EFFECT OF NATURAL PHENOMENA ON EXISTING PLUTONIUM FABRICATION FACILITIES

Response of Structures to Extreme Wind Hazard

at the

Exxon Nuclear Company
Mixed Oxide Fuel Fabrication Plant

Richland, Washington

Volume I

Institute for Disaster Research

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VOLUME I

by
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December 1979

FOREWORD

The U.S. Nuclear Regulatory Commission has undertaken a project to analyze the effects of natural phenomena upon existing plutonium fabrication facilities. The work is being accomplished by a task force of experts who are contributing to the various phases of the project. This report is one of a series of reports, to be produced by Texas Tech University, which examines the response of structures and the damage consequences to a specific existing plutonium fabrication facility caused by severe wind. The Exxon Nuclear Company Mixed Oxide Fuel Fabrication Plant (MOFP) located at Richland, Washington is the subject of this report. Volume I of this report presents the methodology, the basic data, the results and the conclusions of the study. Volume II contains the structural calculations on which the results are based.

The project tasks are performed by Texas Tech University under subcontract from Argonne National Laboratory (Contract Number 31-109-38-3712). Mr. James E. Carson, Division of Environmental Impact Studies, Argonne National Laboratory, is the project manager. Dr. James R. McDonald and Dr. Kishor C. Mehta of Texas Tech University are the principal investigators for the project. Mr. Douglas A. Smith of Texas Tech University (now of Southwestern Public Service Company) served as research associate. The project is coordinated through the Department of Civil Engineering and the Institute for Disaster Research, Texas Tech University.

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I. INTRODUCTION

This report is part of a study sponsored by the U. S. Nuclear Regulatory Commission to assess the potential radiological consequences of natural phenomena (flood, earthquakes, and severe winds) on existing plutonium fabrication facilities. The study involves determination of hazard risk, structural response, source term, dispersion, demographic patterns and dose levels. The paper by J. A. Ayer and W. Burkhardt, "Analyses of Effect of Abnormal Natural Phenomena on Existing Plutonium Fabrication Plants" [1]*, provides background on the overall hazards evaluation. The response of structural systems and components to wind hazard at the Exxon Nuclear Company Mixed Oxide Fuel Fabrication Plant (MOFP) located at Richland, Washington is the subject of this report.

The windstorm risk assessment was made by Fujita [2] based on tornado and other severe wind records from the geographical region surrounding the plant site. The windstorm hazard at the site consists of straight line winds or tornadoes and is expressed in terms of expected value of windspeed for a given probability of occurrence. Associated with tornadic windspeeds are implications of atmospheric pressure change and windborne debris.

Structural response of the building and the potential of windborne debris are expressed in terms of threshold values of windspeed to produce postulated damage to the building enclosure. The damage postulation is based on nine years of windstorm damage investigation experiences involving more than forty windstorm incidents by the senior authors. The structural response and missile impacts are subsequently translated into consequences of damage to glove boxes and filters. These consequences then provide information to the source term evaluators, who, in turn, determine the amount and form of plutonium that would be available for dispersion into the atmosphere.

The type of structural systems and construction material properties at the Exxon Nuclear MOFP facility are discussed in Section II of this

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*Numbers in brackets pertain to References, Section VI report. The structural systems and the material properties are documented from the plant drawings and specifications, the EDAC Task I report [3] and a site visit. A general discussion of structural response to the windstorm hazard, including the effects of wind, atmospheric pressure change and windborne debris, is contained in Section III. The consequences of damage to glove boxes and filters also are defined in Section III. Section IV contains postulated failure modes, calculated threshold windspeed values, and a summary of postulated damage for the Exxon facility. Actual calculations of the values presented in Section IV are contained in Volume II of this report [4]. Scenarios of expected structural damage and the consequences of damage to plutonium containments for selected windspeeds are presented in Section V.

II. STRUCTURAL SYSTEMS AND MATERIAL PROPERTIES

In this section the structural systems employed in the Exxon MOFP facility are described and the material properties which are common to them are defined. Only those features of the structure that are critical to wind hazard assessment are presented herein.

A. General Layout of the MOFP Facility

The Exxon MOFP facility is located in Richland, Washington. A floor plan of the facility is shown in Figure 1. Areas of concern as defined by Mishima [5] are indicated by crosshatching. The areas of concern are the Mixed Oxide Preparation Area, the Cold Lab Area, the Mass Spec Area, the Poison Rod Fab Area, and the Vault, as indicated in Figure 1.

B. Structural Systems

This building is of one story construction. A mezzanine at the north end of the building contains offices and a cafeteria. A plan view of the building with designated areas of concern is shown in Figure 1. The building is approximately 100 ft. x 114 ft. in plan. The wall height is typically 29 ft.

For discussion purposes, the building can be divided into a lab area and an office area. The two areas are separated by a hallway. The north end of the lab area has a 10-in. cast-in-place reinforced concrete wall, (Ref. Figure 1). All the areas of concern, except the Vault, are located in the lab area. Therefore, discussion of the structural systems of the building is limited to the lab area.

