, 9 ft wide, and 7 ft high. The TMIF facility consists of four primary components:

1. Missile launcher (cannon)
2. Control panel
3. Reaction frame
4. Timing gate

Table 4.5 Reinforced Masonry Barrier Schedule

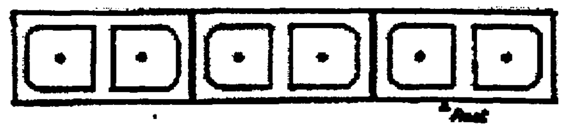
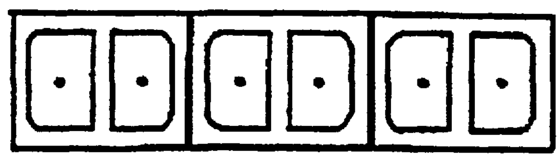
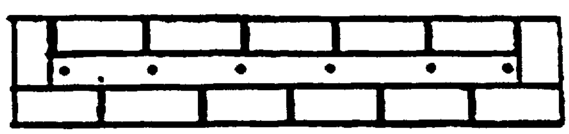
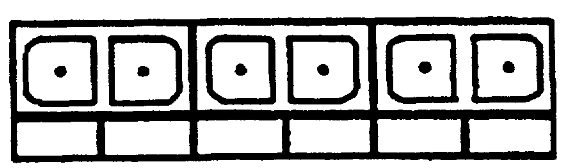
Barrier Description	Barrier X-Sec
CMU-8.1 : *8-in.thick. CMU wall, 48-in. by 48-in.; each cell was grouted and vertically reinforced with # 4 rebar spaced 8-in o.c. Wall was horizontally reinforced with truss ties 16-in. o.c.; missile impact speed: 50 mph*	
CMU-12.1 : *12-in.thick. CMU wall, 48-in. by 48-in.; each cell was grouted and vertically reinforced with # 4 rebar spaced 8-in o.c. Wall was horizontally reinforced with truss ties 16-in. o.c.; missile impact speed: 75 mph*	
CBM-(9.50).1 : *9.50-in.thick. Brick Cavity wall, 52-in. by 52-in.; cavity was grouted and vertically reinforced with # 4 rebar spaced 8-in o.c. Wall was horizontally reinforced with truss ties 16-in. o.c.; missile impact speed: 50 mph*	
CBCMU-12.1 : *12-in.thick. Combination wall, 48-in. by 48-in.; 8-in. thick CMU was grouted and vertically reinforced with # 4 rebar spaced 8-in o.c. A single wythe of brick was attached to the front face. Wall was horizontally reinforced with truss ties 16-in. o.c.; missile impact speed: 50 mph*	

Table 4.6 Reinforcing Arrangement Comparison

Panel Thick	Reinforcing Arrangement	Missile Impact Speed (mph)	Panel Damage Description	Comments
6-in.	**CR-6.1: #3 spaced 9-in. o.c. each way, 1.5-in. from panel front face**	35	0.25-in. penetration; 0.19-in. wide radial cracks on back face, total propagation	Reinforcement in front face reduced penetration depth
	CR-6.2: #3 spaced 12-in. o.c. each way, 1.50-in. from panel back face	36	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Reinforcement in back face reduced radial crack size
	CR-6.3: #4 spaced 9-in. o.c. each way, 1.50-in. from panel back face	37	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Reinforcement in back face reduced radial crack size; closer rebar spacing did not influence damage
8-in.	**CR-8.1: #4 spaced 9-in. o.c. each way, in the middle of panel**	44	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Closer rebar spacing appeared to reduce penetration depth
	CR-8.2: #4 spaced 12-in. o.c. each way, in the middle of panel	44	0.63-in. penetration; 0.09-in. wide radial cracks on back face, total propagation	
	CR-8.3: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face	50	0.69-in. penetration; 0.09-in. wide radial cracks on back face, 3/4 propagation	Double rebar mats prevented total propagation of cracks
9-in.	**CR-9.1: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face**	50	0.44-in. penetration; hairline radial cracks on back face, 1/2 propagation	Double rebar mats again resist crack propagation through panel
	CR-9.2: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face	78	1.50-in. penetration; scabbing, 1.0-in. by 0.50-in. fragments.	Double rebar mats again resist crack propagation through panel
10-in.	**CR-10.1: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face**	74	0.81-in. penetration; hairline radial cracks on back face, 1/2 propagation	Double rebar mats again resist crack propagation through panel

4.4.1 Missile Launcher

The missile launcher (see Figure 4.5) is an air cannon that propels a missile to the desired impact speed. Air pressure is built up in a 60- gallon tank (see Figure 4.6). A 4-in. diameter Schedule 80 Polyvinyl Chloride (PVC) manifold links the air tank to the back end of a 4-in. diameter solid core ball valve (see Figure 4.7). The ball valve rapidly releases the compressed air when the firing mechanism is activated. Attached to the front end of the valve is a 4-in. diameter x 20-ft long PVC pipe, which serves as the cannon barrel. Test missiles are muzzle-loaded into the barrel. The barrel is held by two supports, one at the middle of the barrel and one at the breech end. The breech support is braced against horizontal recoil by three angle struts that run along the floor to the back wall of the chamber. Both barrel supports are also braced against vertical recoil with sand bags.

To accelerate a missile to some desire speed, compressed air in the tank is released by remotely opening the ball valve. The ball valve is opened by a lever arm that is actuated by an air cylinder. A round plywood sabot is attached to the back end of the missile to prevent air from flowing through or around the end of the missile.

4.4.2 Control Panel

The control panel (see Figure 4.8) contains all the instrumentation and controls needed to safely fire missile and measure its impact speed. It is located outside the test chamber in an adjacent cell, well protected from missile impact debris. Along with air pressure control, the panel also controls electrical power for the firing mechanism and two safety releases. The control panel contains the following:

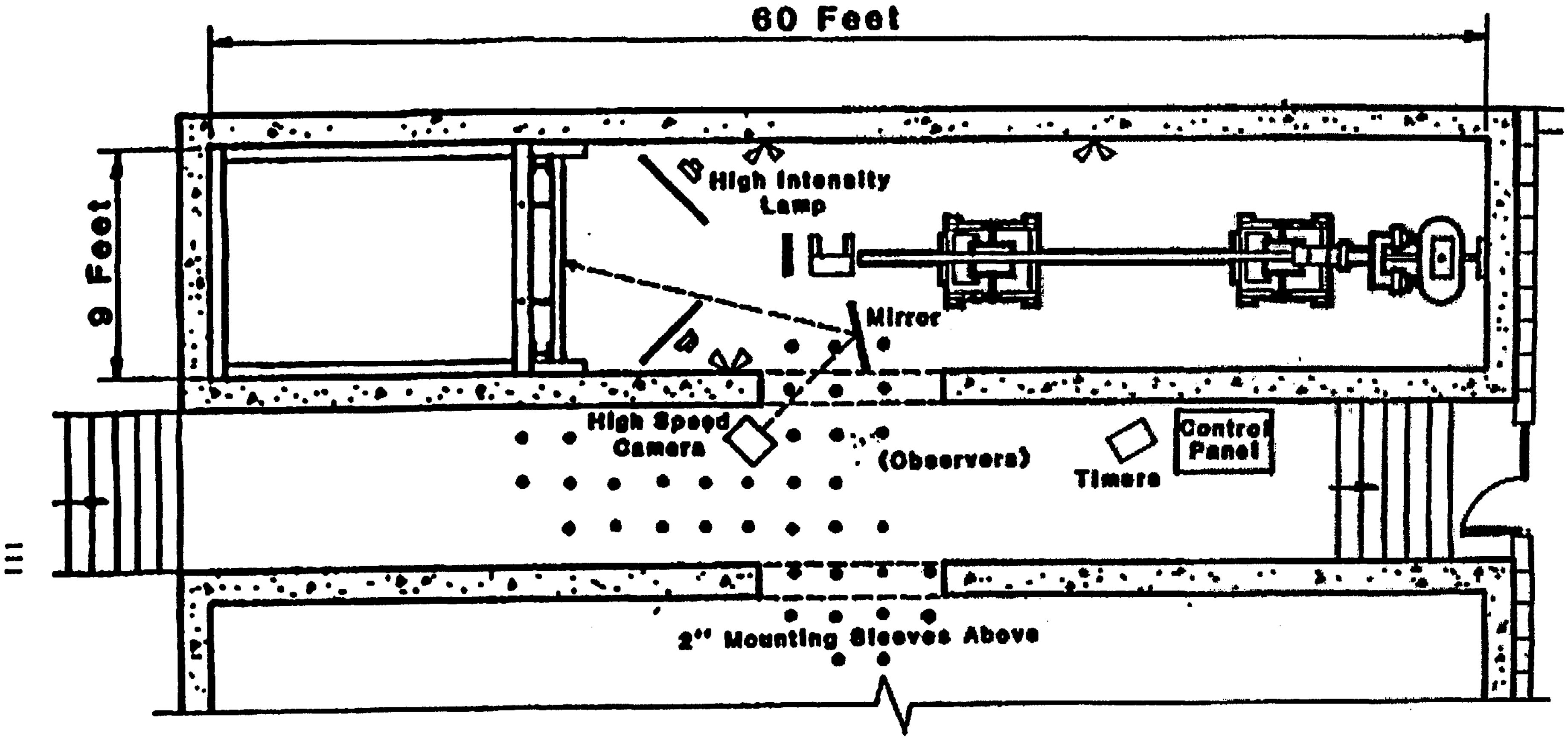
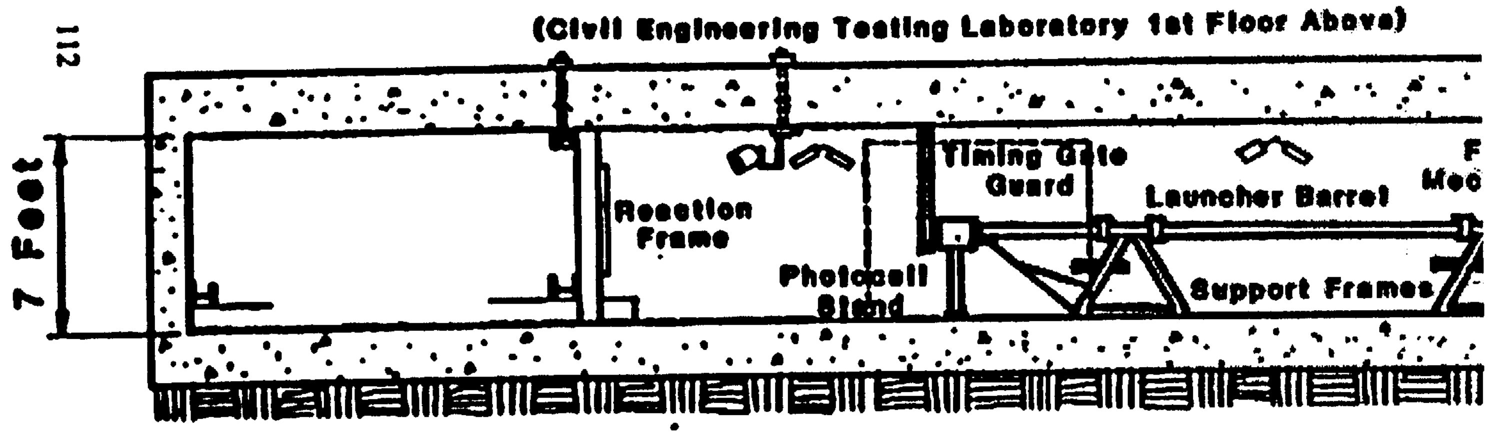


FIGURE 4.3 PLAN VIEW OF MISSILE LAUNCHING FACILITY

FIGURE 4.4 ELEVATION OF MISSILE LAUNCHING FACILITY



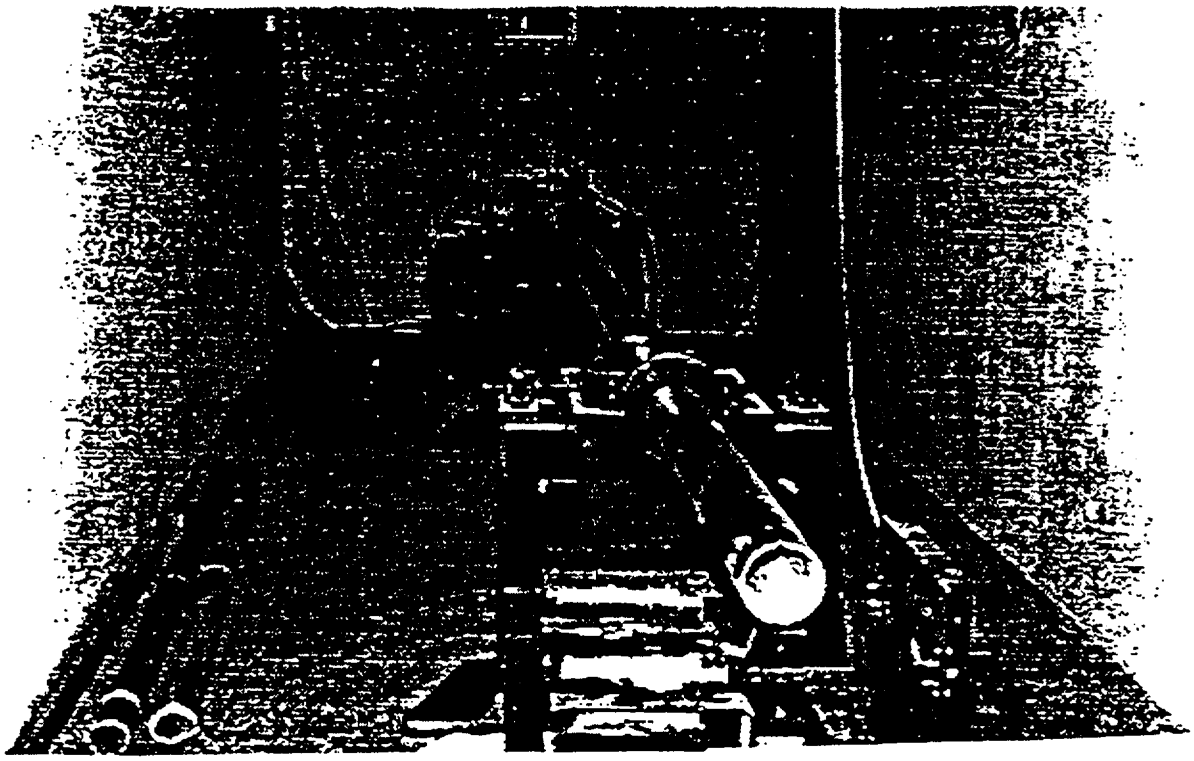


FIGURE 4.5 MISSILE LAUNCHER

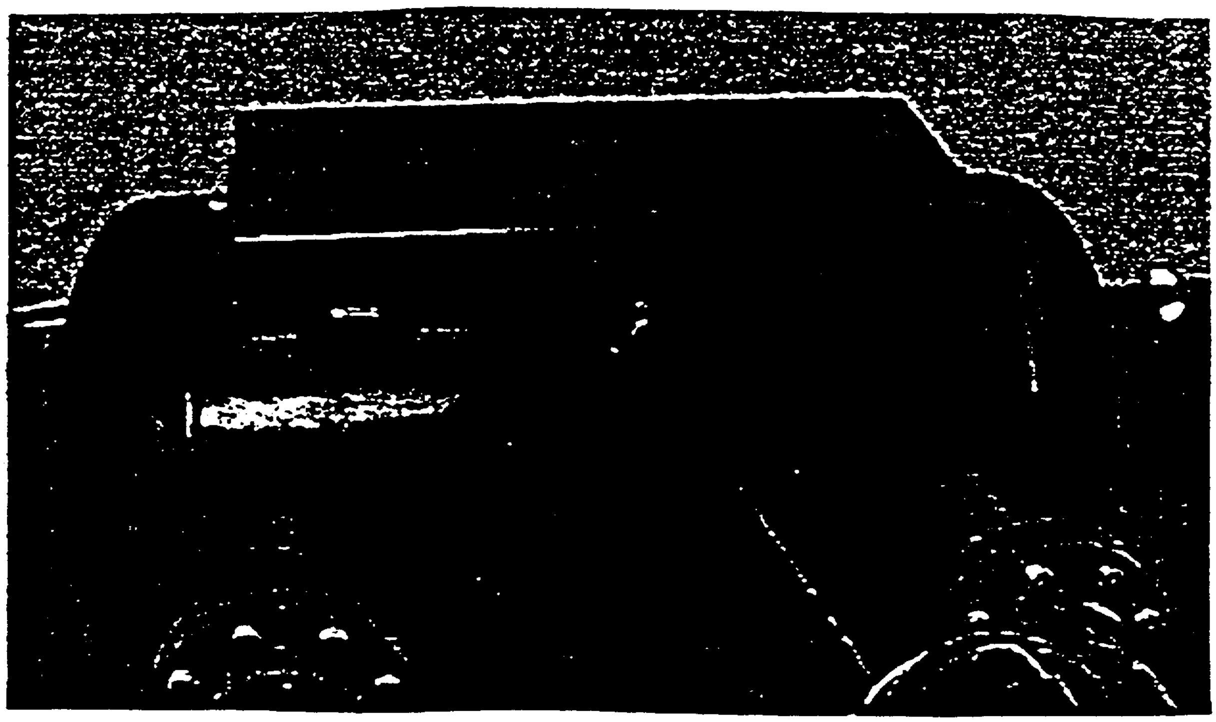


FIGURE 4.6 AIR TANK

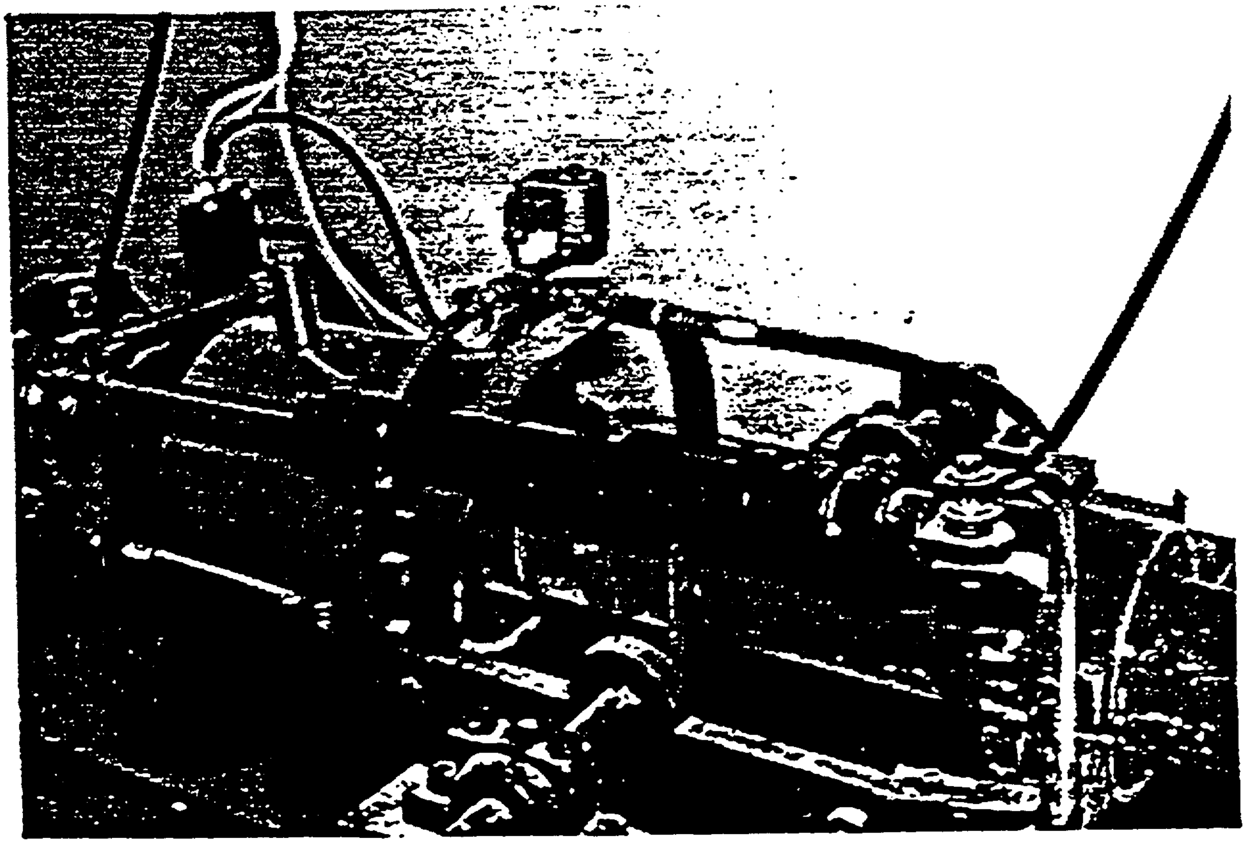


FIGURE 4.7 BALL VALVE ASSEMBLIES

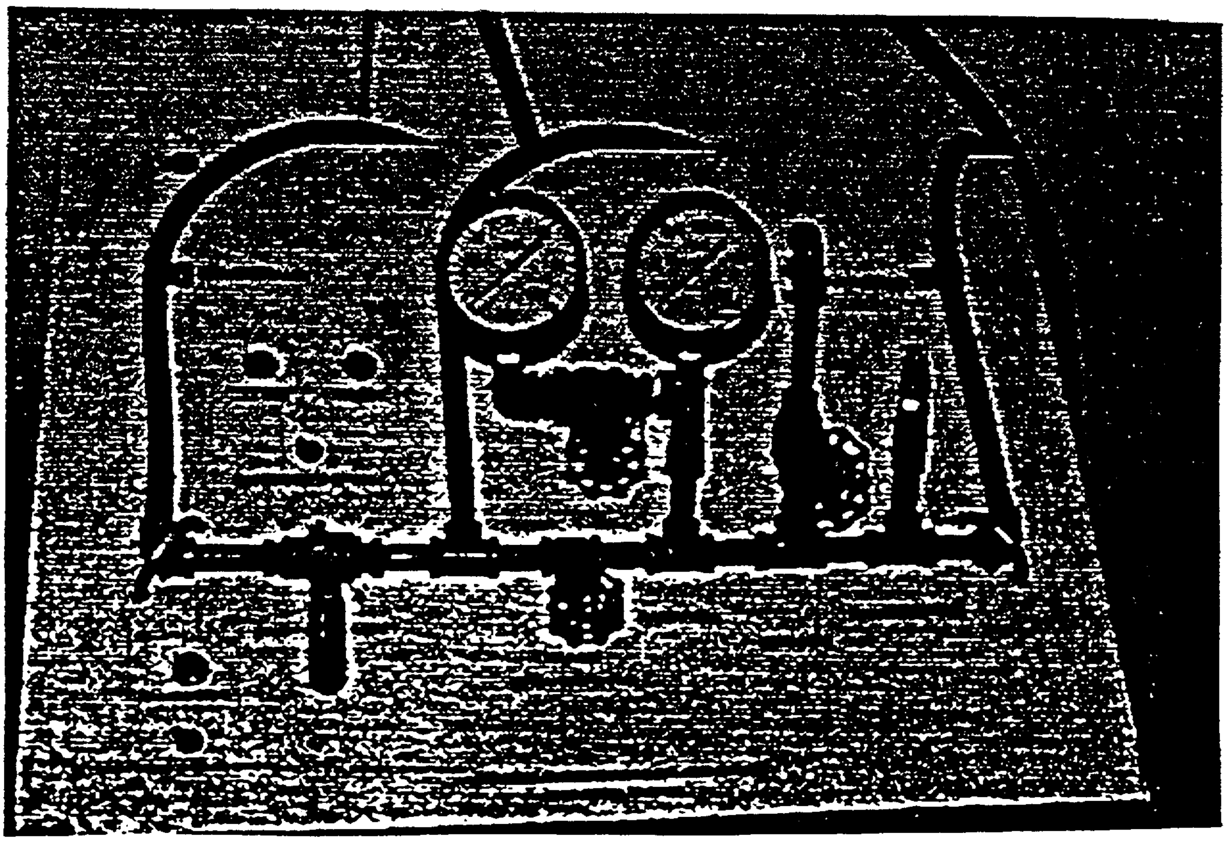


FIGURE 4.8 CONTROL PANEL

1. Valves for pressurizing and releasing pressure in air the tank
2. A "trigger" that remotely opens the valve and "fires" the missile
3. Electrical switches that control a high speed movie camera
4. A pressure release valve
5. Indicator lights that show if the firing sequence was properly executed.

4.4.3 Reaction Frame

A Reaction frame provides rigid support for the test specimens (see Figure 4.9). The vertical members are W8x18 steel wide-flange beams; the horizontal members are W6x30. The base of the frame is supported by steel members that extend to the north end wall of the test cell. The top is fastened by bolts through sleeves in the ceiling. A hand wench attached to the top horizontal beam lifts test specimens for mounting in the reaction frame. A specimen rests on two L2 ½ x 2 ½ - in. angle seats that are welded to the bottom horizontal beams. Four C-clams secure the specimen to the two vertical beams. Once the test panel is in place, the reaction frame provides simple support conditions around the perimeter of the specimen.

4.4.4 Missile Velocity Measurement System

A photoelectric timing gate is used to measure the speed of the missile as its trailing end clears the barrel. At the end of the barrel, two light beams shine on two pairs of photo cells (see Figure 4.10), which are located one foot apart. The light beams are blocked by the missile as it leaves the barrel. When the trailing end of the missile passes the first pair of photo cells, the light beams starts the two independent timers (Figure

4.11). When the end of the missile passes the second pair of photocells, the light beam stops the timer. The resulting measurement in milliseconds is the time for the trailing end of the missile to travel one foot. The reciprocal of this value is the speed of the missile in feet per second which is than be converted to miles per hour. Light emitting diodes on a circuit board indicate light source interruption, indicating that the timing circuits operated properly.

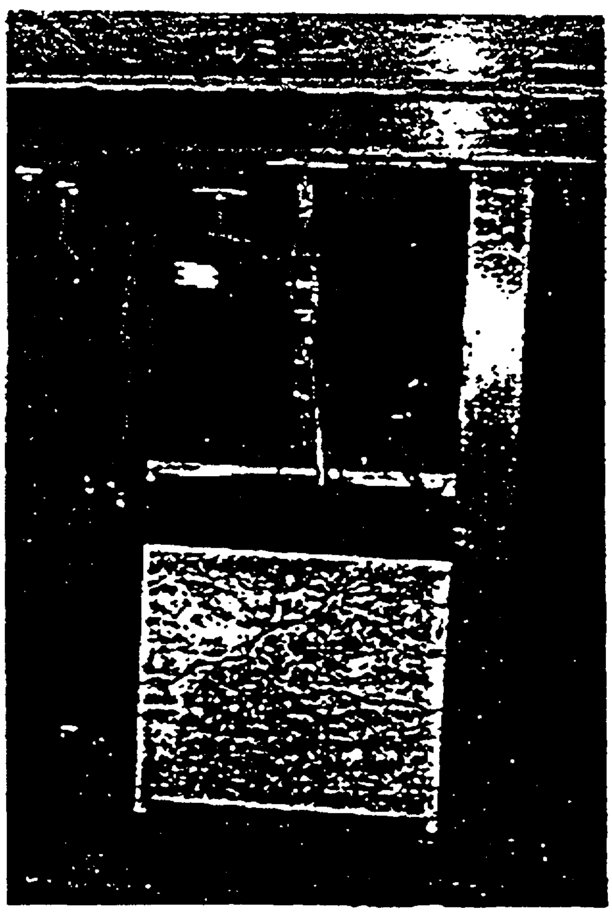


FIGURE 4.9 BACK SIDE OF REACTION FRAME

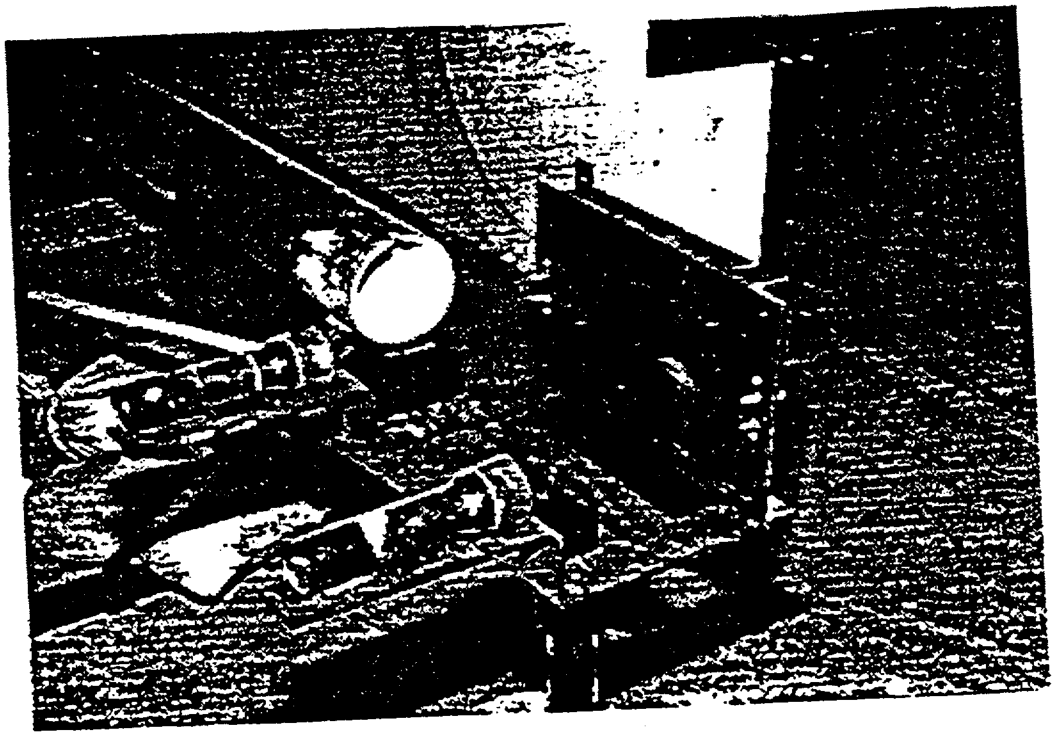


FIGURE 4.10 TIMING GATES

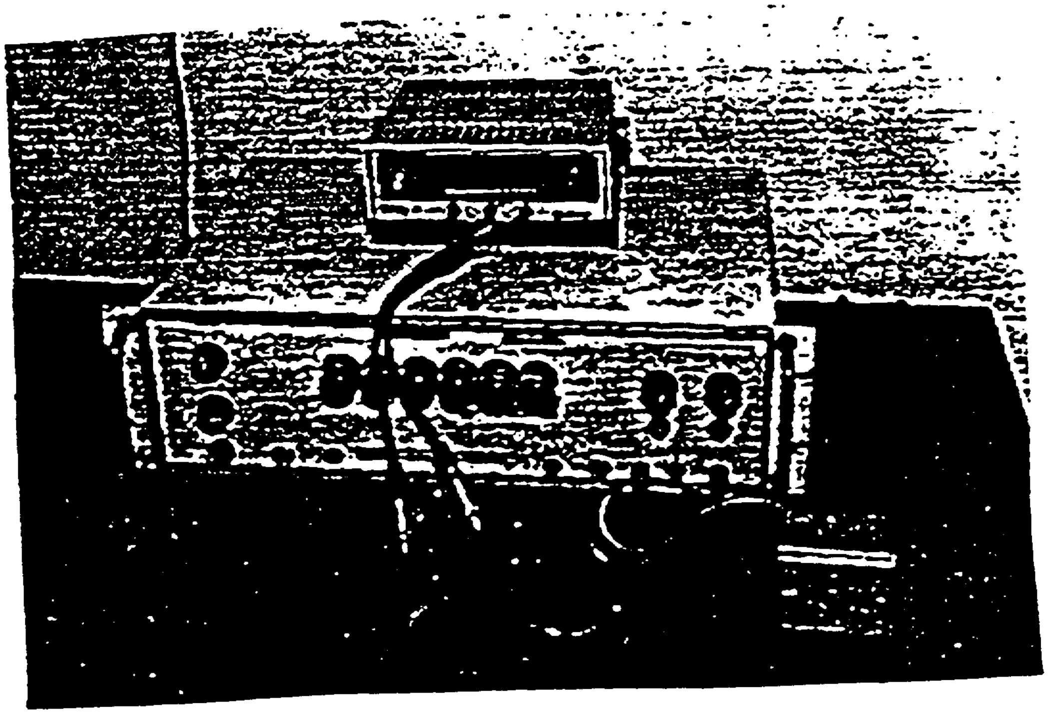


FIGURE 4. 11 TIMERS

The missile speed measuring system is calibrated by connecting an oscilloscope to the photocells. When the missile is fired, the wavelength frequency in milliseconds is compared to the missile speed measuring system's readings. Errors ranged from 0.74 mph at 20 mph missile speed to 1.04 mph at 75 mph missile speed. See Appendix G for calibration test results.

The end of the cannon barrel is located so the missile impacts the test specimen within two to three feet after clearing the barrel. Hence, the missile speeds measured by the timing gate are essentially the impact speed of the missile.

4.5 Material Properties and Procedures

4.5.1 Construction of Test Panels

Eight 39-in.x39-in. reinforced concrete panels were cast in the Civil Engineering Testing lab. Grade 40 reinforcing bars were placed in each form; concrete was placed from the same batch mix to ensure that the concrete properties in all of the panels were the same. The concrete was obtained from a commercial ready-mix plant and had a target compressive strength of 4000 psi. After curing for 28 days in a 70 °F environment, the concrete slabs were lowered to the basement and moved one at a time into the test chamber.

The concrete block (CMU) and clay brick masonry wall sections were built in the cell adjacent to the test chamber by a journeyman mason. The CMU blocks and the clay bricks were laid in a running bond pattern with Type S mortar. Grade 40 reinforcing bars and grout meeting ASTM 476 specifications were placed in the wall sections. The panels were allowed to cure for at least seven days before testing. For both the concrete and masonry wall sections, standard construction practices were followed. Care was taken not to subject the panels to excessive loads during the movement. Samples of concrete, mortar, and grout were tested in the Texas Tech Civil Engineering Testing Laboratory. ASTM testing procedures were followed. Properties of the CMU block and clay bricks were obtained from tests performed on the material supplied.

4.5.2 Material Properties

The ready-mix concrete used in the construction of eight concrete test panels had a target compressive strength of 4000 psi 28 days. The mix design consisted of Type I Portland cement, sand, gravel (approximately 1.0-in. diameter), water, and Pozz LL761 and MBVR admixtures.

The masonry test panels consisted of CMUs, clay brick, mortar, grout, and rebar. The CMU widths were a nominal 8 in. and 12 in. The standard clay bricks were 2.25 in. high by 3.625 in. wide by 7.75 in. long. The Type S mortar contained specific volumes of Type III Portland cement, sand, hydrated lime, and water. The grout contained specific volumes of Type I Portland cement with high early strength admixture, sand, pea gravel, and water.

The 3-in. diameter pipe missiles were approximately 10 ft long. The Schedule 40 pipe weighs 7.58 lbs/ft. The pipe had an outside diameter of 3.50in., an inside diameter of 3.07 in., and a cross sectional area of 2.23 in.^{2}. A pipe missile was not used more than three times became after each test, the impacted end was sawed to remove deformed material.

4.5.3 Testing Procedures

An established testing procedure was followed to ensure accurate and repeatable test results. The test procedure can be divided into three main activities:

1. Prelaunch
2. Launch
3. Post launch

Detail description of the procedures are presented below.

4.5.4 Prelaunch

To start, a barrier is selected and mounted on the reaction frame, with four C-clams. The missile is weighed and a plywood sabot is attached to the end of the pipe. The missile impact speed is achieved by pressuring the air tank to a predetermined value. An air pressure versus missile velocity curve gives the appropriate air tank pressure. This curve was acquired by making a number of test shots at different pressures. Experience with this approach allows the missile to be fired within ± 2 mph of the desired impact velocity. Still photographs of the panels are taken before the test. The VHS video camera is set up along with a high speed movie camera.. Timing gate light sources, timers, and circuit boards are turned on to activate the missile velocity measurement system. The timers are zeroed and the circuit board is reset. Finally, the missile is loaded into the barrel.

4.5.5 Launch

To initiate the launch sequence the bleeder valve is closed and the air tank pressure control valve is opened. During pressurization, the video camera is turned on. The air tank control valve is closed when desired pressure is reached. The system is now ready to fire. Three seconds before firing, the high-speed camera is turned on. The missile is launched by quickly rotating the trigger control, which opens the valve between the air tank and the barrel. The released air pressure pushes against the sabot as the missile accelerates through the 20 ft long barrel. The timing gate measures the missile speed as the trailing end of the missile clears barrel. After impact, the trigger is returned to the closed position and the bleeder valve is opened to release any pressure that remains in the air tank.

4.5.6 Post Launch

The timers are read and their values recorded. The power to the microswitch is also turned off. The operator then enters the chamber and resets the firing mechanism valve to the closed position. Still photographs and video footage of specimen are obtained. The speed of the missile is obtained using the average of the two timer readings and converting to miles per hour. Crack patterns, penetration depth, the debris shape and size, and other damage characteristics are recorded in detail on the test data sheet. The missile launching facility is then inspected for damage and the debris from the test is cleaned up.

4.5.7 Data Collection

All data associated with an impact test are recorded on a test data sheet. These sheets are presented in Appendix C. Test data sheet information includes panel characteristics, missile characteristics, launch data, impact data, and other forms of documentation. Panel characteristics, include size, composition, strength, and age of the panel. The launch data include air tank pressure readings, missile velocity, and any additional comments made about the launch. Impact data consists of information on spall, penetration, scabbing, or perforation, along with information and comments concerning damage to the panels. Since the primary objective of these tests was to identify panels that would survive the missile impact, strains, accelerations, and contact pressures were not measured. The final documentation on the test data sheet describes the photographs, video and high speed movies that were obtained as part of the test.

Video and high speed movies record the visual aspects of the impact tests. The video camera records every impact test in "real time," while the high speed movie camera records the impact in extremely slow motion. The 16-mm high speed camera, called a Fastax camera, operates at 18,000 frames per minute (a shutter speed of 1/3000 sec.). Minute details of missile/barrier interaction during the impact can be observed in the high speed films.

4.5.8 Quality Assurance

A pre-planned program of quality assurance (QA) was developed as part of the test program. Great care was taken in the construction of the concrete and masonry panels. Where applicable, ASTM test procedures were followed to obtain the material properties. The panels were carefully mounted on the reaction frame to assure uniform support around all four sides of the test specimen. The timing system used to measure the impact velocity of the missile was calibrated prior to conducting the test series. Each experiment was meticulously recorded in the form of physical measurements, photographs, videos, and highspeed movies. All tests were witnessed and certified by the laboratory supervisor. A general certification of the test data is found in Appendix C.

4.6 Test Results

Fourteen impact tests were conducted on the twelve different test panels. Careful examination of each test panel revealed the extent of damage and the panel's resistance to impact. The effects of the various rebar patterns in the reinforced concrete panels were noted. From results of these tests, those panel configurations that satisfy the missile criteria of DOE STD 1020-94 are identified. These panel recommendations are presented in Section 4.7.

4.6.1 6-In. Reinforced Concrete Slabs

Three 6-in. reinforced concrete panels were designed and constructed to resist the 35 mph vertical impact speed of the steel pipe missiles specified by DOE STD 1020-94. In addition, each slab contained a different reinforcing arrangement to determine the effect, if any, on impact resistance.

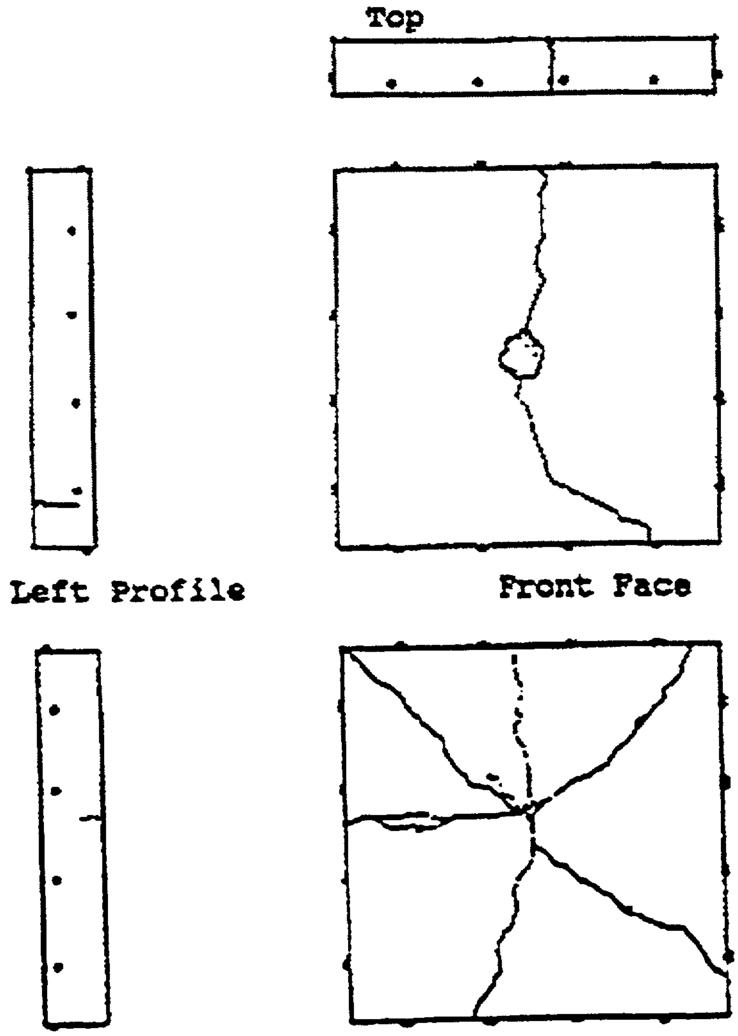
All three slabs successfully withstood the impact of the pipe missile traveling at approximately 36 mph. The missile struck near the center of each panel at a point between the reinforcing bars. The back face of each panel remained intact with no scabbing. Only minor damage was inflicted on the slabs. Radical cracks were observed on the back of the panel. Figures 4.12 through 4.17 show the results of the impact tests on the 6-in. concrete panels.

Minor damage included pipe penetration of the front faces Panel RC-6.1, with reinforcement 1.5 in. from the front face, had a 0.25-in. depth of missile penetration. The other two panels, which had their reinforcement 1.5 in. from the back face, both had a 0.38-in. depth of penetration on the front face.

All three panels had radial tensile cracks on their back face. Not all of the radial cracks propagated through the panel thickness. The vertical and horizontal cracks tended to pass completely through the panel thickness. Crack propagation was determined by tracing the crack continuously from front face to the back face. The fact that CR-6.1 had a larger tensile cracks than the other two panels could be due to the reinforcement being placed near the front face in CR-6.1. Since the concrete had no steel near the back face, the impact caused larger cracks on the back face of CR-6.1, as opposed to the other two panels that did not have steel near the back face. The closer spacing of smaller bars in CR-6.3 (#3's, 6 in. o.c.) did not appear to make a difference in crack pattern when compared to CR-6.2(#4's,12 in. o.c). The percent steel in the two slabs was the same.

4.6.2 Eight -In. Reinforced Concrete Panels

Three 8-in. reinforced concrete panels were designed and constructed to resist the 50 mph impact of the steel pipe missile as required by DOE STD 1020-94. Each 8-in. panel had different rebar bar patterns.



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
6-in. slab with #3's 9-in. o.c. each way, 1.5-in. from front face.	35	• 0.25 in. penetration • Radial cracks with a 0.19 in. maximum width of cracks propagated through slab

FIGURE 4.12 CR-6.1 DATA

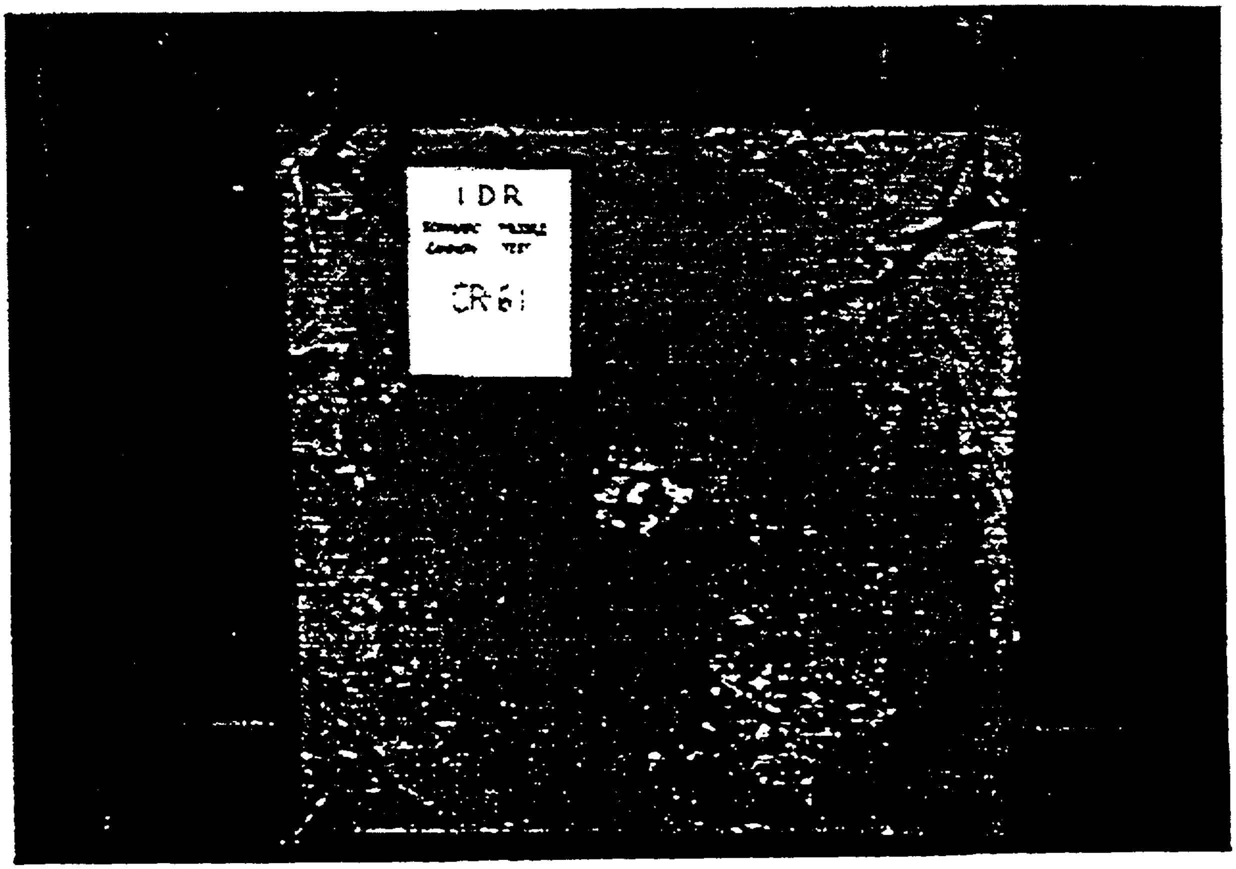


FIGURE 4.13a FRONT FACE OF CR-6.1

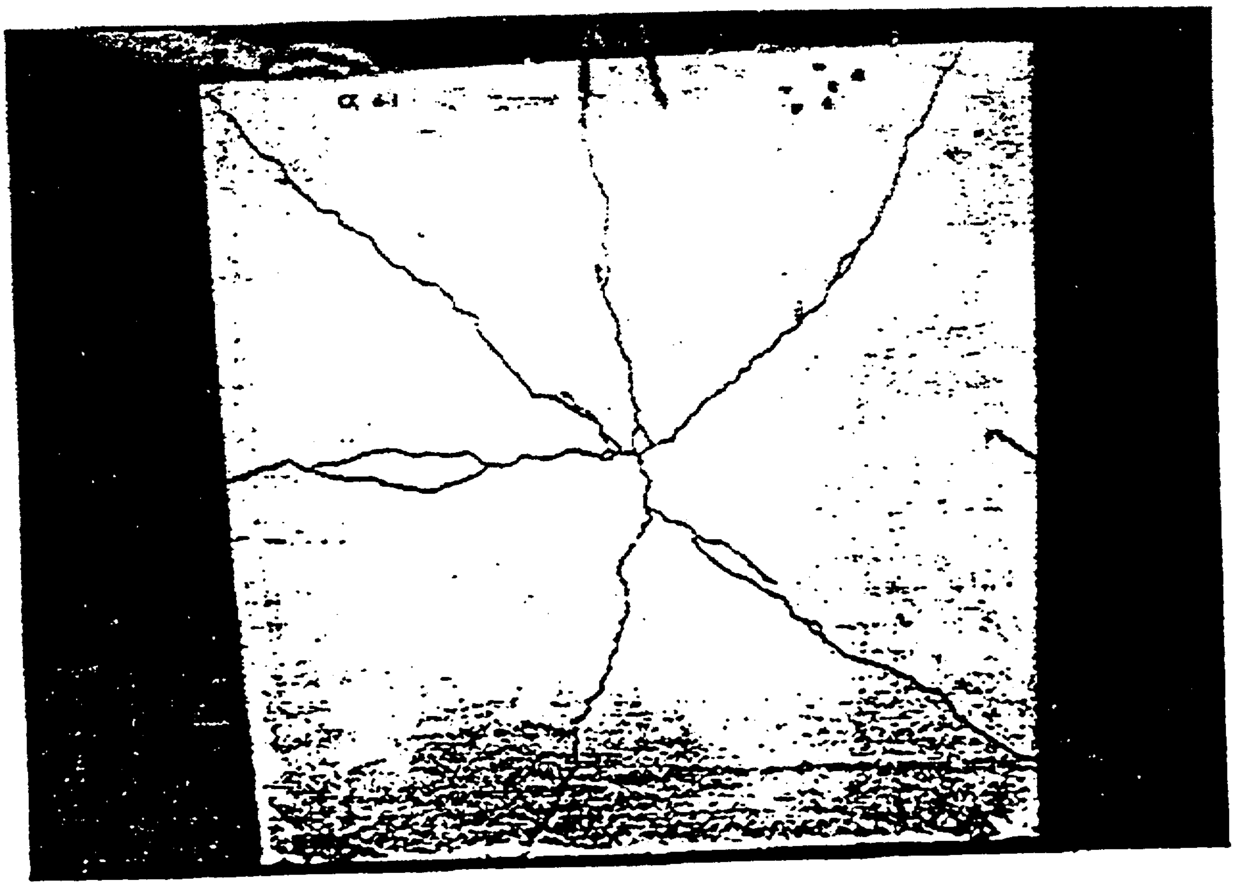
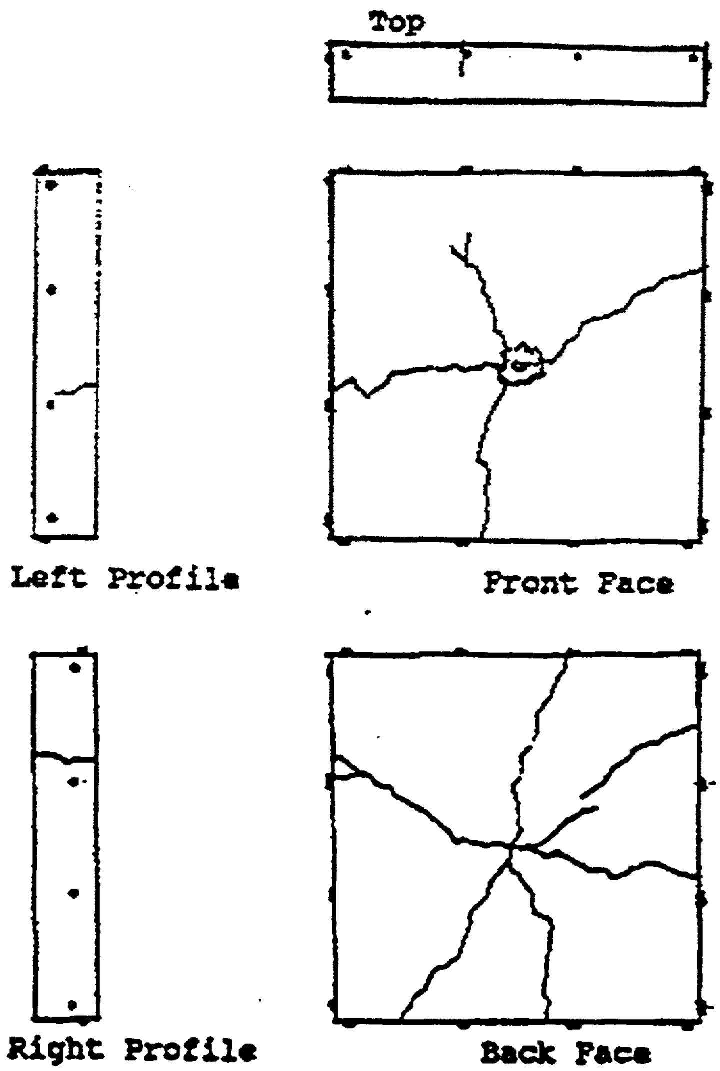


FIGURE 4.13b BACK FACE OF CR-6.1



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
6-in. slab with #4's 12-in. o.c. each way, 1.5-in. from back face.	36	• 0.38 in. penetration • Radial cracks with a 0.06 in. maximum width of cracks propagated through slab

FIGURE 4.14 CR-6.2 DATA

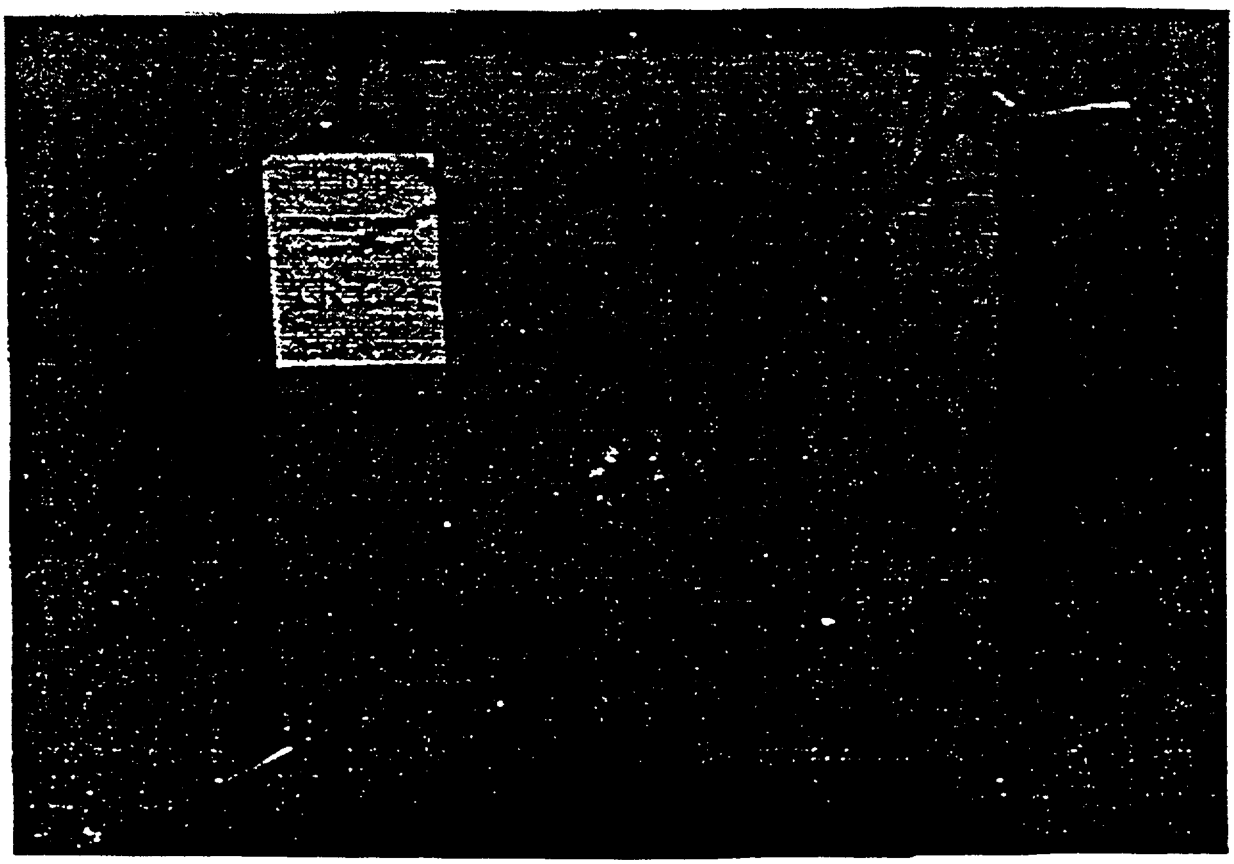


FIGURE 4.15a FRONT FACE OF CR-6.2

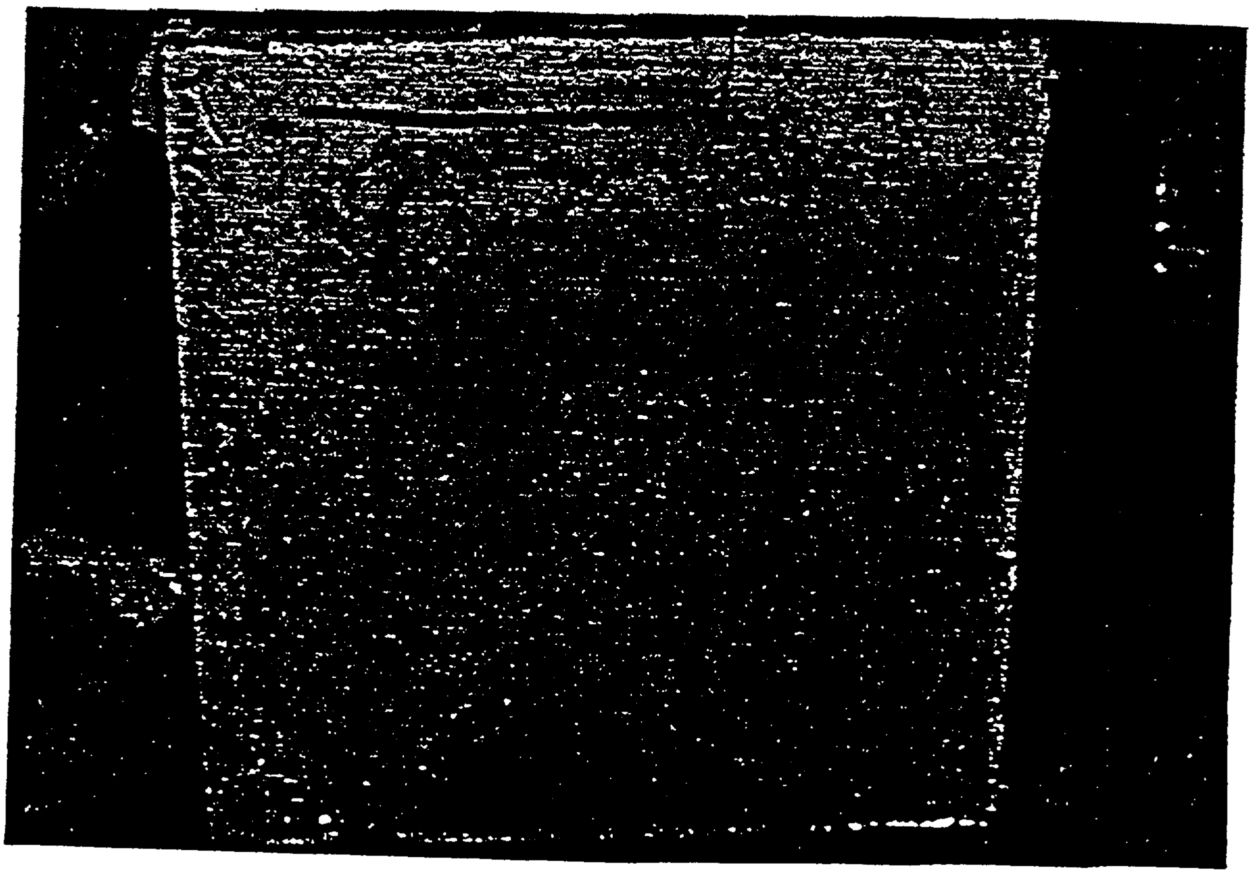
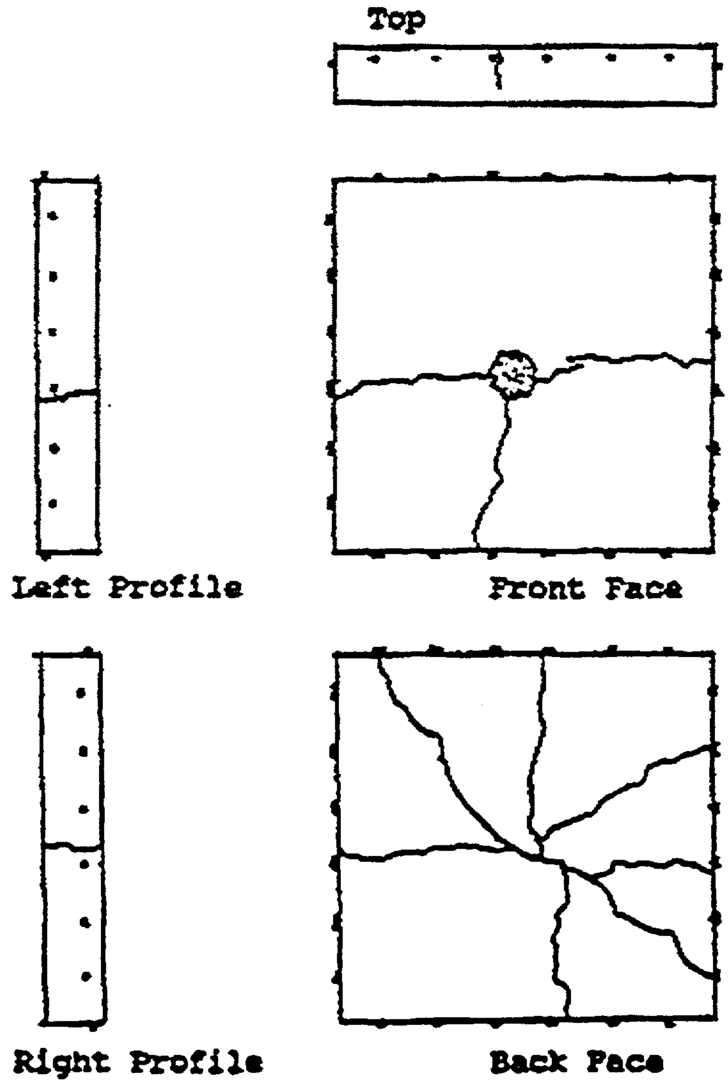


FIGURE 4.15b BACK FACE OF CR-6.2



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
6-in. slab with #3's 6-in. o.c. each way, 1.5-in. from back face.	37	• 0.38 in. penetration • Radial cracks with a 0.06 in. maximum width of cracks propagated through slab

FIGURE 4.16 CR-6.3 DATA

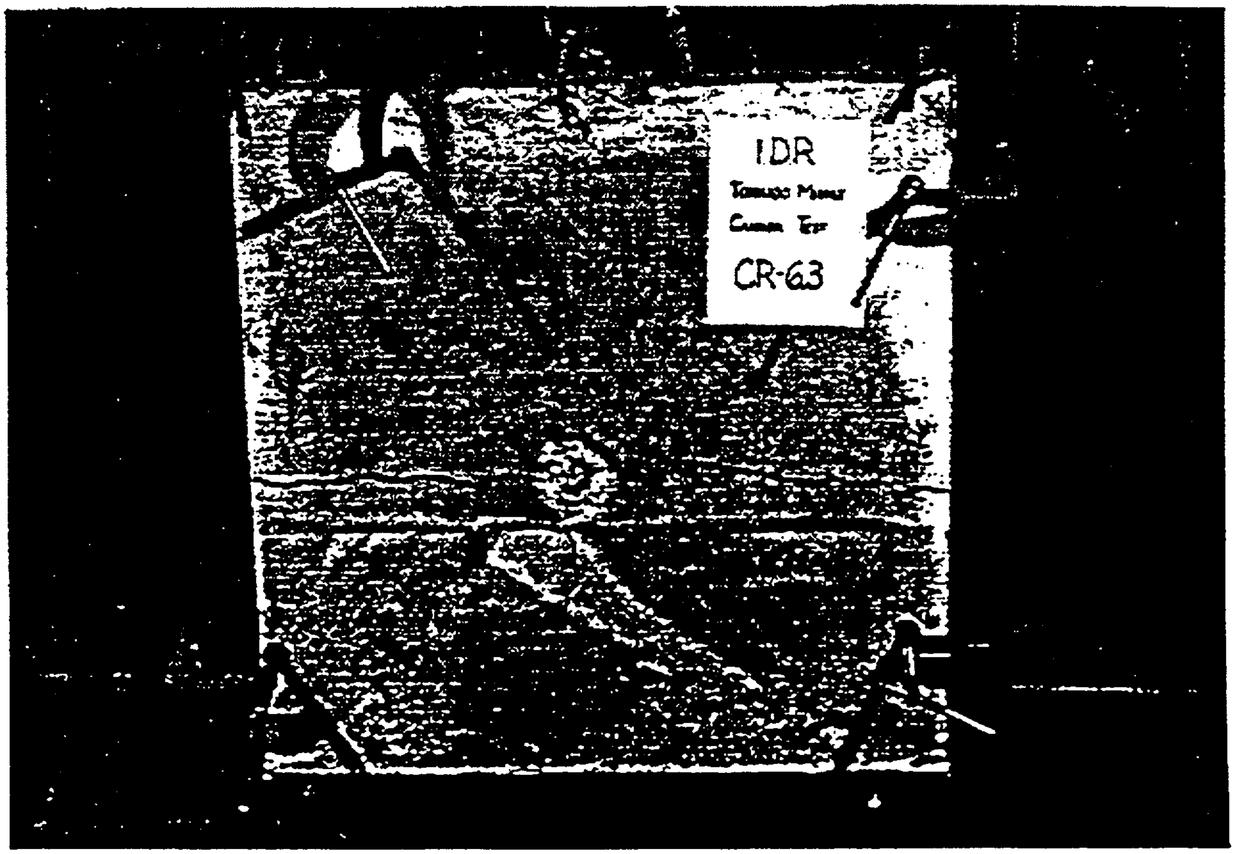


FIGURE 4.17a. FRONT FACE OF CR-6.3

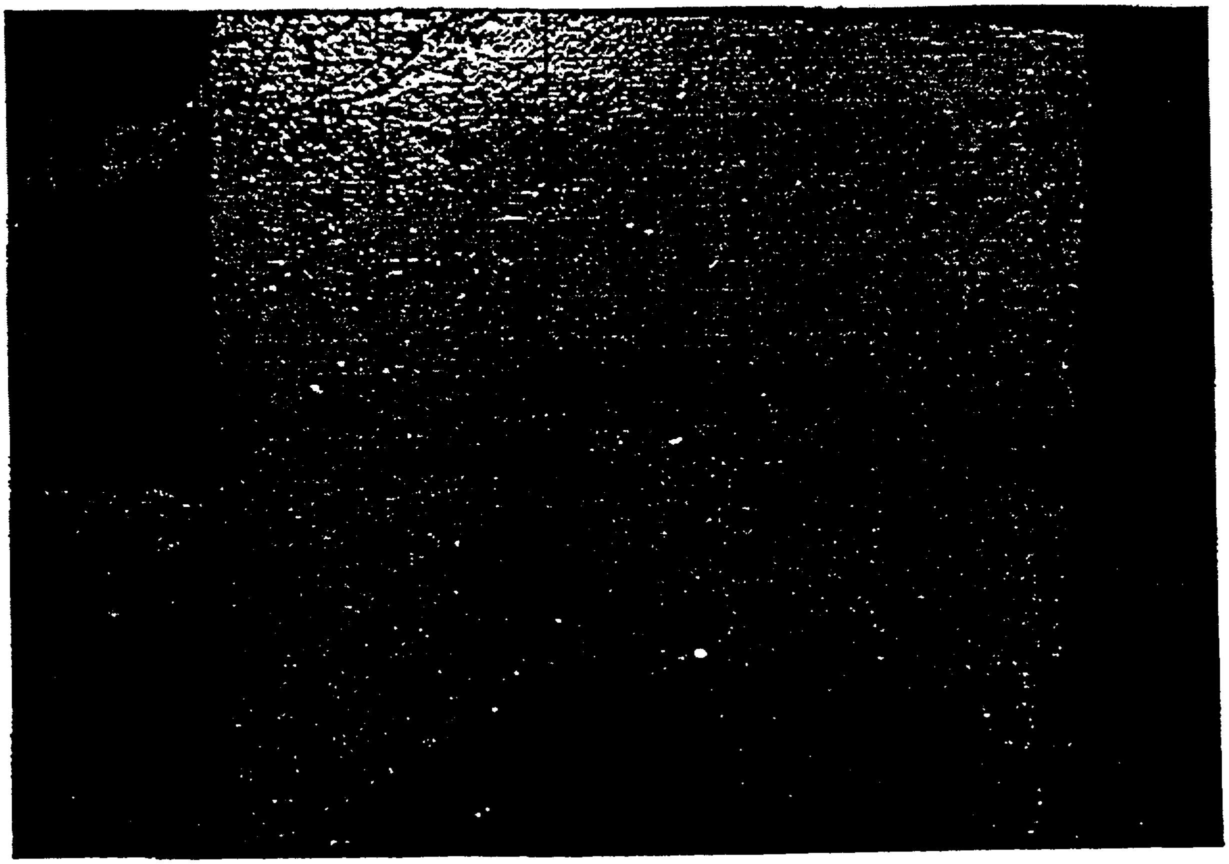


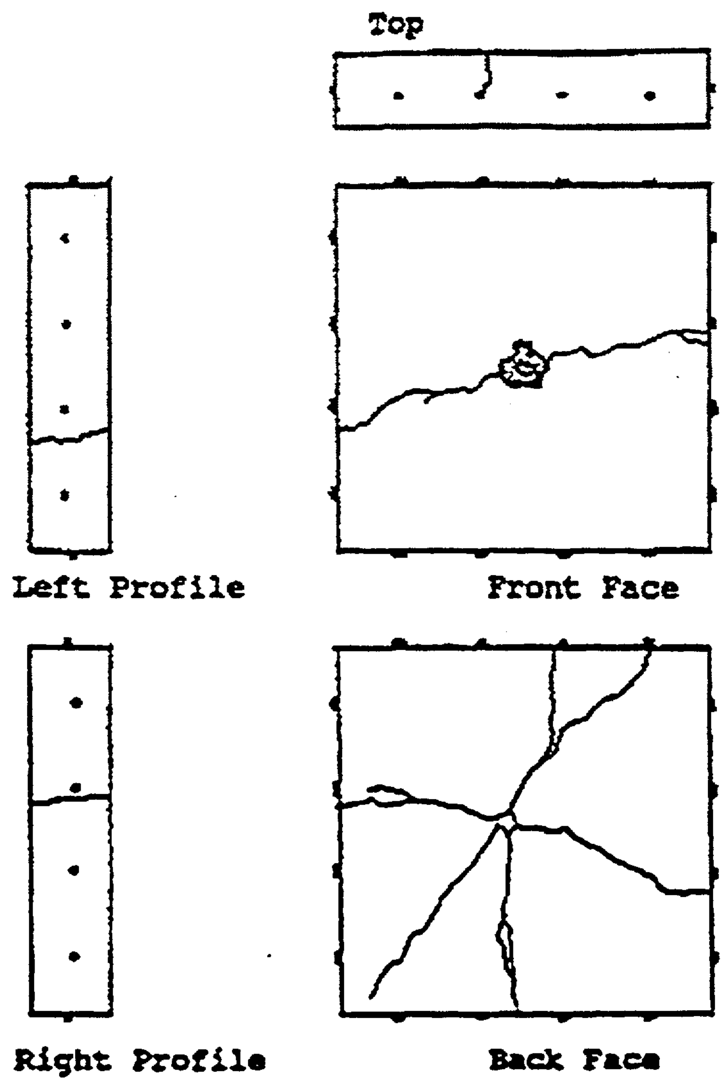
FIGURE 4.17b. BACK FACE OF CR-6.3

All three 8-in. panels successfully resisted impact of the pipe missiles without back face scabbing. The impact speed of the first two panels tested fell slightly below the targeted speed of 50 mph. Panel RC-8.3 was impacted at a slightly larger speed (50 mph) than other two (44 mph). The results of the missile impacts on the 8-in. panels are shown in Figures 4.18 through 4.23. Each panel exhibited a penetration crater on the front face. Radial cracks were found on the back face of each panel due to tensile stresses set up in the panels. These cracks propagated through the thicknesses of panels CR-8.1 and CR-8.2, but cracking in CR-8.3 only propagated three quarters of the way through its thickness because of the reinforcing near the front face. The maximum crack width was about the same in all three panels.

CR-8.1 appeared to resist impact slightly better than CR-8.2 because of the closer steel spacing. CR-8.3 (reinforcement placed 1.5 in. from each face) had a larger penetration depth but no cracks on the front face. The larger penetration depth was likely due to the higher impact speed. The absence of cracks on the front face was due to the presence of rebar near the front face. Thus, the reinforcing pattern in CR-8.3 appears to be the best of the three.

4.6.3 Nine-In. Reinforced Concrete Panels

The 9-in. (Figure 4.24) panel was first impacted at 50 mph (CR-9.1) in order to compare results with the 8-in. panel (CR-8.3). At 50 mph, the impact on CR-9.1 produced a 0.44 in. penetration on the front face and hairline radial tensile cracks on the back face that only propagated halfway through thickness. With this small amount damage, it was decided the impact the 9-in. panel a second time at 75 mph.



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
8-in. slab with #4's 9-in. o.c. each way, placed in the middle of slab.	44	• 0.38 in. penetration • Radial cracks with a 0.06 in. maximum width of cracks propagated through slab

FIGURE 4.18 CR-8.1 DATA

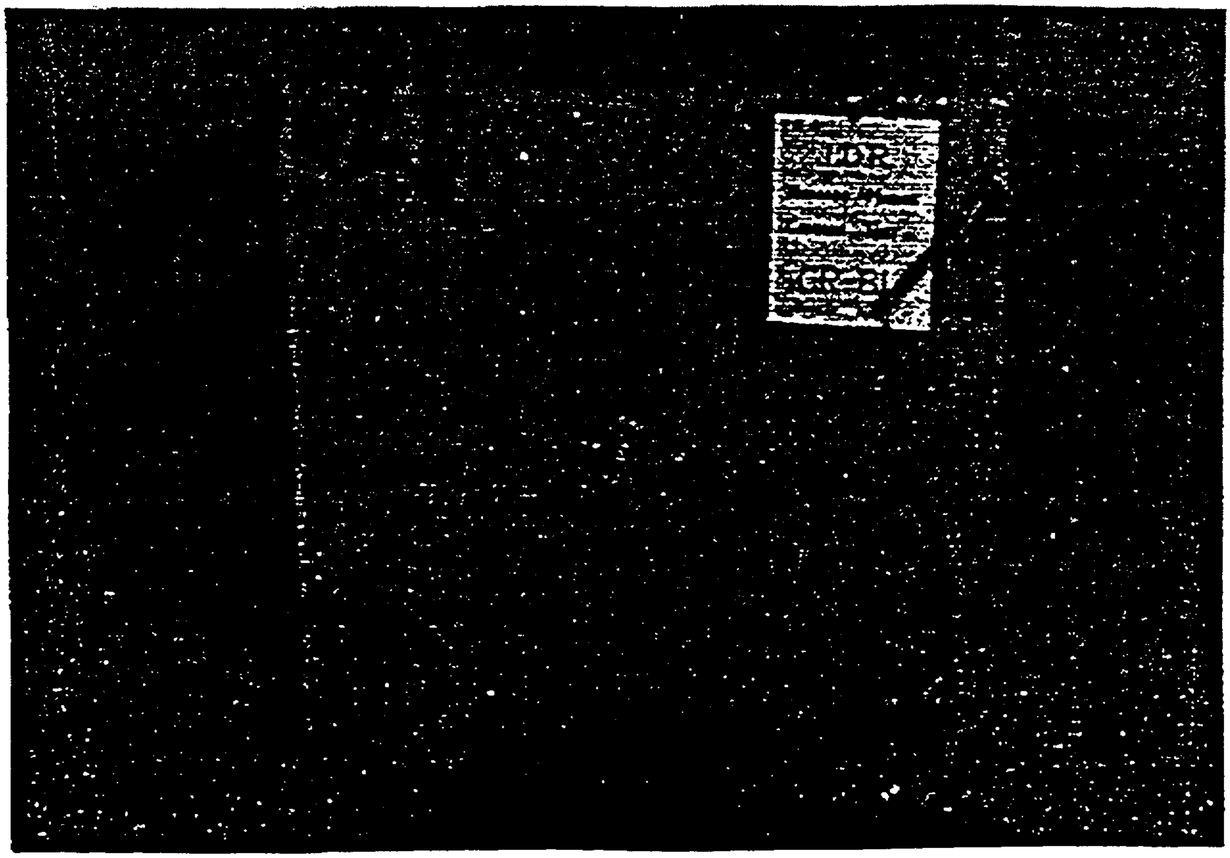


FIGURE 4.19a. FRONT FACE OF CR-8.1

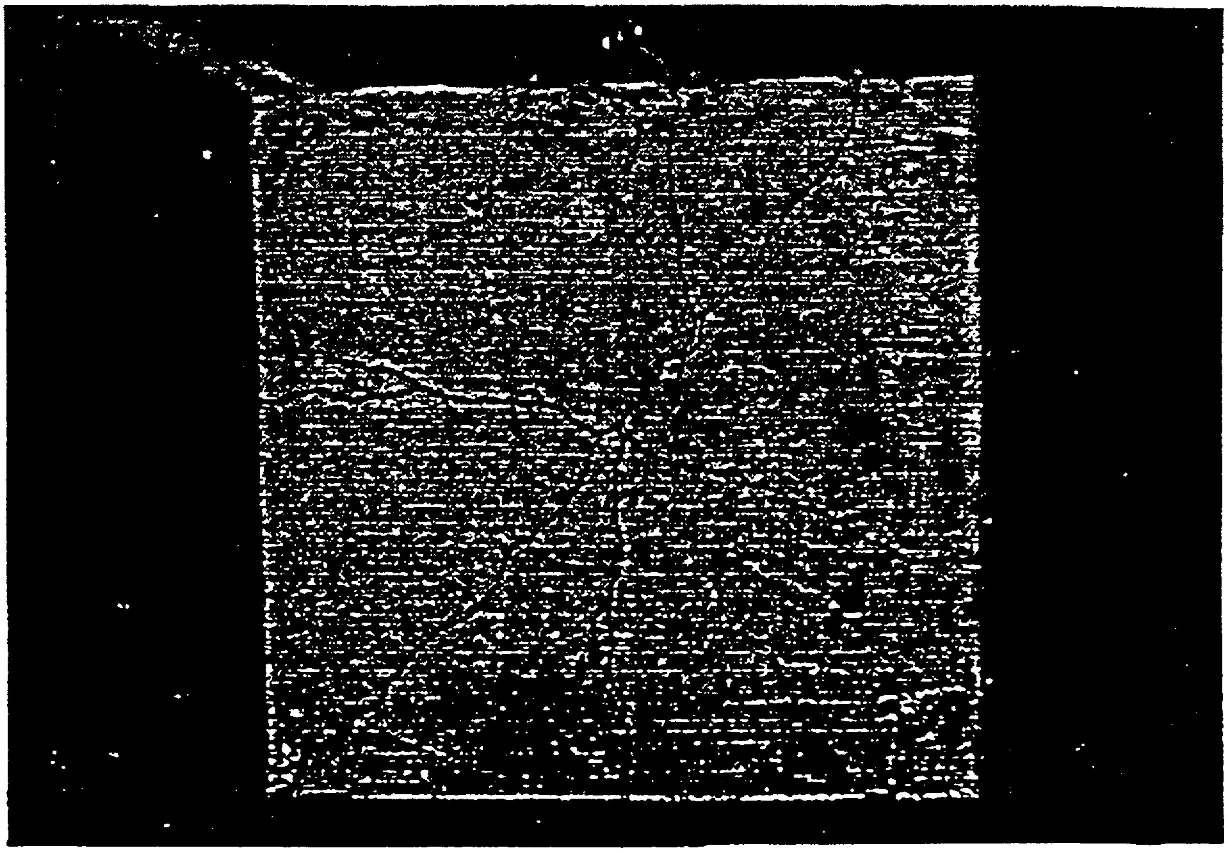
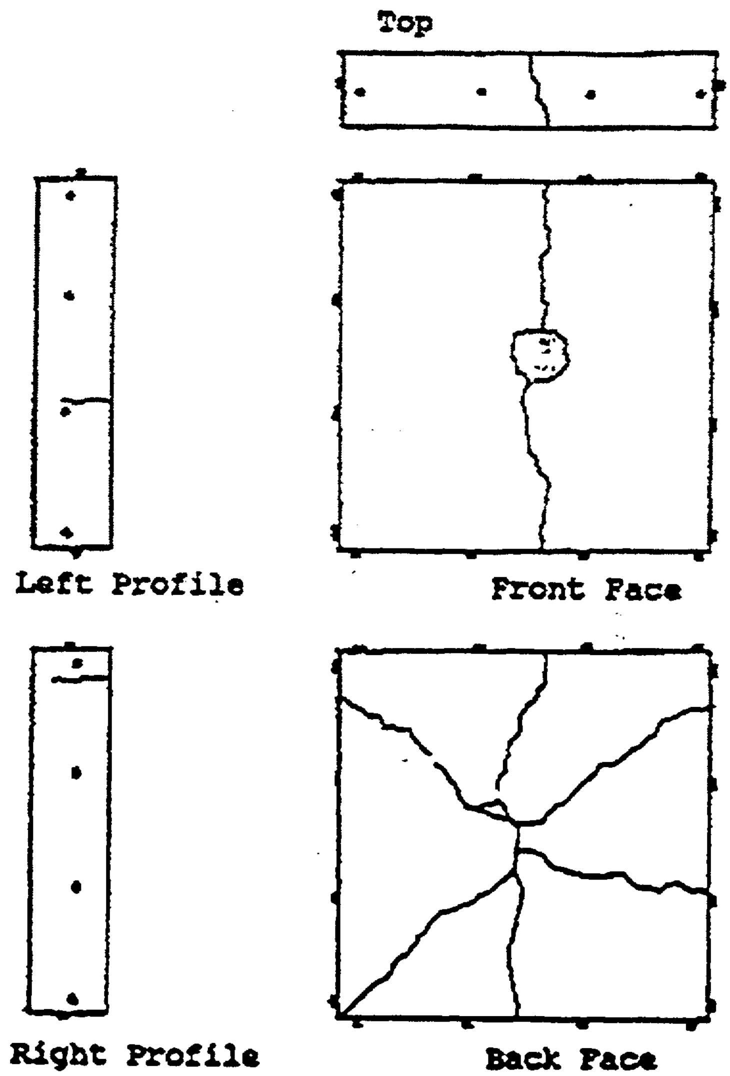


FIGURE 4.19b BACK FACE OF CR-8.1



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
8-in. slab with #4's 12-in. o.c. each way, placed in the middle of slab.	44	• 0.63 in. penetration • Radial cracks with a 0.06 in. maximum width of cracks propagated through slab

FIGURE 4.20 CR-8.2 DATA

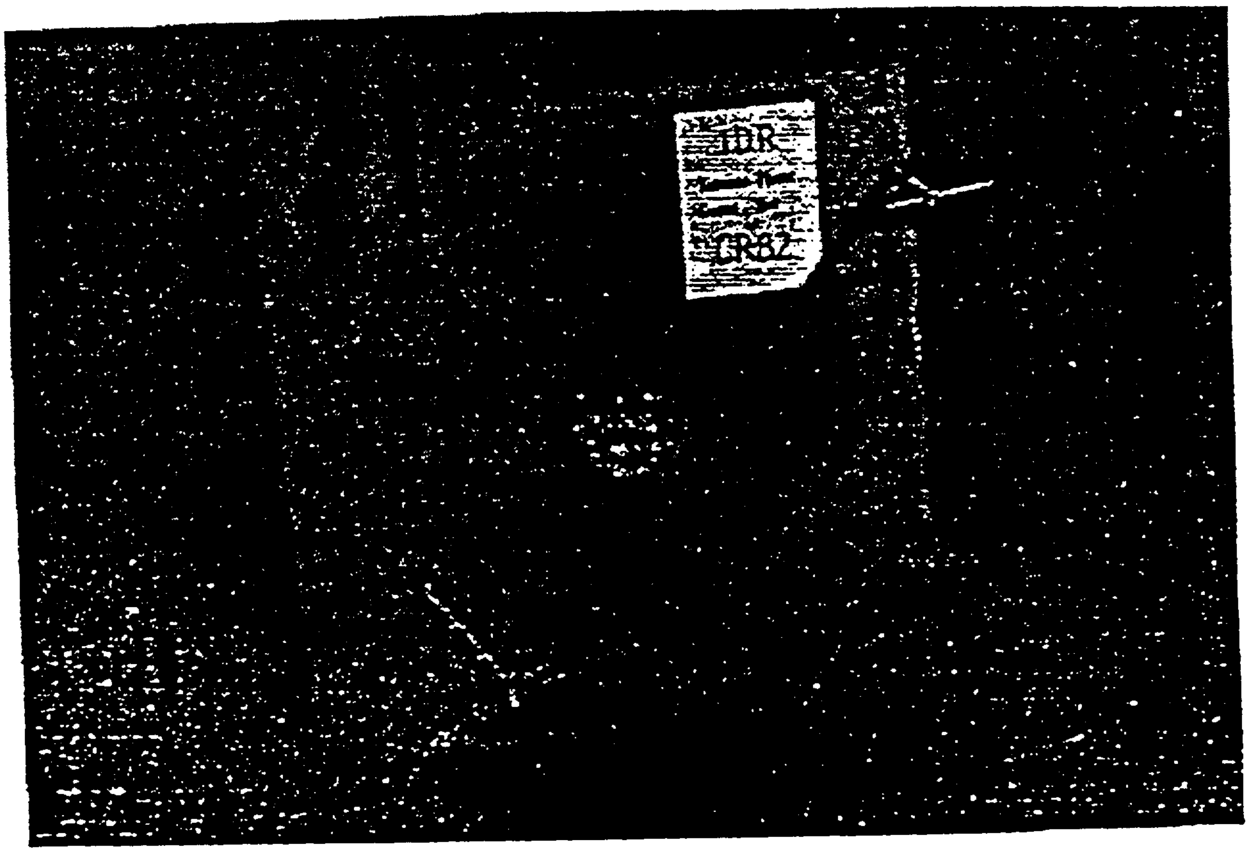


FIGURE 4.21a. FRONT FACE OF CR-8.2

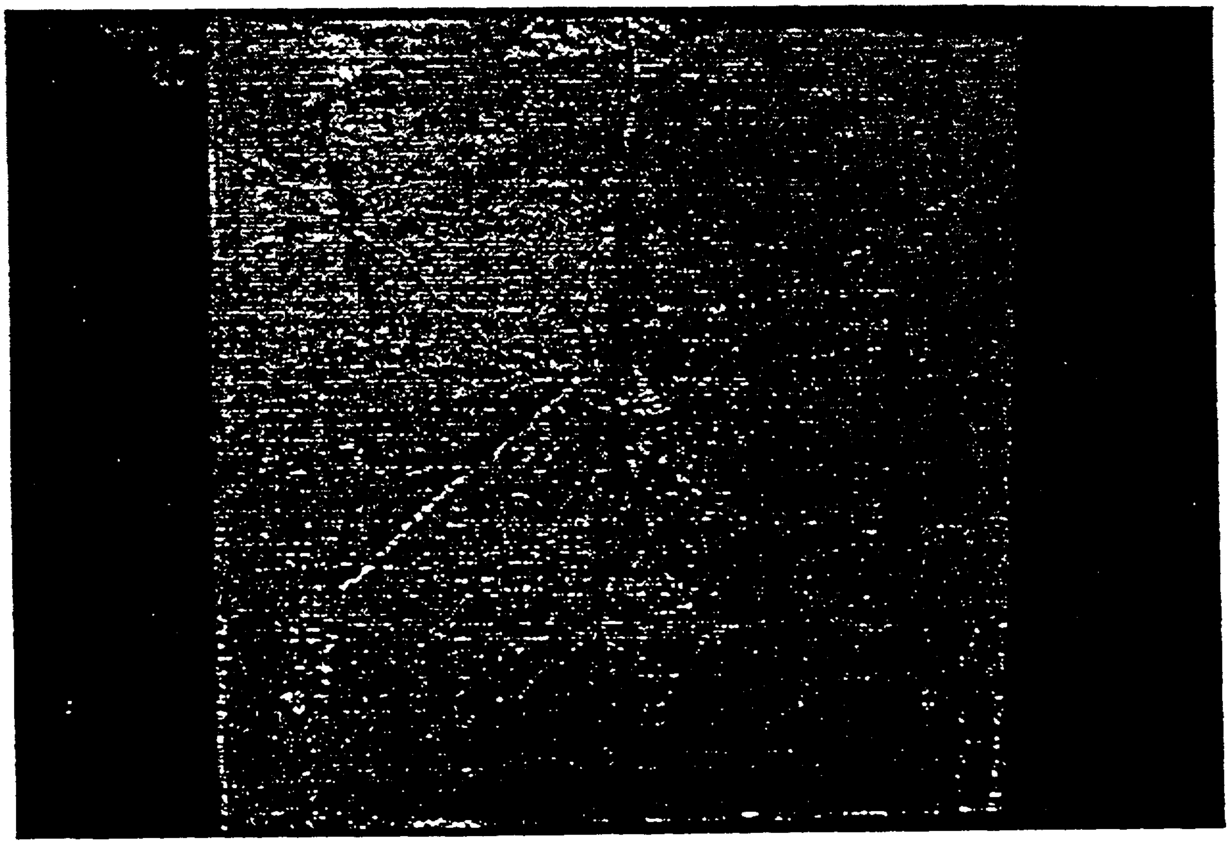
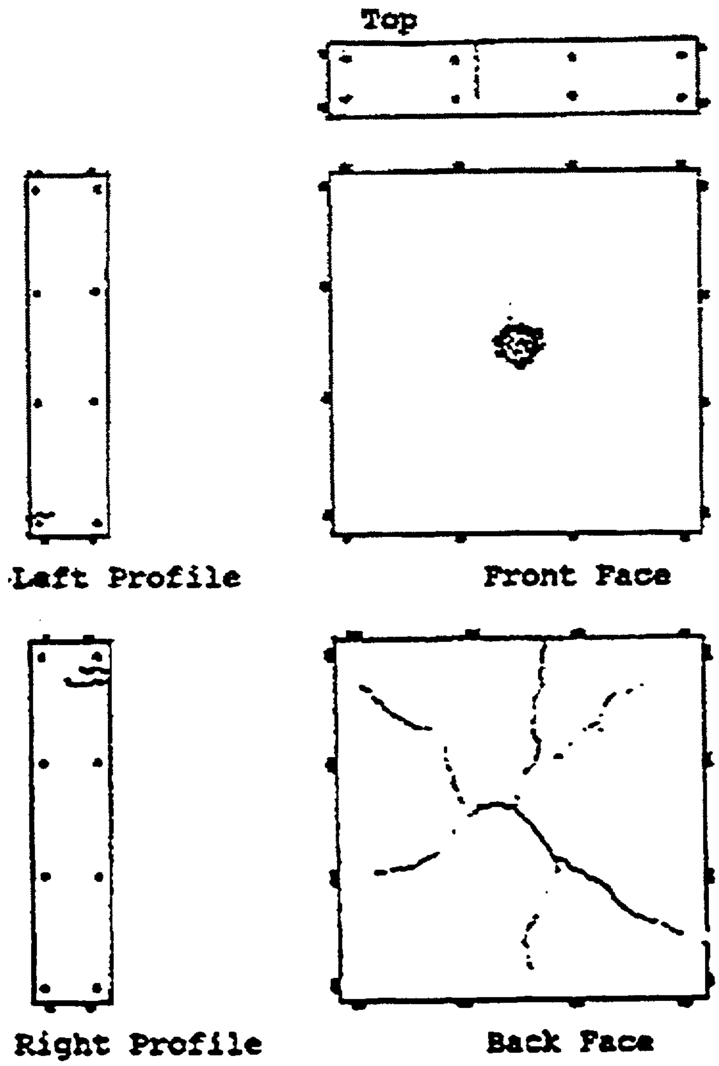


FIGURE 4.21b BACK FACE OF CR-8.2



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
8-in. slab with #3's 12-in. o.c. each way, placed 1.5-in. from each face.	50	• 0.69 in. penetration • Radial cracks with a 0.09 in. maximum width of cracks propagated through ¾ of slab width

FIGURE 4.22 CR-8.3 DATA

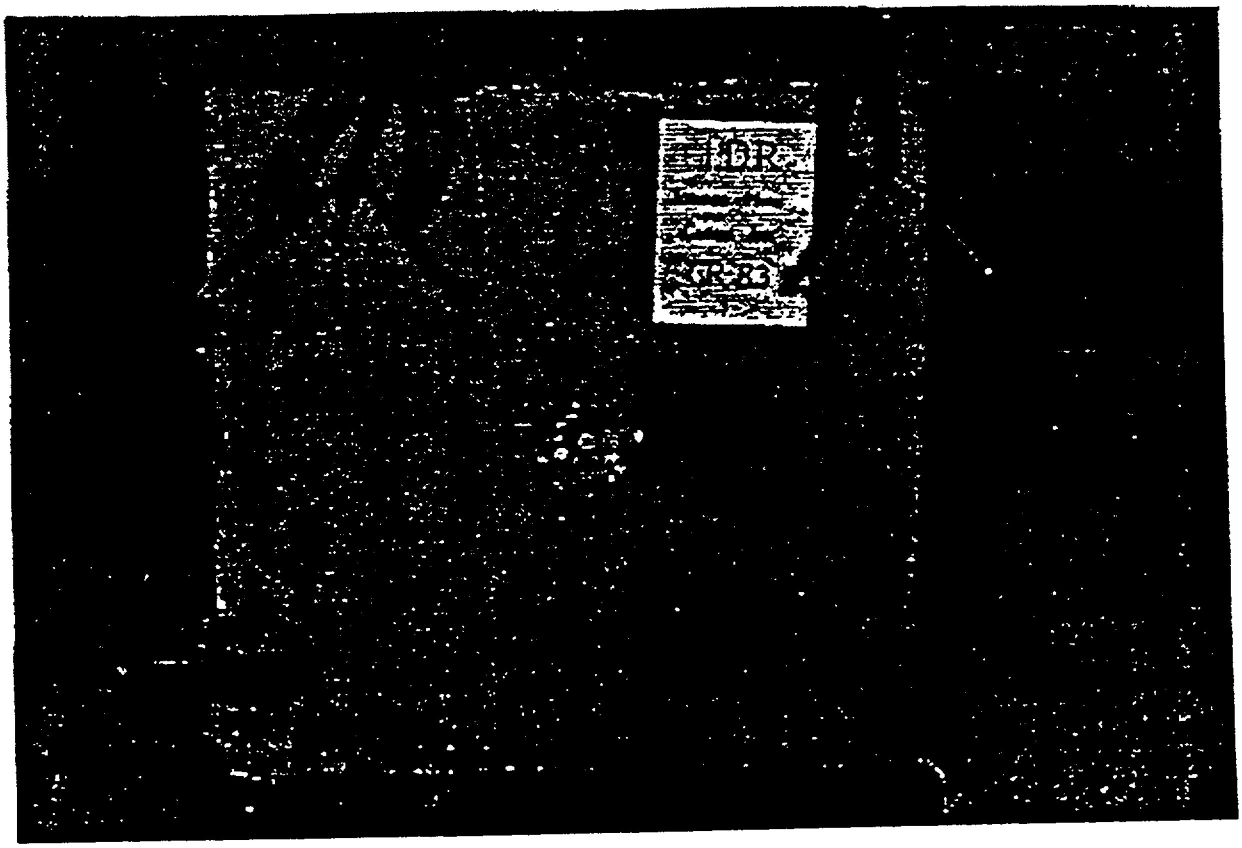


FIGURE 4.23a FRONT FACE OF CR-8.3

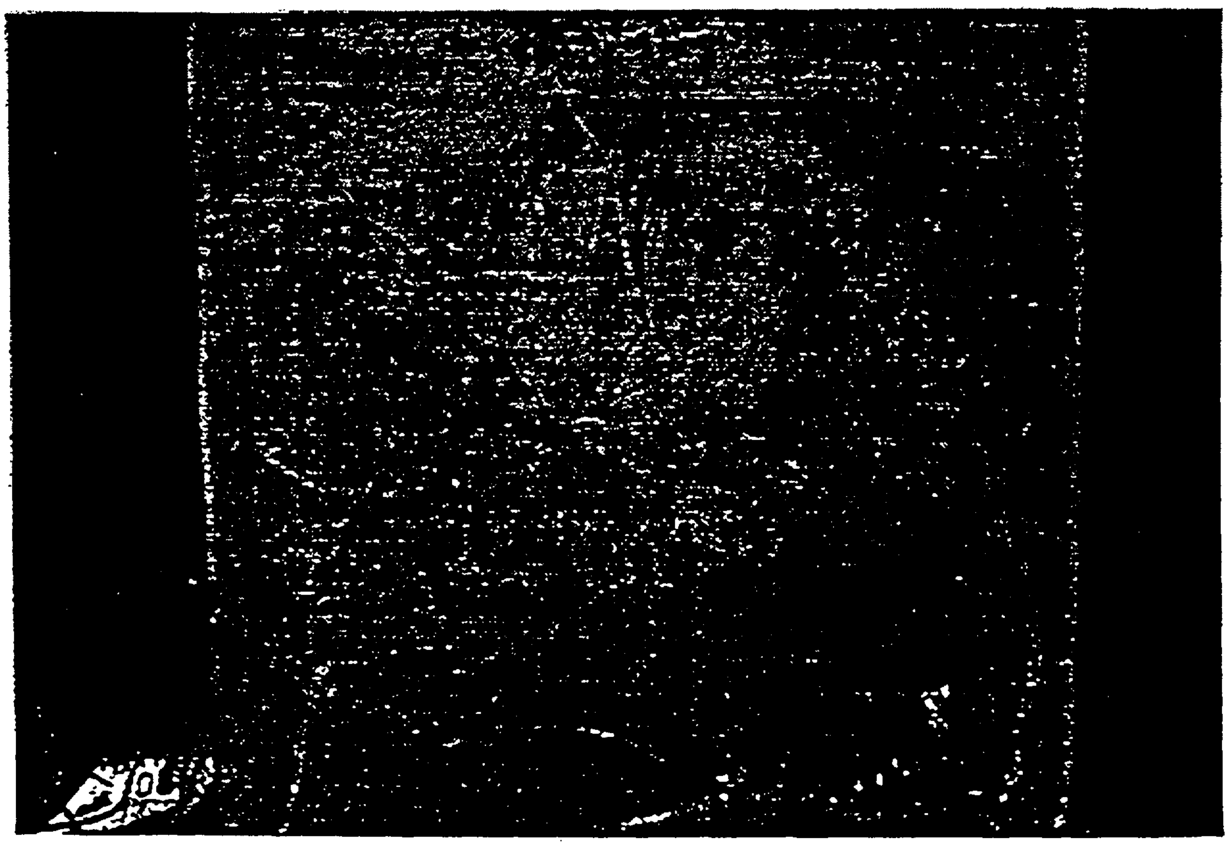


FIGURE 4.23b BACK FACE OF CR-8.3

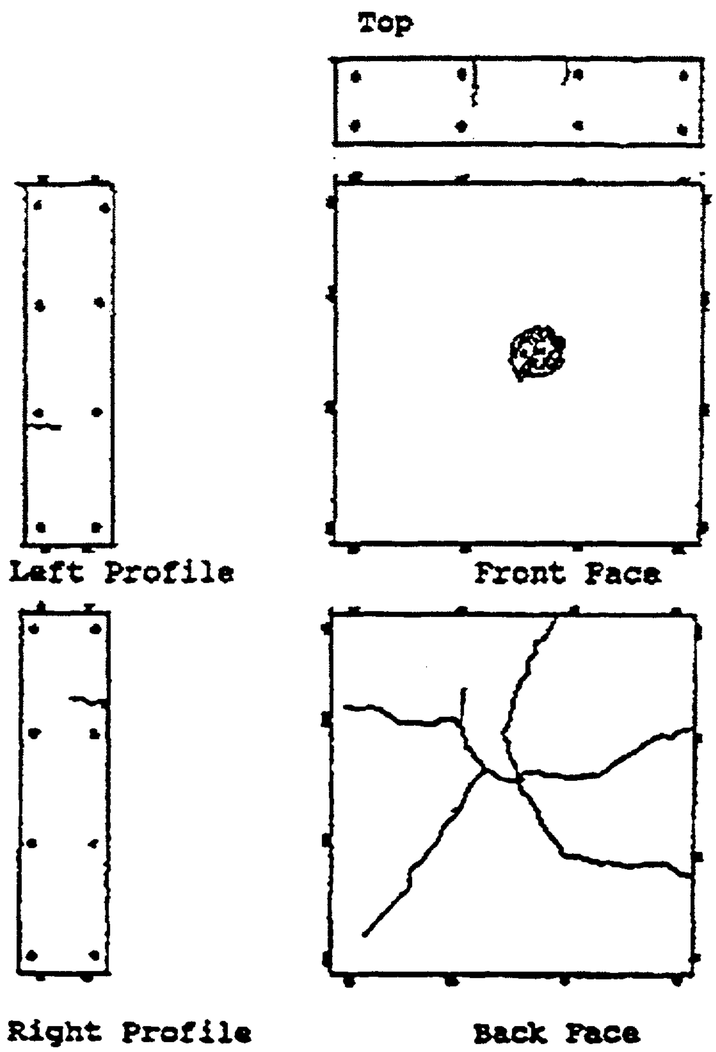
The 9-in. panel was impacted again at the same location at a speed of 78 mph (RC-9.2). The penetration depth increased to 1.50 in. and radial cracks increased to a point where several scabbing fragments with dimensions of 1.00 in. by 0.5 in. ejected from the back face. This second impact at 78 mph was judged to be very near the threshold speed for back face scabbing.

A single impact test, CR-10.1, was performed on the 10-in. panel (see Figures 4.27,4.28a and 4.28b), which resulted in no back face scabbing. The pipe, at a speed of 74 mph, hit the panel 4.5 in. to the right of center. The missile penetrated 0.81 in. and produced hairline cracks on the back face. The cracks perforated through less than half the thickness.

Thus, both the 9-in. and 10 in. panels successfully resisted the 75 mph pipe impact. The 10-in. panel performed slightly better than the 9-in., as expected.

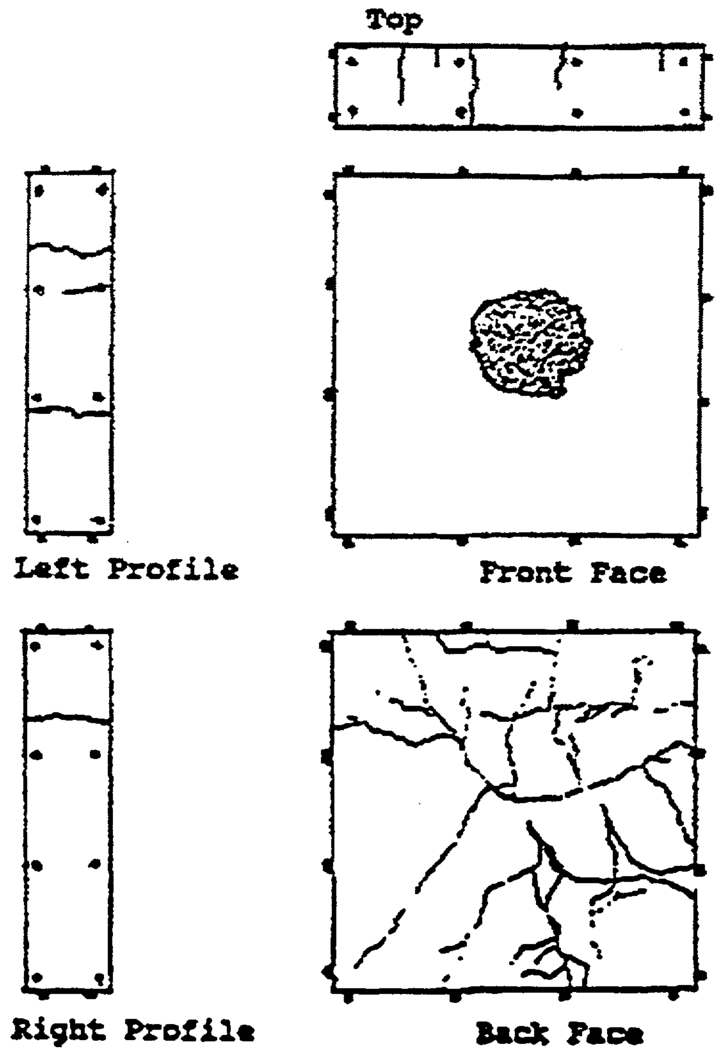
4.6.4 Concrete Reinforcing Patterns

Some reinforcing arrangements proved to be slightly more effective than others in improving impact resistance. Table 4.6 presents the different arrangements for each panel and the corresponding damage inflicted. The test results suggest that steel reinforcement placed in the middle or back face of the panel appear to be effective in reducing crack width. Reinforcing steel placed at both front face and back face appeared to negate crack propagation. Panels with the closest steel spacing showed signs of improved impact resistance, but results were not conclusive.



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
9-in. slab with #4's 12-in. o.c. each way, placed 1.5-in. from each face.	50	• 0.44 in. penetration • Hairline radial cracks propagating through half the slab thickness

FIGURE 4.24 CR-9.1 (NO PHOTOS AVAILABLE)



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
9-in. slab with #4's 12-in. o.c. each way, placed 1.5-in. from each face.	78	• 1.5 in. penetration • Radial cracks with scabbing, scab fragments had dimensions of (1.0x0.5)-in.

FIGURE 4.25 CR-9.2

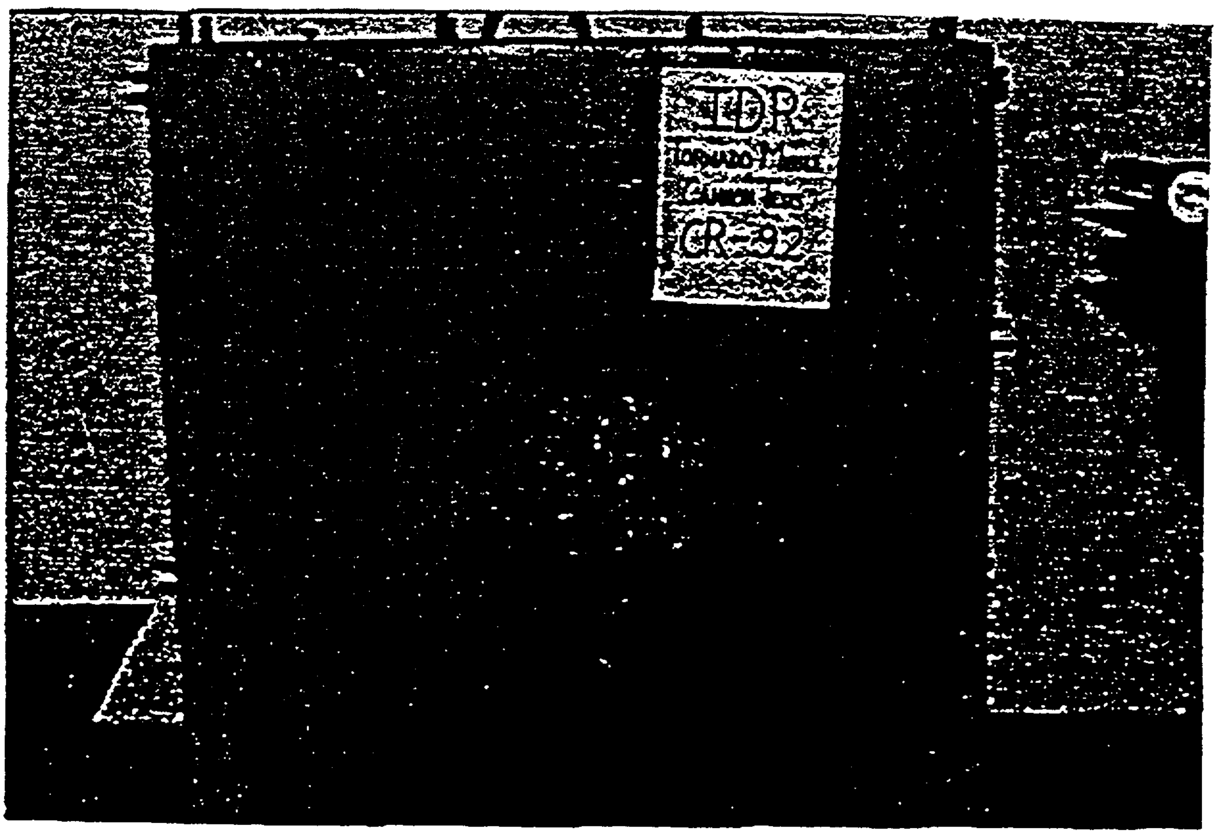


FIGURE 4.26a FRONT FACE OF A CR-9.2

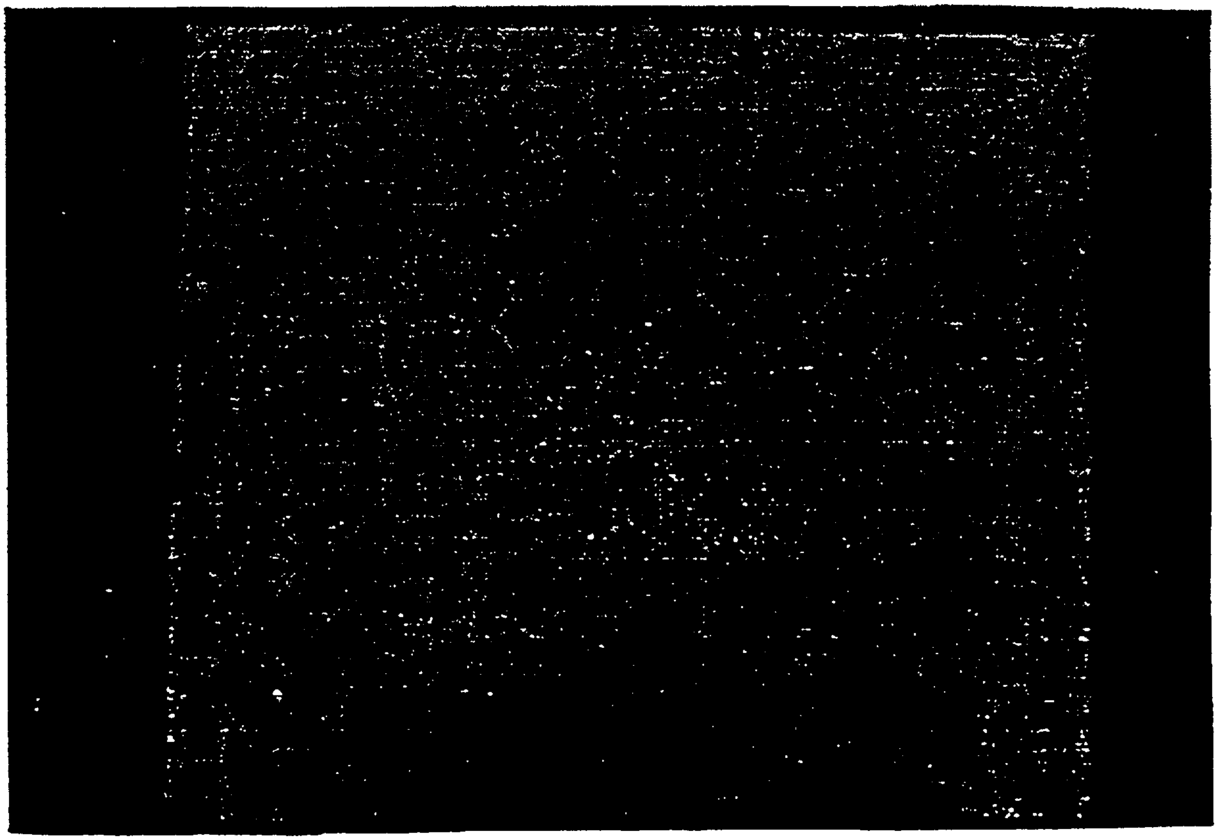
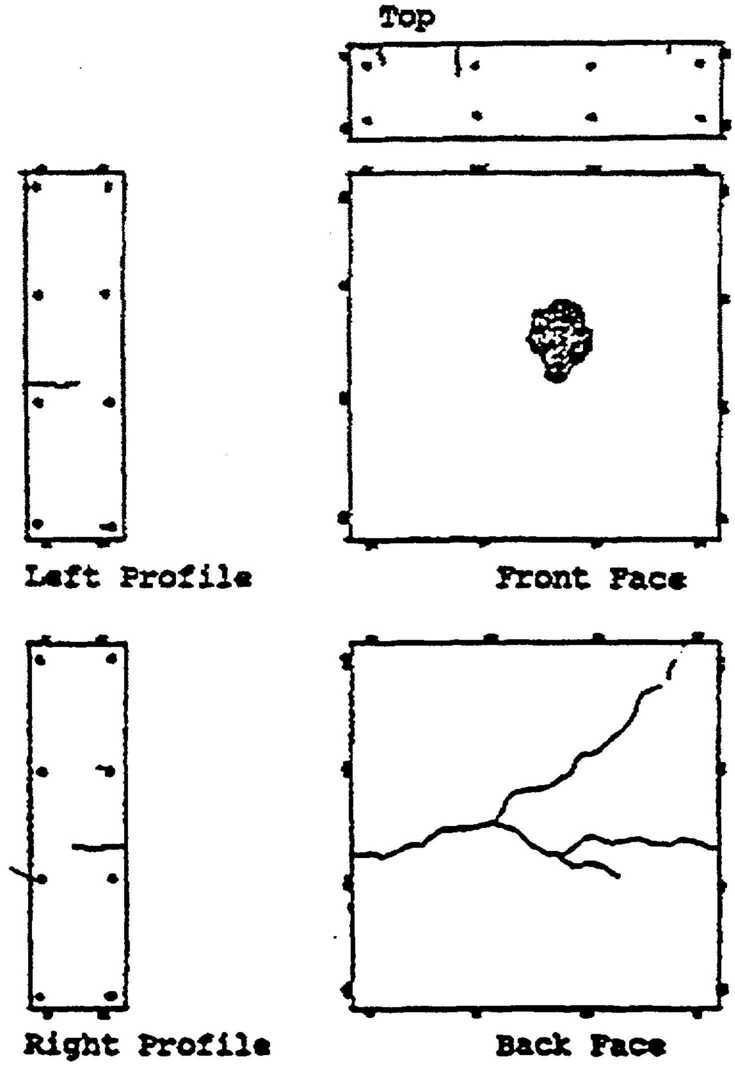


FIGURE 4.26b BACK FACE OF CR-9.2



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
10-in. slab with #4's 12-in. o.c. each way, placed 1.5-in. from each face.	74	• 0.81 in. penetration • Radial cracks with hairline width, cracks did not propagated through slab

FIGURE 4.27 CR-10.1 DATA

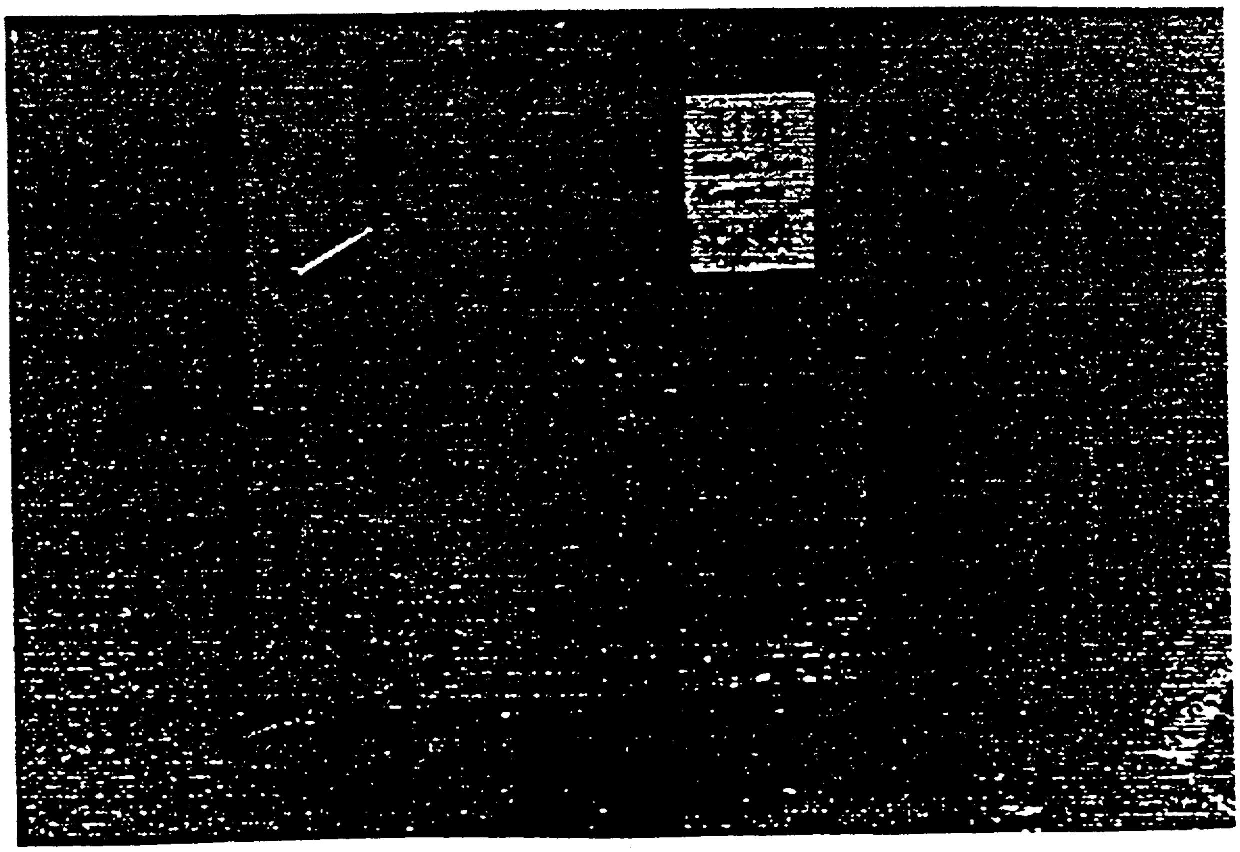


FIGURE 4.28a. FRONT FACE OF CR-10.1

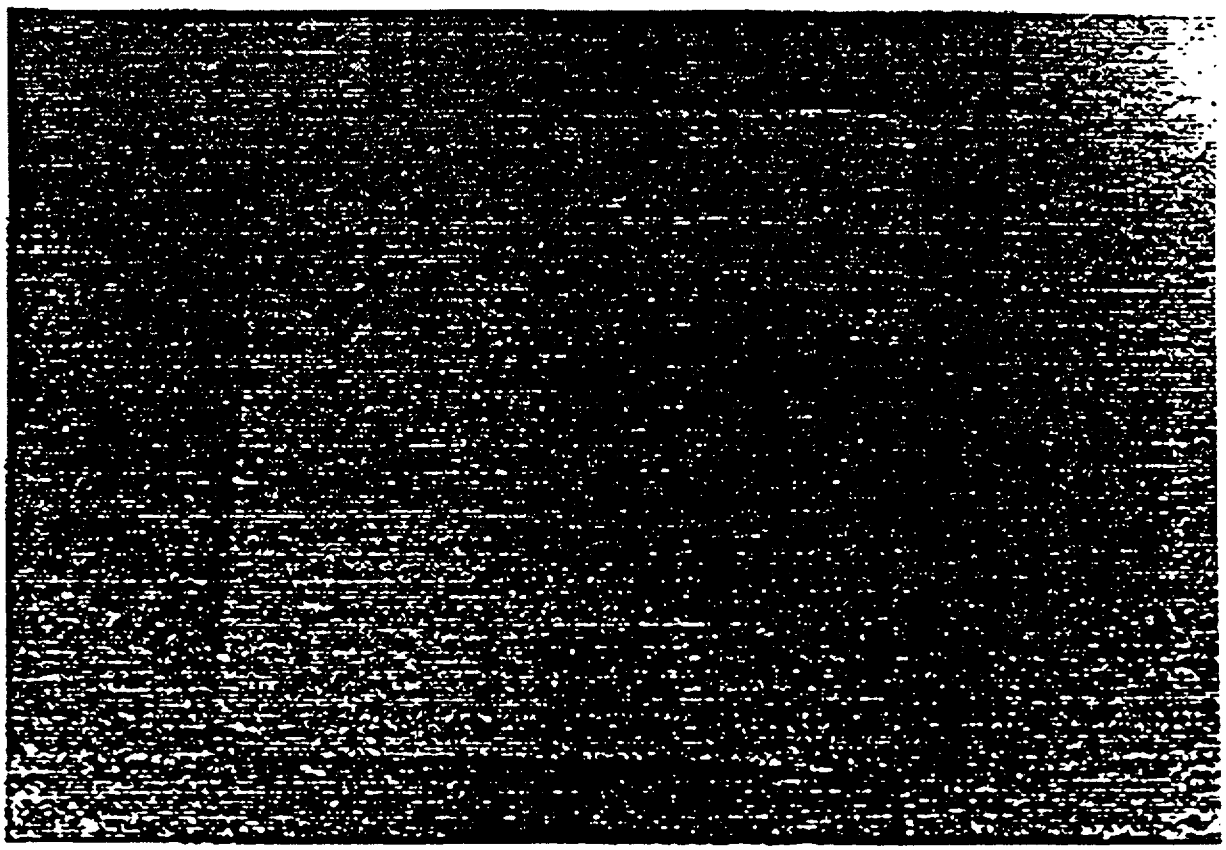


FIGURE 4.28b BACK FACE OF CR-10.1

Table 4.6. Reinforcing Arrangement Comparison

Panel Thick	Reinforcing Arrangement	Missile Impact Speed (mph)	Panel Damage Description	Comments
6-in.	**CR-6.1: #3 spaced 9-in. o.c. each way, 1.5-in. from panel front face**	35	0.25-in. penetration; 0.19-in. wide radial cracks on back face, total propagation	Reinforcement in front face reduced penetration depth
	CR-6.2: #3 spaced 12-in. o.c. each way, 1.50-in. from panel back face	36	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Reinforcement in back face reduced radial crack size
	CR-6.3: #4 spaced 9-in. o.c. each way, 1.50-in. from panel back face	37	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Reinforcement in back face reduced radial crack size; closer rebar spacing did not influence damage
8-in.	**CR-8.1: #4 spaced 9-in. o.c. each way, in the middle of panel**	44	0.38-in. penetration; 0.06-in. wide radial cracks on back face, total propagation	Closer rebar spacing appeared to reduce penetration depth
	CR-8.2: #4 spaced 12-in. o.c. each way, in the middle of panel	44	0.63-in. penetration; 0.09-in. wide radial cracks on back face, total propagation	
	CR-8.3: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face	50	0.69-in. penetration; 0.09-in. wide radial cracks on back face, 3/4 propagation	Double rebar mats prevented total propagation of cracks
9-in.	**CR-9.1: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face**	50	0.44-in. penetration; hairline radial cracks on back face, 1/2 propagation	Double rebar mats again resist crack propagation through panel
	CR-9.2: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face	78	1.50-in. penetration; scabbing, 1.0-in. by 0.50-in. fragments	Double rebar mats again resist crack propagation through panel
10-in.	**CR-10.1: #4 spaced 12-in. o.c. each way, 1.50-in. from each panel face**	74	0.81-in. penetration; hairline radial cracks on back face, 1/2 propagation	Double rebar mats again resist crack propagation through panel

4.6.5 Reinforced Masonry Panels

Four reinforced masonry wall panels were designed and constructed to resist the 50 mph and 75 mph impacts of the pipe missile as required by DOE STD 1020-94 for PC3 and PC4 SSCs. Two panels were constructed of reinforced and grouted CMUs. The other two consisted of a clay brick cavity wall and a clay brick veener/CMU combination wall.

The 8-in. CMU wall (CMU-8.1)was perforated by the steel pipe at an impact speed of 51 mph (see Figures 4.29, 4.30a, and 4.30b). This was the only wall in the test series that was perforated. Large pieces of block and grout weighing between 7 and 14 lb were found 8 to 10 ft behind the panel. A vertical crack passed through the impact point and propagated through the wall thickness. The missile perforation produced a 4-in. diameter entrance hole on the front face. A volume of material 25.2 in. by 14.5-in. in a conical, oval shape was ejected from the back face. The impact point was between the vertical reinforcing bars, which represents a worst case location.

Two impact tests were performed on the 12-in. CMU wall. In the test, the pipe missile accidentally struck the metal rebound guard that protects the timing gate. The missile was due to missile launcher recoil. After striking the rebound guard, the missile hit the test panel at an unknown velocity that was estimated at less than 20 mph. The missile penetrated 0.50. Into the panel at a point 3.50 in.to the right of center and one-half inch from where a vertical rebar was located. The impact caused a 0.13 in. wide vertical crack on the back face.

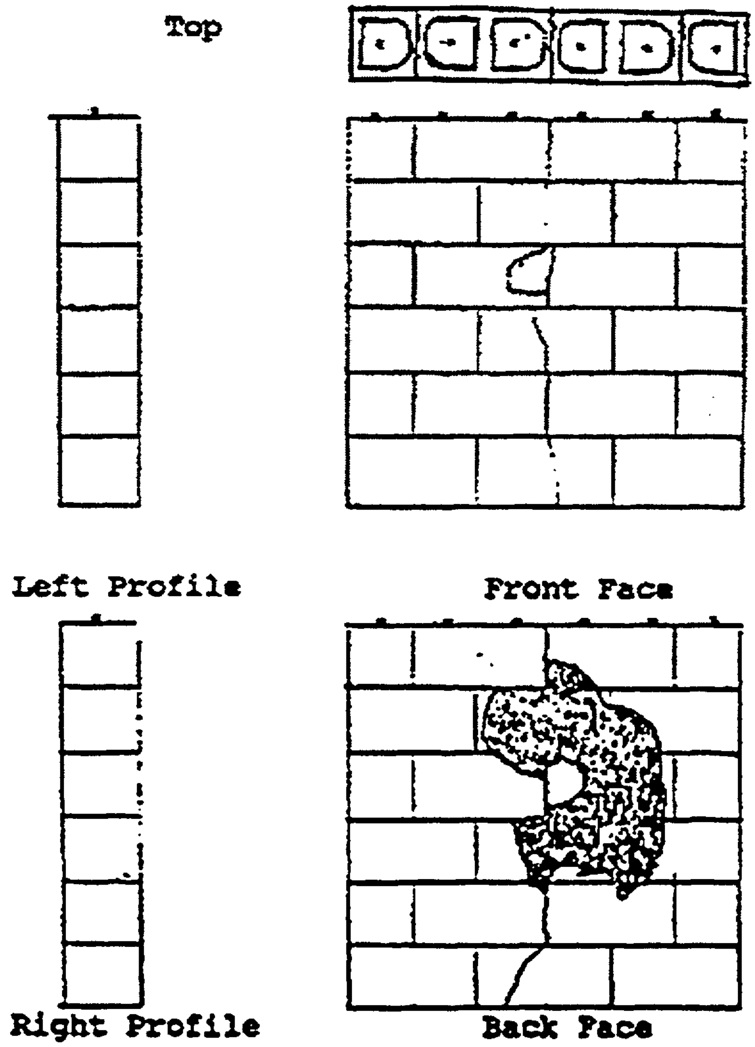
Before the second test, the slab was moved about 4-in. to the left to avoid the previous impact point. Since CMU –8.1 was perforated at 50 mph, it was assumed that

CMU-12.2 would not withstand a 75 mph impact without scabbing. Therefore, a CMU-12.2 was struck at an impact speed of 59 mph, 6-in. to the left of center and 2-in. from a vertical rebar. This impact caused a 1.38 penetration and a large vertical crack on the back face. Small block and grout fragments weighing less than 0.6 lb ejected from the back face, indicating that the scabbing threshold was near 60 mph. The crack and scabbing pattern, as illustrated in Figures 4.31, 4.32a and 4.32b, appeared to independent of damage created by the first impact. The vertical cracking on this panel and on the 8-in. CMU panel suggest that both panels need additional horizontal joint reinforcement to mitigate cracks.

Neither of the CMU barriers performed as expected. CMU-8.1 could not resist the 50 mph pipe missile. CMU-12.2 could not resist the 75 mph impact without significant scabbing. However, since the scabbing threshold velocity for the 12-in. CMU was approximately 60 mph, this panel satisfies the 50 mph impact criteria of the steel pipe missile.

4.7 Recommended Missile barriers

Based on data from literature and results of impact tests at Texas Tech University, the following guidelines are recommended for missile barriers to resist missiles specified in DOE STD 1020-94



Barrier Description	Missile Speed	Barrier Impact Damage
8 in. grouted CMU wall with #4's 8 in. o.c., horizontal ties 16 in. o.c.	51 mph	-Total perforation -Pieces of scabbing weighing between 7 and 14 lbs. -Entrance hole: 4 in. dia., exit hole: 25.5 in. x 14.5 in. oval

FIGURE 4.29 CMU-8.1 DATA

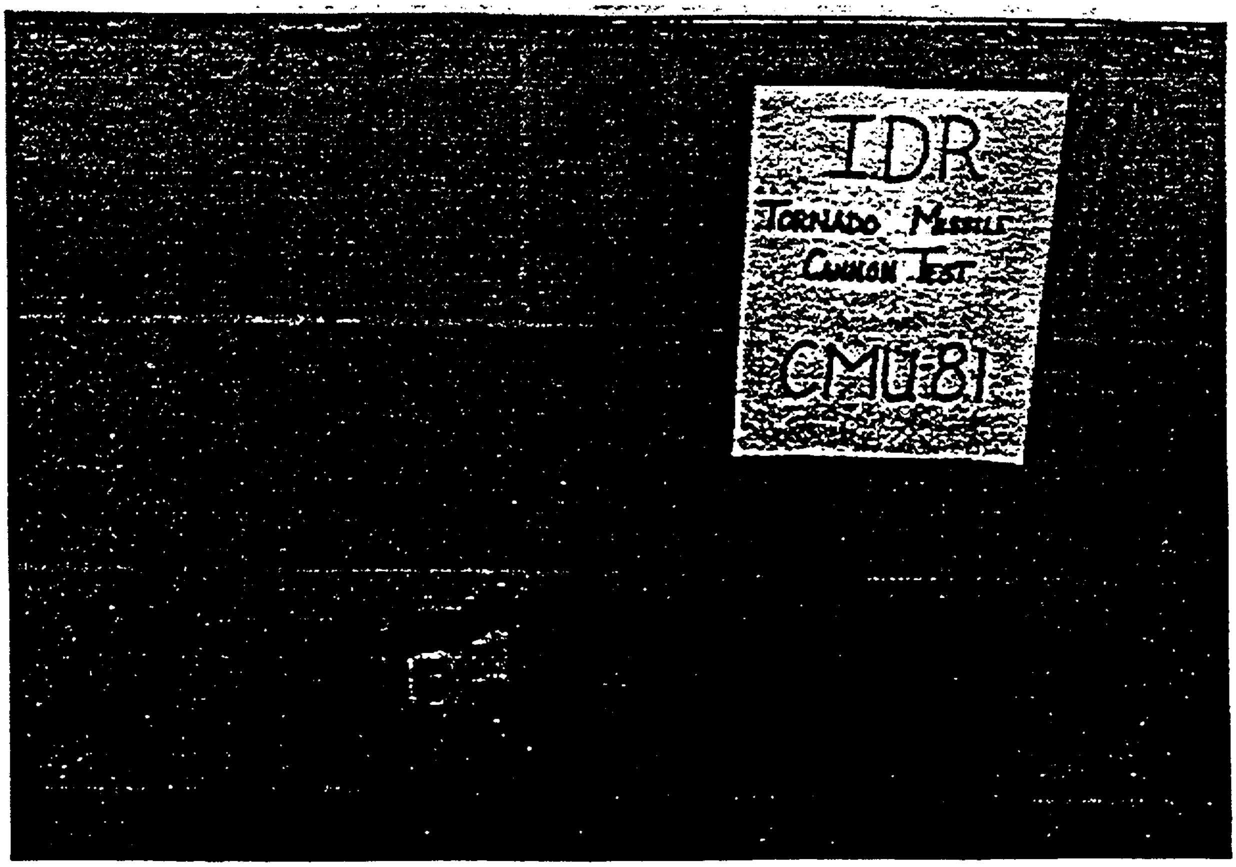


FIGURE 4.30a. FRONT FACE OF CMU- 8.1

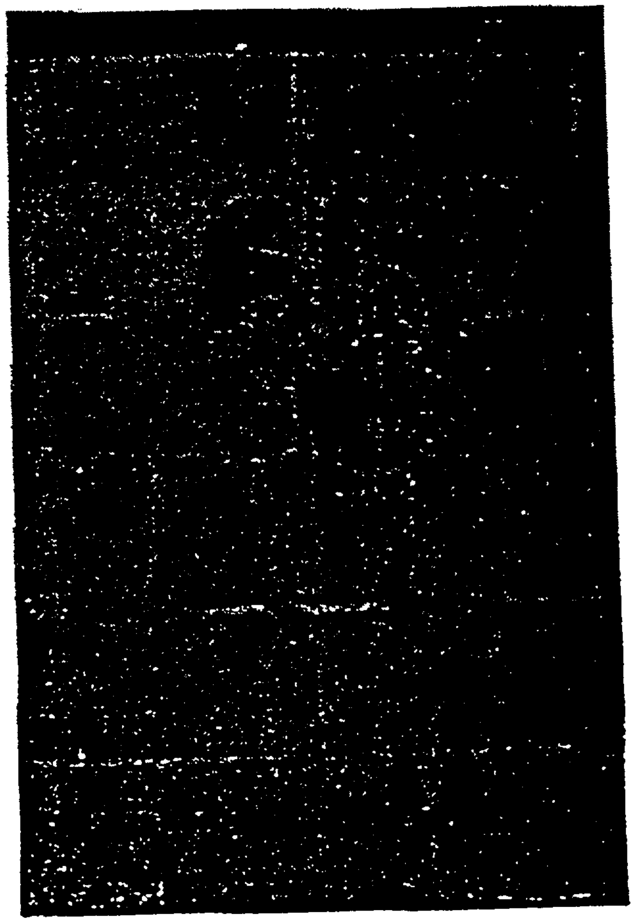
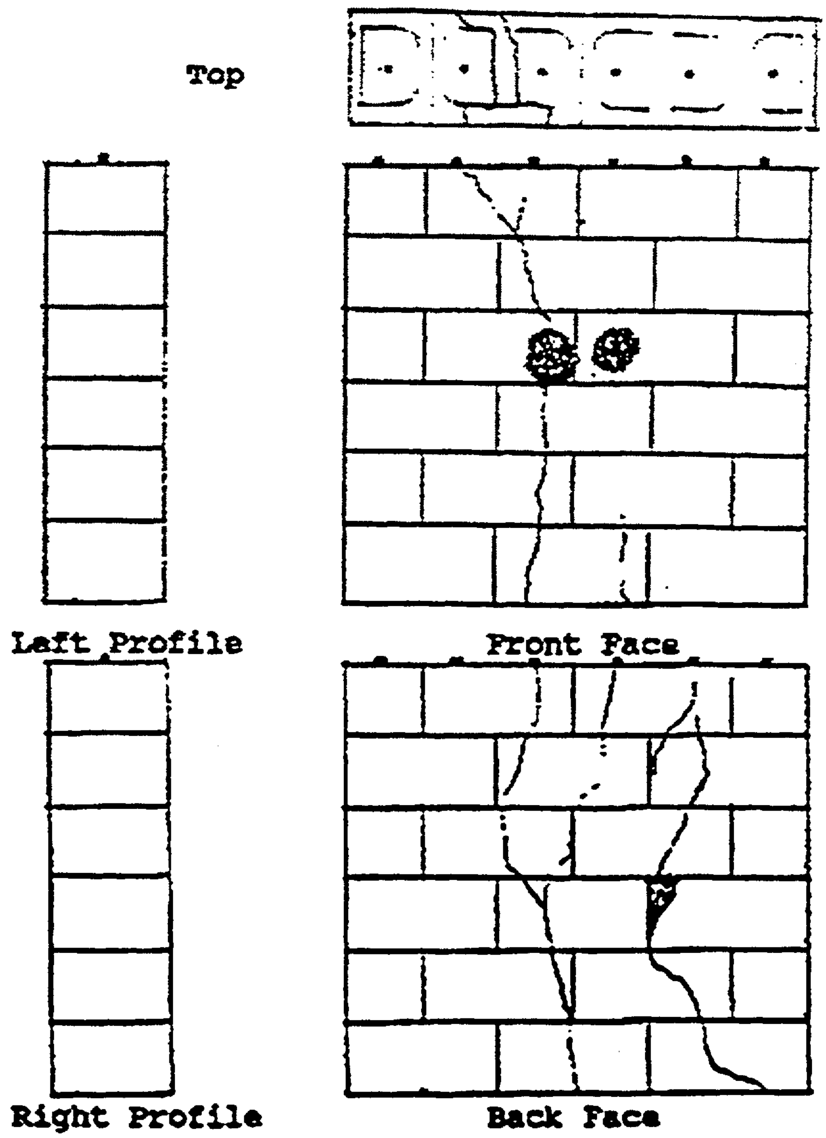


FIGURE 4.30b. BACK FACE OF CMU-8.1



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
12 -in. grouted CMU wall with #4's, 8in.o.c. horizontal ties 16-in. o.c..	59	• 1.38 in. penetration • Threshold of scabbing reached, scabbing pieces weighed up to 0.6 lbs.

FIGURE 4.31 CMU-12.2 DATA

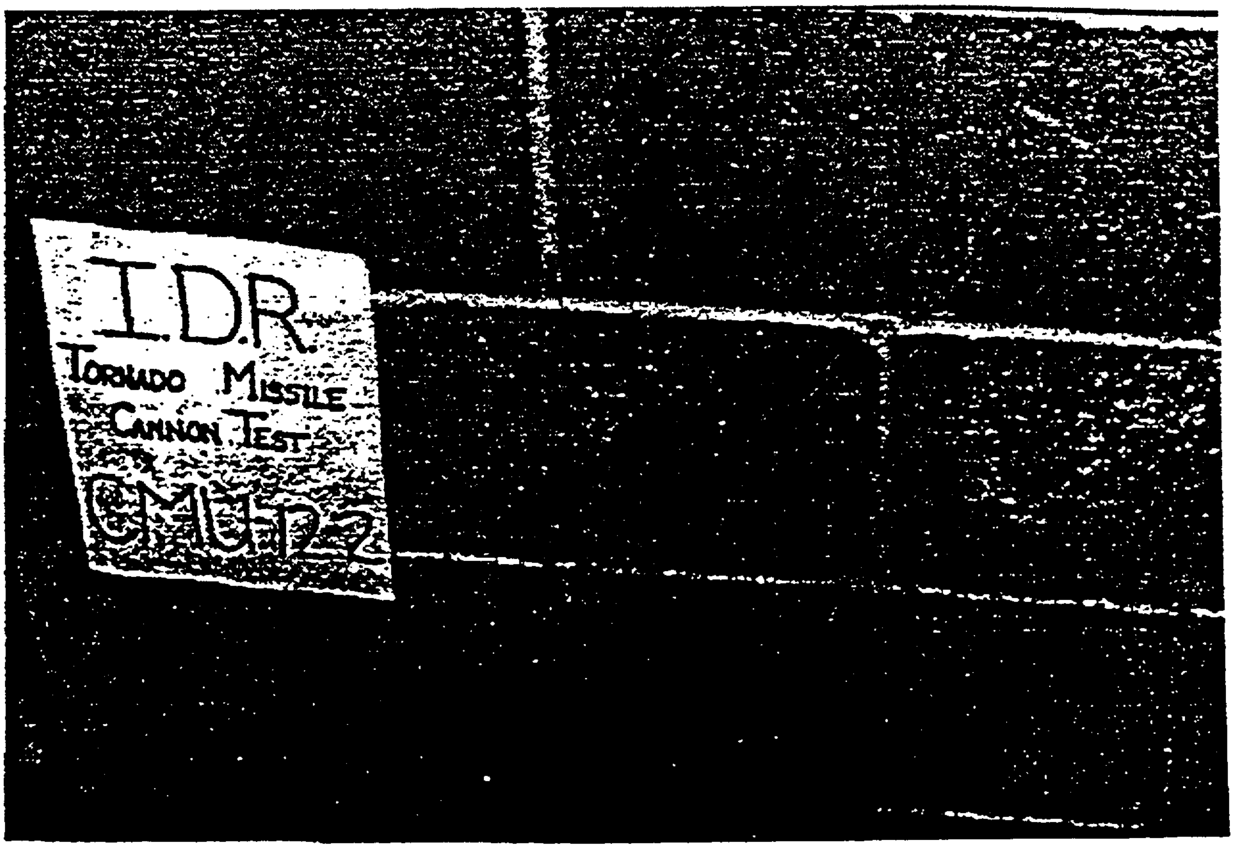
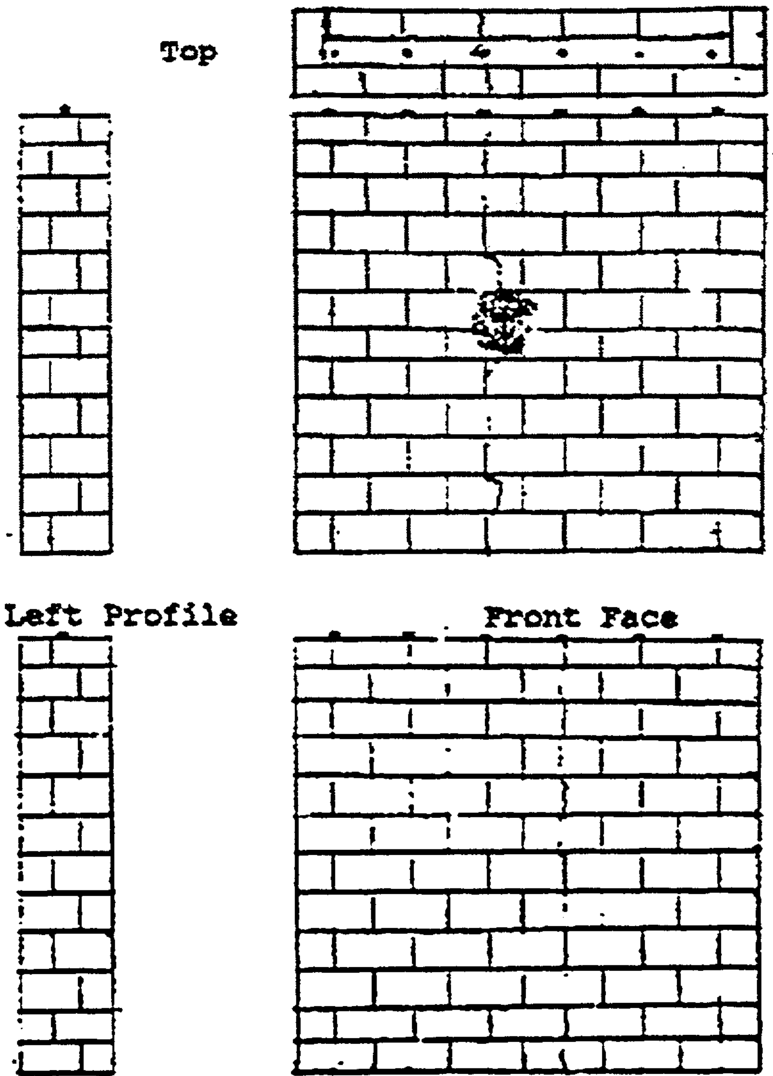


FIGURE 4.32a FRONT FACE OF CMU-12.2



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
9.5-in. brick cavity wall (grouted) with #4's, 8in.o.c. and horizontal ties 16-in. o.c.	50	• 1.13-in. penetration • Vertical crack with 0.25-in. width, crack propagated through wall

FIGURE 4.33 CBM-(9.5).1 DATA

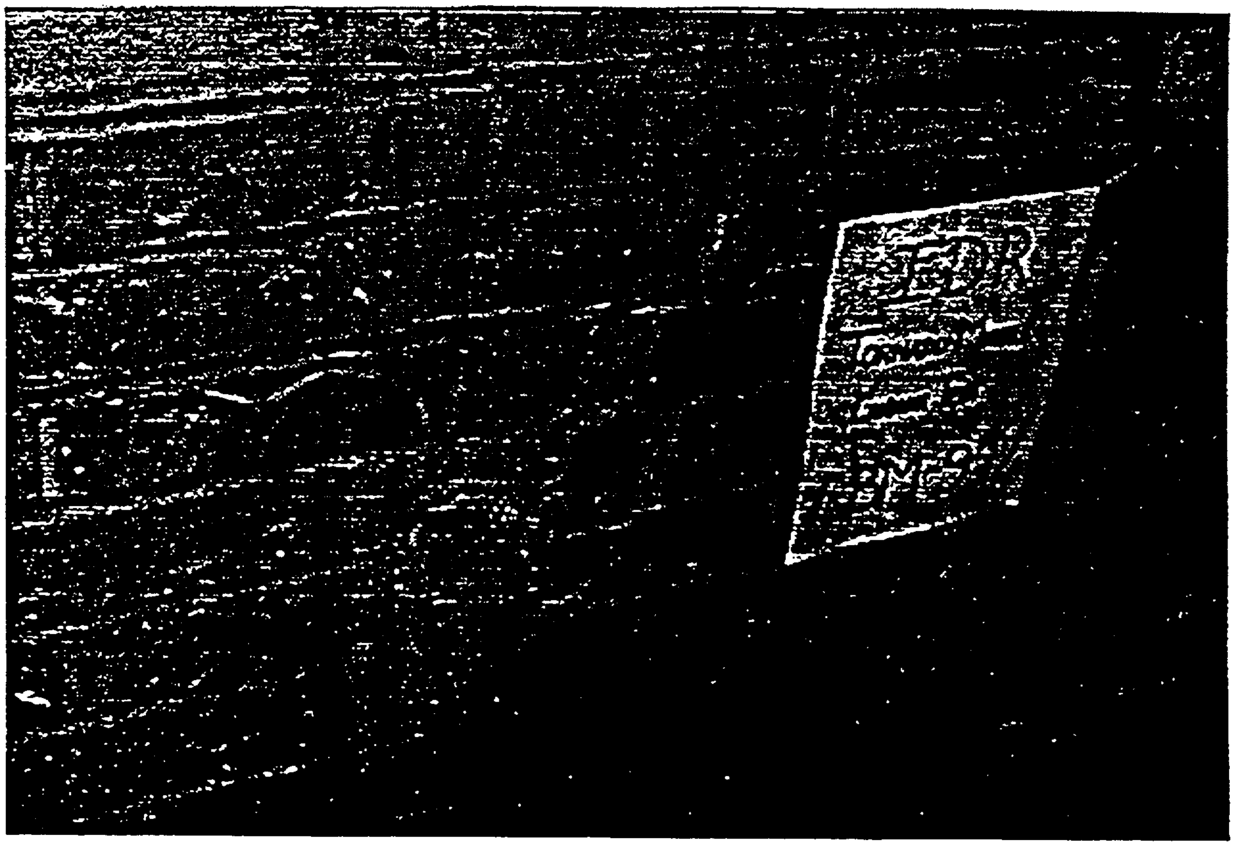


FIGURE 4.34a. FRONT FACE OF CBM-(9.5).1

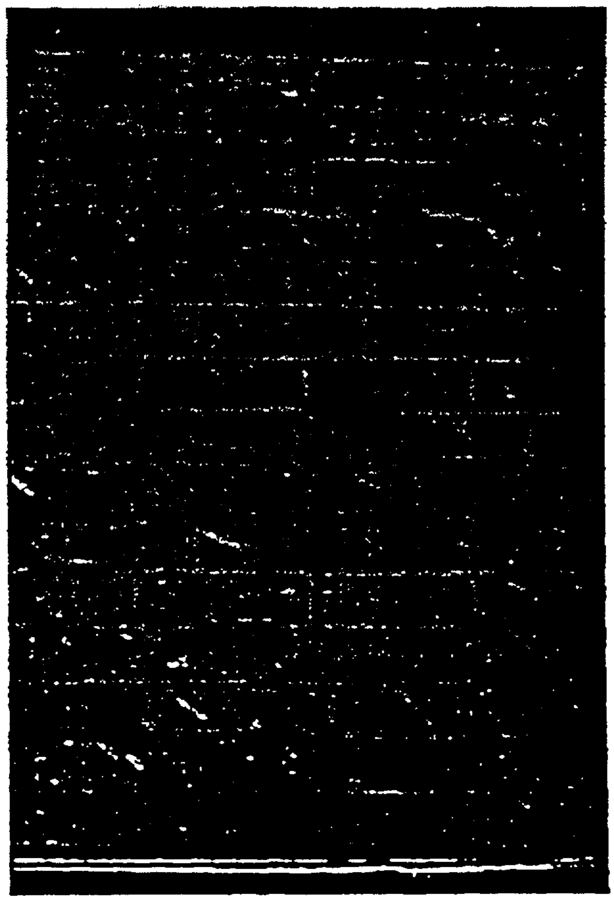
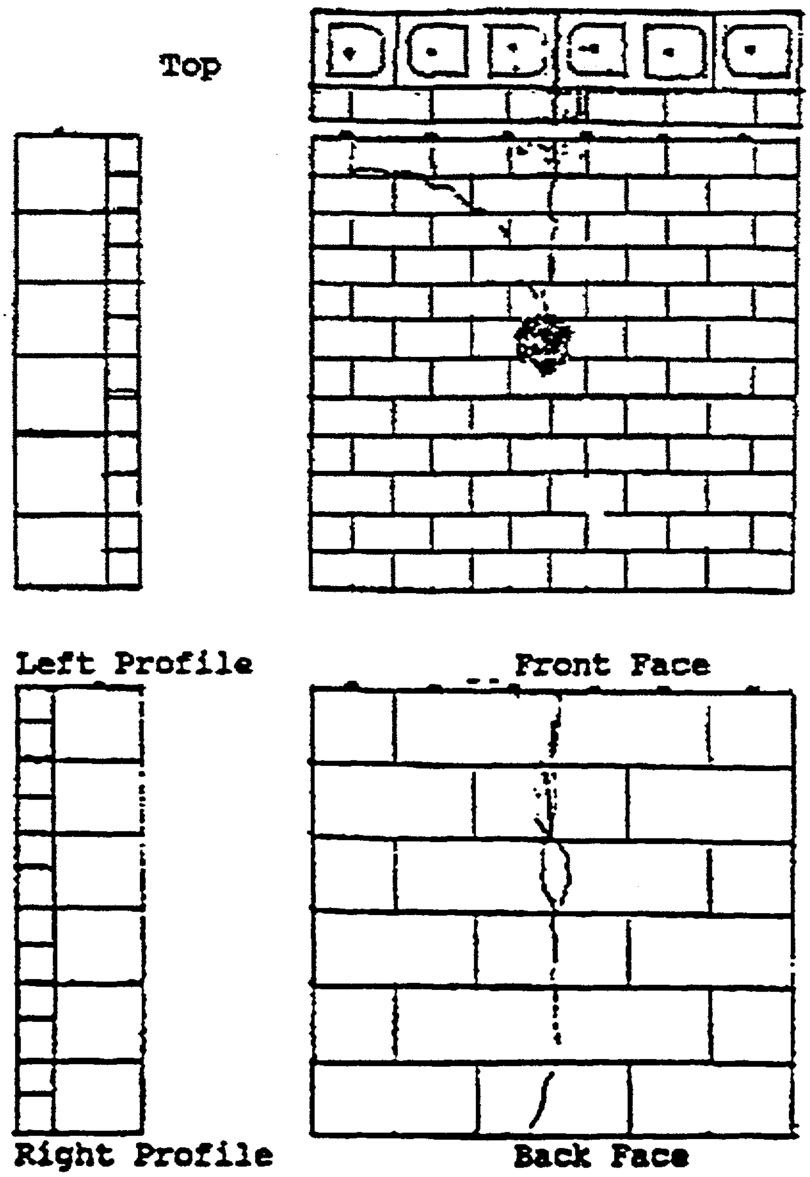


FIGURE 4.34b. BACK FACE OF CBM-(9.5)-1



Barrier Description	Missile Speed (mph)	Barrier Impact Damage
8-in. grouted CMU wall with #4's, 8in.o.c. horizontal ties 16-in. o.c. single brick wythe on the front face	50	• 1.13-in. penetration • Vertical crack with max. width of 0.38-in.crack propagated through wall

FIGURE 4.35 CBCMU-12.1 DATA

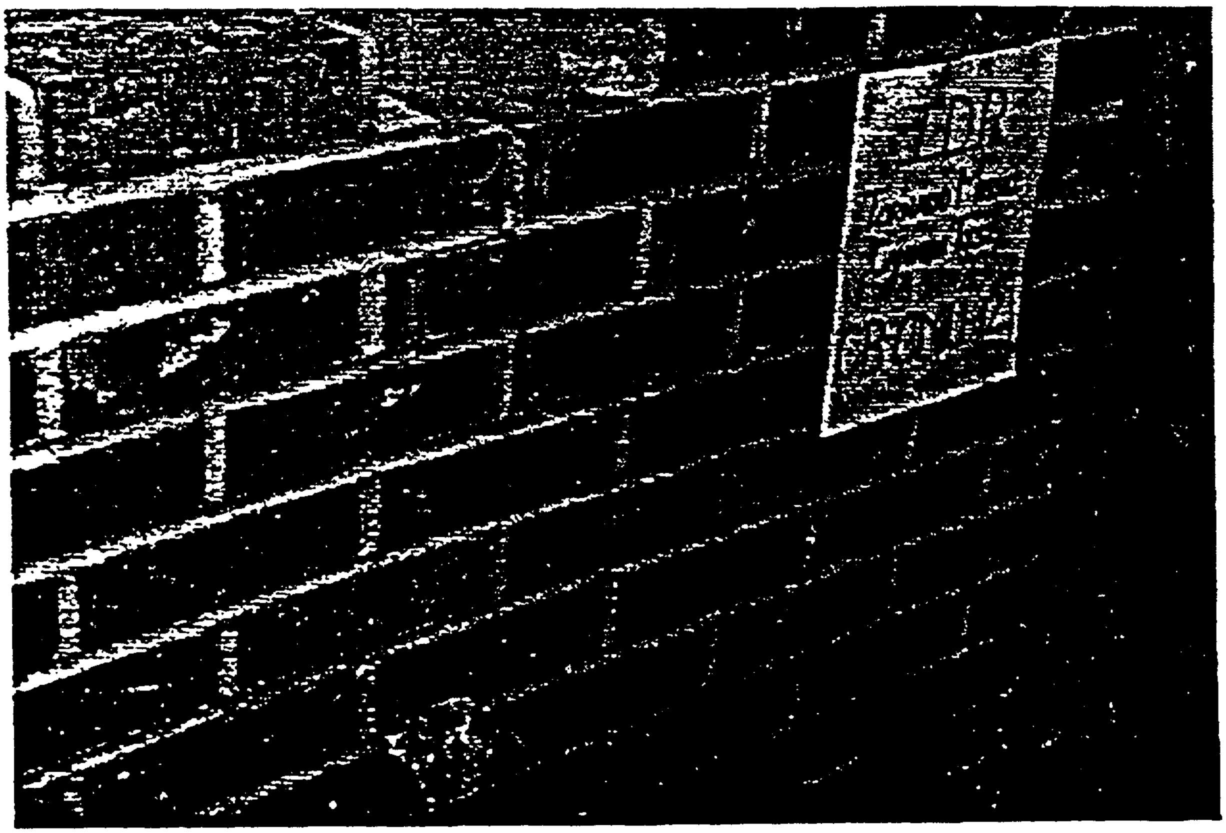


FIGURE 4.36a. FRONT FACE OF CBCMU-12.1

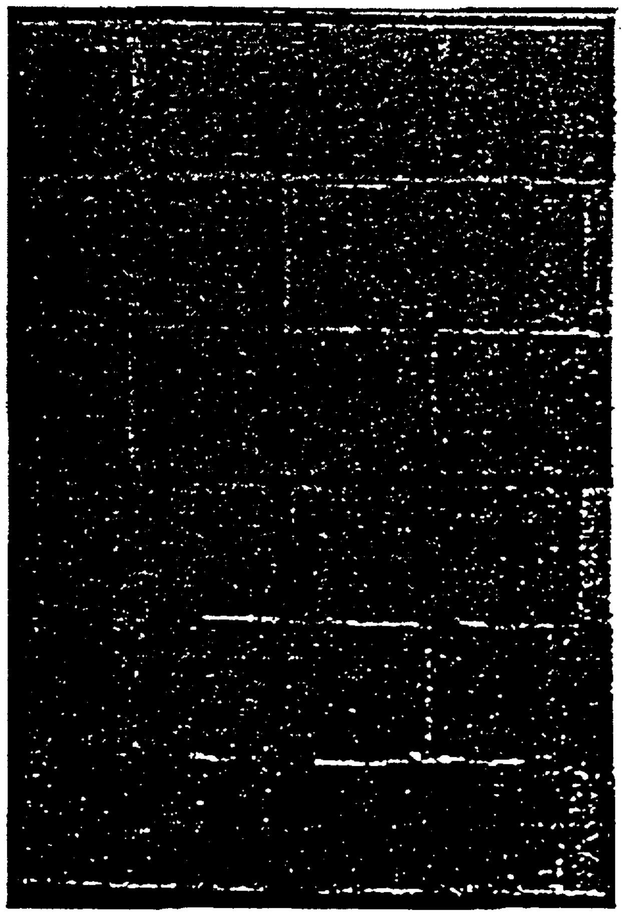


FIGURE 4.36b. BACK FACE OF CBCMU-12.1

4.7.1 Barriers for Performance Category 3

The missile criteria is

Horizontal Missile Component:

2x4 timber (15 lb.) at 100 mph, maximum height above ground 150 ft.

Recommended Barrier:

1. 8-in. CMU wall with one #4 rebar grouted in each vertical call and trussed horizontal joint reinforcement at 16 in. on center,
2. Single wythe brick veneer attached to stud wall with metal ties,
3. 4-in. concrete slab with # 3rebar at 6 in. on center each in the middle of slab.

Vertical Missile Component

2x4 timber (15 lb) at 100 mph

Recommended Barrier:

1. 4-in. concrete slab with # 3 rebar at 6 in.on center each in the middle of slab.

Horizontal Missile Component:

3-in. diameter steel pipe lb at 50 mph; maximum height above ground 75 ft.

Recommended Barrier:

1. 12-in. CMU wall with #4 rebar in each vertical cell and grouted; #4 rebar horizontal at 8 in. on center.
2. Nominal 12-in. wall consisting of 8-in. CMU with #4 rebar in each vertical cell and grouted; #4 rebar horizontal at 8 in. on center; single wythe clay brick masonry on outside face of wall; horizontal ties at 16 in. on center
3. 9.5-in. reinforced brick cavity wall with #4 rebar at 8-in. center each way in the cavity; cavity filled with 2500 psi concrete; horizontal ties at 16 in. on center,

4. 8-in. concrete slab with # 4 rebar in on center each way 1.5 in. from inside.

Vertical Component:

3-in. diameter steel pipe 75 lb. At 35 mph

Recommended Barrier:

1. 6-in. concrete slab with #4 rebar at 12 in. on center each way 1.5 in. from inside face.

Wind-borne Missile

2x4 timber (15) at 50 mph; maximum height above ground 30 ft.

Recommended Barriers:

1. 8-in. CMU wall with one #4 rebar grouted in each vertical cell
2. Single wythe brick veneer attached to stud wall with metal ties
3. 4-in. concrete slab with # 3 rebar at 6 in.on center each in the middle of slab

4.7.2 Barriers for Performance Category 4

The Missile Criteria is

Horizontal Missile Component:

2x4 timber (15 lb.) at 150 mph, maximum height above ground 200 ft.

Recommended Barrier:

1. 6-in. concrete slab with # 4 rebar in on center each way 1.5 in. in the middle of the slab.
2. 8-in. CMU wall with one #4 rebar grouted in each vertical cell and horizontal trussed joint reinforcement at 16 in. on center.

Vertical Component:

2x4 timber (15 lb.) at 100 mph

Recommended Barrier:

1. 4-in. concrete slab with #3 rebar at 6 in. on center each in the middle of the slab

Horizontal Missile Component:

3-in. diameter steel pipe 75 lb. At 75 mph; maximum height above ground 100 ft.

Recommended Barrier:

1. 10-in. concrete slab with #4 rebar at 12 in. on center each way 1.5 in. from inside face.

Vertical Component:

3-in. diameter steel pipe 75 lb. At 50 mph

1. 8-in. concrete slab with #4 rebar at 8 in. on center each way 1.5 in. from inside face.

Windborne Missile

2x4 timber (15 lb.) at 50 mph maximum height above ground 30 ft.

1. 8-in. CMU wall with #4 rebar grouted in each vertical cell,
2. Single wythe brick veneer attached to stud wall with metal ties
3. 4-in. concrete slab with # 3 rebar at 6 in.on center each in the middle of slab.

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APPENDIX A
DISTRUBUTION OF TIMBER MISSILES
TABLES:

Table A-1. Missile Data for Hubbard, Texas Tornado (F2)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
1	8.16	4.92	1.53	13.32
2	6.12	4.08	1.54	8.32
3	4.08	2.40	1.57	3.33
4	4.08	2.40	1.57	3.33
5	2.72	4.08	1.54	3.70
6	4.76	3.24	1.55	5.18
7	8.84	5.76	1.53	16.83
8	3.74	6.48	1.03	5.43
9	10.20	6.48	1.03	14.82
10	3.40	4.08	1.54	4.62
11	8.16	2.40	1.58	6.70
12	3.06	2.88	1.52	2.91
13	3.40	6.48	1.03	4.94
14	4.08	4.08	1.54	5.55
15	3.40	4.92	1.53	5.55
16	5.44	3.24	1.55	5.92
17	6.80	3.24	1.55	7.40
18	5.78	5.76	1.53	11.01
19	3.74	4.08	1.54	5.10
20	6.12	3.24	1.56	6.70
21	8.84	2.40	1.57	7.21
22	6.80	7.32	1.03	11.11
23	3.06	7.32	1.03	5.00
24	4.08	4.08	1.54	5.55
25	4.08	3.24	1.55	4.44
26	3.40	3.24	1.55	3.70
27	5.44	2.40	1.57	4.44
28	2.72	3.24	1.55	2.96
29	3.40	2.40	1.57	2.77
30	4.76	2.40	1.57	3.88
31	4.76	3.24	1.56	5.20
32	4.76	3.24	1.56	5.20
33	5.44	3.24	1.55	5.92
34	2.72	4.92	1.53	4.44
35	8.84	6.48	1.03	12.84
36	3.40	4.08	1.54	4.62
37	4.76	3.24	1.55	5.18
38	6.80	8.16	1.54	18.50
39	7.48	5.76	1.53	14.24
40	8.16	4.08	1.54	11.10

Table A-1 Missile Data for Hubbard, Texas Tornado (F2) (cont.)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
41	9.52	4.92	1.53	15.54
42	4.76	4.92	1.53	7.77
43	8.84	4.08	1.54	12.02
44	6.80	6.48	1.03	9.88
45	6.80	5.76	1.53	12.95
46	3.06	4.92	1.53	4.99
47	5.44	5.76	1.53	10.36
48	10.88	8.16	1.03	19.75
49	3.40	7.32	1.03	5.55
50	6.12	5.76	1.53	11.65
51	6.12	3.24	1.55	6.66
52	3.40	3.24	1.55	3.70
53	4.08	5.76	1.53	7.77
54	4.76	3.24	1.55	5.18
55	5.44	7.32	1.03	8.89
56	6.46	6.48	1.03	9.38
57	8.16	7.32	1.03	13.33
58	3.40	6.48	1.03	4.94
59	4.08	3.24	1.55	4.44
60	5.44	3.24	1.55	5.92
61	3.40	7.32	1.03	5.56
62	10.20	4.92	1.53	16.65
63	7.48	5.76	1.53	14.24
64	4.08	2.40	1.57	3.33
65	4.76	4.92	1.53	7.77
66	4.42	6.48	1.03	6.42
67	3.40	4.92	1.53	5.55
68	6.12	3.24	1.55	6.66
69	4.08	3.24	1.55	4.44
70	6.12	5.76	1.53	11.65
Average	**5.44**			**7.74**

Table A-2 Missile Data for Sweetwater, Texas Tornado (F3)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
1	9.65	10.56	1.02	22.61
2	9.21	7.92	1.03	16.20
3	10.53	9.48	1.03	22.20
4	10.53	9.96	1.03	23.43
5	7.68	6.36	1.02	10.79
6	7.02	8.40	1.03	13.20
7	8.34	9.96	1.03	18.55
8	12.30	4.68	1.56	19.40
9	8.34	3.72	1.52	10.24
10	11.41	3.12	1.56	12.01
11	9.65	3.72	1.52	11.85
12	10.09	3.12	1.56	10.62
13	8.77	4.68	1.56	13.86
14	6.14	5.28	1.02	7.19
15	5.26	4.68	1.56	8.31
16	4.39	5.28	1.02	5.14
17	4.83	4.20	1.54	6.77
18	5.26	3.12	1.56	5.54
19	4.83	5.76	1.03	6.22
20	4.39	5.28	1.02	5.14
21	4.83	5.28	1.02	5.65
22	15.79	5.28	1.02	18.50
23	7.90	3.12	1.56	8.31
24	6.14	4.20	1.54	8.62
25	4.83	3.72	1.52	5.93
26	10.97	3.12	1.56	11.55
27	13.16	3.72	1.52	16.17
28	7.90	3.12	1.56	8.31
29	7.90	5.28	1.02	9.25
30	8.77	4.20	1.54	12.32
31	9.65	3.72	1.52	11.86
32	4.83	5.76	1.03	6.22
33	9.21	4.20	1.54	12.93
34	7.46	5.76	1.03	9.61
35	12.72	3.12	1.56	13.40
36	7.02	4.20	1.54	9.85
37	6.58	3.72	1.53	8.10
38	13.16	2.64	1.53	11.55
39	5.70	7.32	1.03	9.35
40	8.77	4.20	1.54	12.32
41	6.58	3.72	1.52	8.08
42	4.83	4.68	1.56	7.62
43	4.39	4.68	1.56	6.93
44	4.83	3.72	1.52	5.93
45	7.46	4.20	1.54	10.47
46	8.34	3.72	1.52	10.24
47	5.26	5.28	1.03	6.17
48	4.39	5.28	1.02	5.14
49	7.90	3.72	1.52	9.70
50	5.27	2.64	1.53	4.62

Table A-2 Missile Data for Sweetwater, Texas Tornado (F3) (cont.)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
51	5.70	5.28	1.02	6.68
52	6.14	3.12	1.56	6.47
53	3.95	3.12	1.56	4.16
54	6.14	3.72	1.52	7.54
55	6.14	5.28	1.02	7.19
56	6.14	4.68	1.56	9.70
57	6.58	3.72	1.53	8.10
58	4.56	3.48	1.53	5.25
59	3.80	3.60	1.56	4.62
60	4.56	1.80	1.56	2.77
61	3.80	5.52	1.52	6.93
62	5.32	3.24	1.52	5.66
63	4.56	4.56	1.54	6.93
64	4.56	2.76	1.54	4.20
65	2.66	3.60	1.56	3.24
66	3.80	7.32	1.02	6.17
67	3.04	3.60	1.56	3.70
68	6.46	3.24	0.85	3.87
69	4.95	6.36	0.15	1.03
70	3.04	4.56	1.54	4.62
71	3.04	4.08	1.54	4.15
72	2.66	3.60	1.56	3.24
73	4.56	3.60	1.56	5.55
74	2.66	3.60	1.56	3.24
75	4.56	3.48	1.53	5.25
76	3.04	5.52	1.53	5.55
77	3.80	6.36	1.03	5.40
78	3.04	2.76	1.52	2.77
79	3.04	8.16	1.03	5.55
80	2.66	6.36	1.03	3.78
81	5.32	3.60	1.56	6.47
82	3.04	6.36	1.03	4.32
83	4.56	3.60	1.56	5.55
84	2.28	5.52	1.54	4.20
85	2.28	8.16	1.03	4.16
86	2.66	2.76	1.53	2.43
87	2.66	3.60	1.56	3.24
88	3.04	8.16	1.03	5.55
Average	6.20			8.32

Table A-3 **Missile Data for Wichita Falls, Texas Tornado (F4)**

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
1	6.15	2.64	1.54	5.40
2	6.53	3.48	1.55	7.62
3	9.22	3.96	1.53	12.13
4	4.61	6.12	1.54	9.43
5	11.53	4.44	1.52	16.83
6	4.61	6.12	0.77	4.71
7	6.53	6.12	0.77	6.68
8	4.61	3.48	1.55	5.38
9	7.69	6.96	0.77	8.98
10	11.53	7.92	0.77	15.16
11	10.73	4.44	1.52	15.66
12	6.92	4.44	1.52	10.10
13	6.15	4.44	1.52	8.97
14	8.46	4.44	1.52	12.34
15	6.15	8.76	0.77	8.99
16	5.38	5.28	1.53	9.43
17	10.76	7.44	0.77	13.35
18	7.69	5.28	1.53	13.47
19	5.77	6.96	0.77	6.74
20	10.76	3.48	1.55	12.56
21	9.22	6.12	0.77	9.43
22	5.38	2.64	1.53	4.72
23	4.61	3.48	1.55	5.38
24	13.07	7.44	0.77	16.21
25	6.15	9.60	0.77	9.89
26	5.38	8.28	0.77	7.46
27	5.38	7.92	0.77	7.08
28	3.84	3.48	1.55	4.48
29	3.84	7.92	0.77	5.05
30	4.61	19.32	0.77	14.82
31	15.37	6.96	0.78	17.97
32	3.84	1.80	1.50	2.25
33	3.08	0.96	0.77	3.59
34	3.84	4.44	1.52	5.61
35	3.84	6.96	0.78	4.49
36	7.69	2.64	1.53	6.75
37	8.47	6.96	0.77	9.88
38	12.30	7.92	0.77	16.17
39	5.38	6.12	0.77	5.50
40	4.61	3.96	1.53	6.06
41	4.61	6.12	0.77	4.71
42	4.10	9.60	0.94	8.03
43	10.76	4.44	1.52	15.70
44	8.47	7.92	0.77	11.12
45	3.84	4.44	1.52	5.61
46	5.38	4.44	1.52	7.87
47	6.15	8.76	0.77	8.99
48	6.92	4.44	1.52	10.10
49	3.84	9.60	0.77	6.18
50	4.61	4.44	1.52	6.73

Table A-3 Missile Data for Wichita Falls Texas Tornado (F4) (cont.)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
51	2.31	11.40	0.95	4.38
52	6.15	6.12	0.93	6.29
53	11.53	3.48	1.40	13.45
54	7.69	9.60	0.59	12.36
55	5.38	6.96	2.07	6.29
56	6.92	9.60	0.33	11.12
57	5.38	4.44	1.29	7.85
58	3.84	4.44	1.46	5.61
59	5.38	4.44	1.74	7.85
60	10.76	4.44	1.46	15.70
61	13.84	6.12	0.85	14.14
62	4.61	7.92	1.28	6.06
63	6.15	4.44	1.52	8.97
64	6.15	4.44	2.09	8.97
65	4.61	4.44	2.03	6.73
66	3.84	4.44	2.55	5.61
67	6.20	5.28	1.88	10.86
68	6.15	5.28	1.91	10.77
69	2.69	6.96	1.66	3.14
70	13.84	6.96	0.60	16.17
71	10.76	9.60	0.42	17.30
72	4.61	4.44	1.06	6.73
73	5.38	3.48	1.33	6.28
74	5.38	5.28	2.63	9.43
75	6.92	6.96	0.95	8.08
76	6.92	4.44	1.12	5.05
77	6.92	8.76	0.54	10.11
78	6.92	8.76	0.34	10.11
79	3.08	7.92	0.96	4.04
80	6.92	7.44	1.33	8.58
81	14.61	7.92	0.72	19.20
82	11.53	7.92	0.11	15.16
83	17.68	9.60	0.10	28.42
84	8.46	7.92	0.39	11.12
85	6.15	6.96	0.48	7.19
86	8.46	6.96	0.53	9.88
87	7.67	6.96	0.85	8.96
88	3.84	6.96	2.79	4.49
89	6.15	6.96	0.59	7.19
90	6.20	8.76	0.51	9.06
91	5.38	7.92	0.51	7.08
92	6.15	6.96	0.87	7.19
93	8.46	8.76	0.98	12.36
94	3.84	8.76	1.53	5.62
95	4.61	4.44	1.26	6.73
96	6.92	5.28	0.99	12.12
97	5.39	5.28	1.46	9.43
98	6.92	5.28	1.28	12.12
99	6.15	7.92	0.59	8.09
100	9.22	7.92	0.43	12.13

Table A-3 Missile Data for Wichita Falls Texas Tornado (F4) (cont.)

Missile No.	Length (ft.)	Width (in.)	Equiv. Thick. (in.)	Weight (lb.)
101	3.84	4.44	1.52	5.61
102	15.37	5.28	0.77	13.47
103	17.68	4.44	0.76	12.90
104	5.38	5.28	1.53	9.43
105	7.69	8.76	0.77	11.23
106	11.53	7.92	0.77	15.16
107	6.15	6.96	0.78	7.19
108	3.84	8.76	0.77	5.62
109	4.61	4.44	1.52	6.73
110	5.38	7.92	0.77	7.07
111	4.61	6.12	0.77	4.71
112	3.88	6.96	0.78	4.54
113	11.53	6.12	0.77	11.79
114	15.37	7.92	0.77	20.21
115	10.76	6.12	0.77	11.00
116	6.92	6.12	0.77	7.07
117	15.37	7.92	0.77	20.21
118	8.46	4.44	1.52	12.34
119	5.38	6.96	0.78	6.29
120	6.15	6.96	0.78	7.19
121	7.69	6.12	0.77	7.86
122	3.08	2.64	1.53	2.70
123	4.61	6.96	0.78	5.39
124	6.15	5.28	1.53	10.77
125	5.38	6.96	0.78	6.29
126	3.08	8.76	0.77	4.49
127	6.92	8.76	0.77	10.11
128	4.61	6.96	0.78	5.39
129	3.15	13.20	0.77	6.90
130	6.15	8.76	0.77	8.99
131	6.92	8.76	0.77	10.11
132	9.22	8.76	0.77	13.48
133	5.38	5.28	1.53	9.43
134	9.99	7.92	0.77	13.14
135	6.92	8.76	0.77	10.11
136	5.38	6.96	0.78	6.29
137	4.61	9.60	0.77	7.41
138	4.61	9.60	0.77	7.41
139	5.38	4.44	1.52	7.86
140	6.15	8.76	0.77	8.99
141	4.61	5.28	1.53	8.08
142	6.15	6.12	0.77	6.29
143	4.61	6.12	0.77	4.71
Average	6.94			9.20

APENDIX B

MAXIMUM SPEEDS AND HEIGHTS OF 15 POUND

2X4 TIMBER MISSILE IN F3 TORNADO

Tabulated below are calculated trajectory parameters of a 15 lb 2x4 timber plank missiles that were picked up by the f3 tornado wind. The mean value, variance and the standard deviation are calculated from the trajectory data:

1. Numbers of missiles picked up 141
2. Mean value:

$$\mu = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{\sum_{i=1}^{141} X_i}{141} = 129$$

3. Variance

$$S = \frac{\sum_{i=1}^{n} (X_i - \mu)^2}{n-1} = \frac{\sum_{i=1}^{141} (X_i - 129)^2}{140} = 362$$

4. Standard Deviation

$$\sigma = (S)^{1/2} = (362)^{1/2} = 19$$

where

X_i is missile horizontal speed, and

n is the number of missiles were picked up.

Trajectory Parameters 15 lb. 2x4 Timber Missile, F3 Tornado

Missile Spaced Number	Missile Trajectory Number	Distance to Tornado Path (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
1		750		No	Release
2		740			
3		730			
4		720			
5		710			
6		700			
7		690			
8		680			
9		670			
10		660			
11		650			
12		640			
13		630			
14		620			
15		610			
16		600			
17		590			
18		580			
19		570			
20		560			
21		550			
22		540			
23		530			
24		520			
25		510			
26		500			
27		490			
28		480			
29		470			
30		460			
31		450			
32		440			
33		430			
34	1	420	181	36	200
35	2	410	174	38	222

Trajectory Parameters !5 lb. 2x4 Timber Missile, F3 Tornado continued:

Missile Spaced Number	Missile Trajectory Number	Distance to Tornado Path (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
36	3	400	170	39	220
37	4	390	172	39	226
38	5	380	168	40	227
39	6	370	167	40	229
40	7	360	165	40	231
41	8	350	162	40	235
42	9	340	163	41	233
43	10	330	161	41	238
44	11	320	161	41	237
45	12	310	159	41	243
46	13	300	158	41	243
47	14	290	157	41	243
48	15	280	156	41	245
49	16	270	155	41	245
50	17	260	155	42	246
51	18	250	154	42	248
52	19	240	153	41	250
53	20	230	153	42	252
54	21	220	152	42	253
55	22	210	153	41	256
56	23	200	150	43	261
57	24	190	149	42	259
58	25	180	147	43	263
59	26	170	145	42	266
60	27	160	143	42	265
61	28	150	142	43	260
62	29	140	140	43	262
63	30	130	139	42	264
64	31	120	138	42	263
65	32	110		42	268
66	33	100	136	43	270
67	34	90	135	44	272
68	35	80	135	44	275
69	36	70	134	44	273
70	37	60	133	42	275

Trajectory Parameters 15 lb. 2x4 Timber Missile, F3 Tornado

Missile Spaced Number	Missile Trajectory Number	Distance to Tornado Path (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
71	38	50	132	43	274
72	39	40	132	41	266
73	40	30	131	41	263
74	41	20	132	40	261
75	42	10	132	40	262
76	43	0	132	40	259
77	44	-10	132	40	261
78	45	-20	131	40	256
79	46	-30	131	41	260
80	47	-40	130	40	255
81	48	-50	130	40	253
82	49	-60	129	40	245
83	50	-70	130	40	249
84	51	-80	129	39	240
85	52	-90	128	39	244
86	53	-100	127	40	243
87	54	-110	127	39	237
88	55	-120	128	39	233
89	56	-130	127	39	230
90	57	-140	128	38	227
91	58	-150	127	38	222
92	59	-160	128	38	223
93	60	-170	127	38	219
94	61	-180	130	38	218
95	62	-190	129	37	214
96	63	-200	130	38	215
97	64	-210	129	37	211
98	65	-220	130	37	210
99	66	-230	131	37	208
100	67	-240	133	37	205
101	68	-250	132	37	207
102	69	-260	133	37	205
103	70	-270	134	36	206
104	71	-280	135	37	207
105	72	-290	136	37	204

Trajectory Parameters 15 lb. 2x4 Timber Missile, F3 Tornado

Missile Spaced Number	Missile Trajectory Number	Distance to Tornado Path (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
106	73	-300	138	37	201
107	74	-310	138	37	198
108	75	-320	146	37	193
109	76	-330	148	37	190
110	77	-340	123	37	185
111	78	-350	122	38	180
112	79	-360	122	36	65
113	80	-370	123	34	68
114	81	-380	122	32	65
115	82	-390	121	29	63
116	83	-400	120	30	64
117	79	-410	121	30	64
118	80	-420	120	29	63
119	81	-430	119	29	63
120	82	-440	120	30	63
121	88	-450	119	29	63
122	89	-450	118	29	62
123	90	-470	119	29	63
124	91	-480	118	29	63
125	92	-490	118	29	63
126	93	-500	117	29	62
127	94	-510	117	29	61
128	95	-520	117	29	61
129	96	-530	117	29	61
130	97	-540	116	29	61
131	98	-550	116	29	62
132	99	-560	115	29	62
133	100	-570	115	29	62
134	101	-580	115	29	61
135	102	-590	114	29	61
136	103	-600	114	29	62
137	104	-610	114	29	61
138	105	-620	114	28	61
139	106	-630	114	29	61
140	107	-640	113	29	61

Trajectory Parameters 15 lb. 2x4 Timber Missile, F3 Tornado

Missile Spaced Number	Missile Trajectory Number	Distance to Tornado Path (ft)	Maximum Horizontal Speed (mph)	Maximum Vertical Speed (mph)	Maximum Height (ft)
141	108	-650	113	28	61
142	108	-660	113	28	61
143	110	-670	113	28	61
144	111	-680	112	28	61
145	112	-690	112	28	60
146	113	-700	111	28	60
147	114	-710	111	28	60
148	115	-720	111	28	59
149	116	-730	111	28	60
150	117	-740	110	28	60
151	118	-750	110	28	60
152	119	-760	109	27	60
153	120	-770	110	28	59
154	121	-780	110	28	60
155	122	-790	109	28	60
156	123	-800	109	28	60
157	124	-810	109	28	60
158	125	-820		28	60
159	126	-830	108	28	59
160	127	-840	108	28	59
161	128	-850	108	28	59
162	129	-860	108	28	59
163	130	-870	107	29	59
164	131	-880	107	28	59
165	132	-890	106	29	59
166	133	-900	106	28	59
167	134	-910	106	28	59
168	135	-920	106	29	58
169	136	-930	106	29	58
170	137	-940	105	29	58
171	138	-950	105	29	58
172	139	-960	105	28	58
173	140	-970	105	28	58
174	141	-980	104	28	58
175 176 177		-990 -1000 -1010		No	Release