The roof over the lab area consists of a built-up roof on a metal deck. The metal deck is supported by long-span steel joists. The framing plan for the laboratory area is shown in Figure 2. At the south wall the steel joists frame into a collector beam, which is anchored to stub beams framed into each column. At the 10-in. cast-in-place concrete wall the joists bear on the wall. At the 10-in. wall a positive connection provides uplift resistance, however the joists

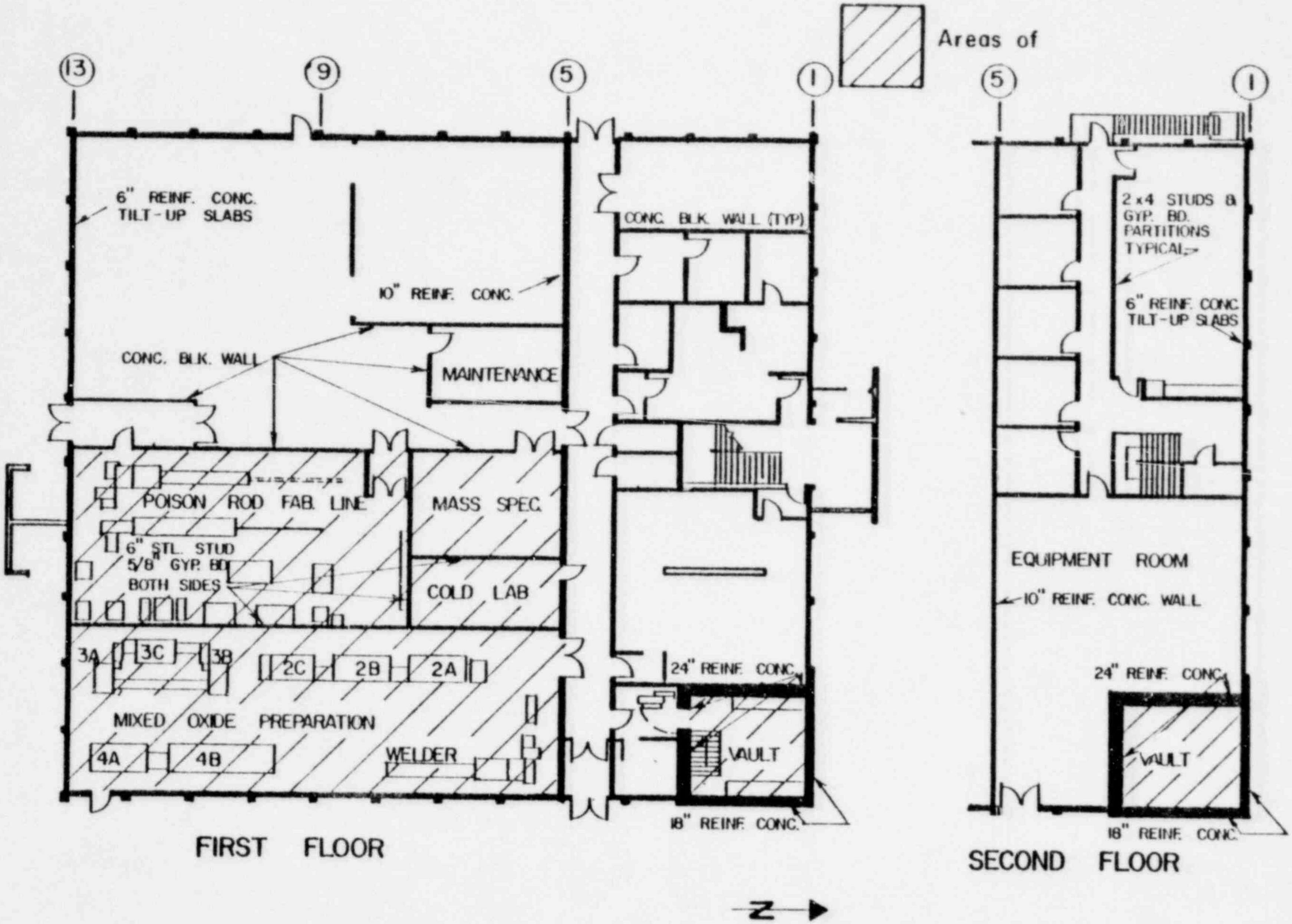


FIGURE 1. MOFP BUILDING FLOOR PLAN SHOWING AREA OF CONCERN

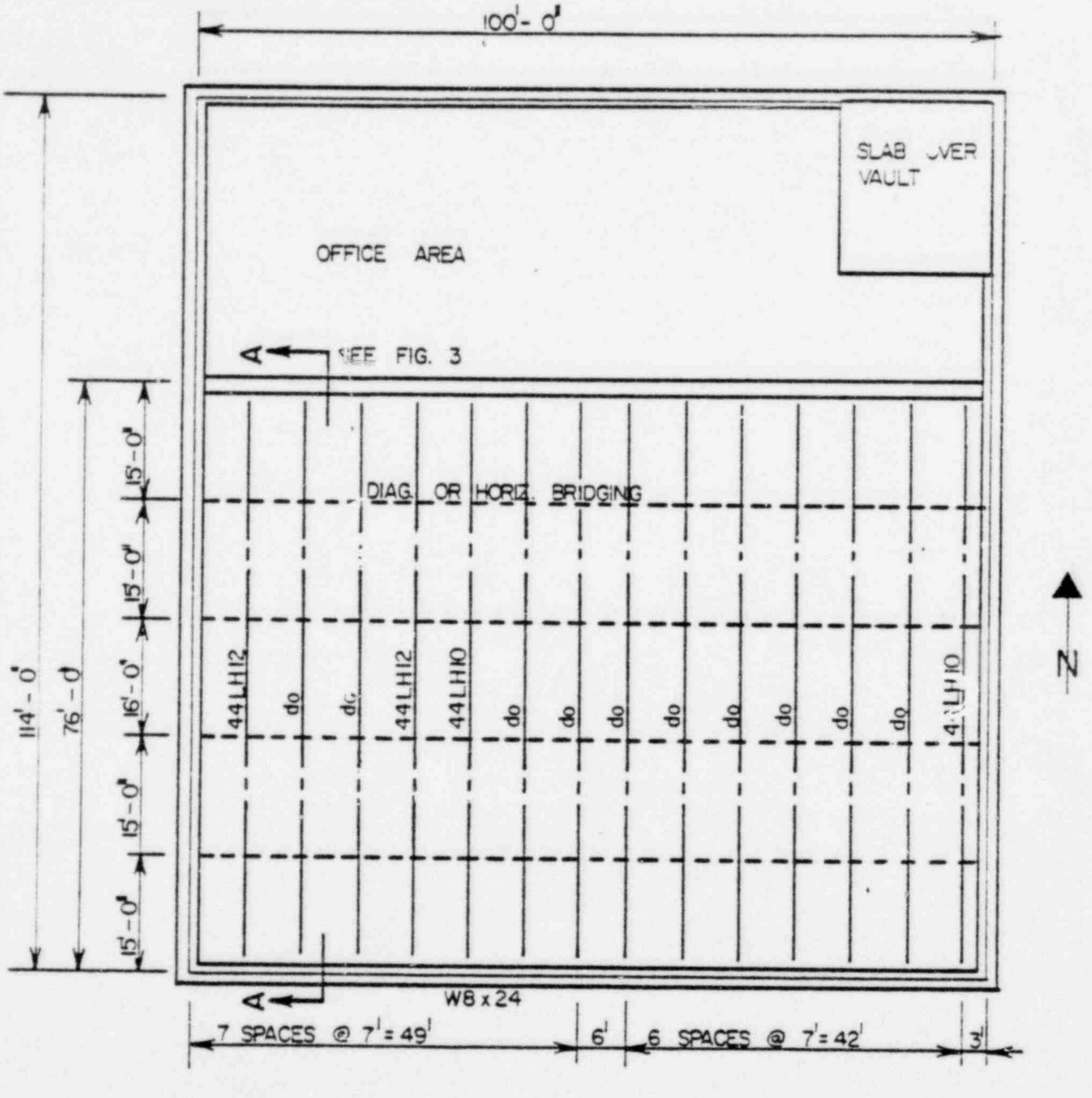


FIGURE 2. ROOF FRAMING PLAN OVER LAB AREA

are free to slip in plane. Details of these two connections are shown in Figure 3.

The exterior walls are precast concrete panels. Typical panels are 28 ft. high, 9 ft. wide and 6 in. thick, as shown in Figure 4. A typical wall panel is reinforced with #3 bars at 12 in. centers in the vertical direction and #4 bars at 12 in. centers in the horizontal direction. The reinforcing steel extends into the cast-in-place columns and parapet beams to provide continuous support for the wall panel. The wall panel is not anchored to the footing. Instead, friction between the panel and grout layer is relied upon to support the bottom edge of the wall. The details of the connections between the precast wall panels and the columns, the parapet beams and the footings are shown in Figures 4 and 5.

The columns and the parapet beams are constructed of cast-in-place reinforced concrete. The column dimensions are typically 13 in. by 14 in. and are reinforced with 4-#8 bars. The columns are anchored to their footings by a single #8 bar and by a shear key as shown in Figure 5. At the top, the column reinforcing extends into the parapet beam to provide positive anchorage.

The parapet beam is 12 in. x 14 in. and is continuous along the top of the wall. Reinforcement used in the parapet beam is typically 4-#4 bars as shown in Figure 4. The in-plane truss system, which is provided for seismic resistance, bears on top of the parapet. It is held in place by means of anchors which are bolted to the column. Because of the support provided by the in-plane truss, the parapet beam resists lateral wind loads as a continuous beam.

The inplane truss system is constructed of rolled steel wide flange sections, round bars, and turnbuckles as shown in Figure 6. It is anchored securely to the parapet beam.

Interior walls in the lab area are constructed of gypsum board and metal studs or unreinforced concrete masonry block. These walls do not significantly affect the response of the structure to wind loads.

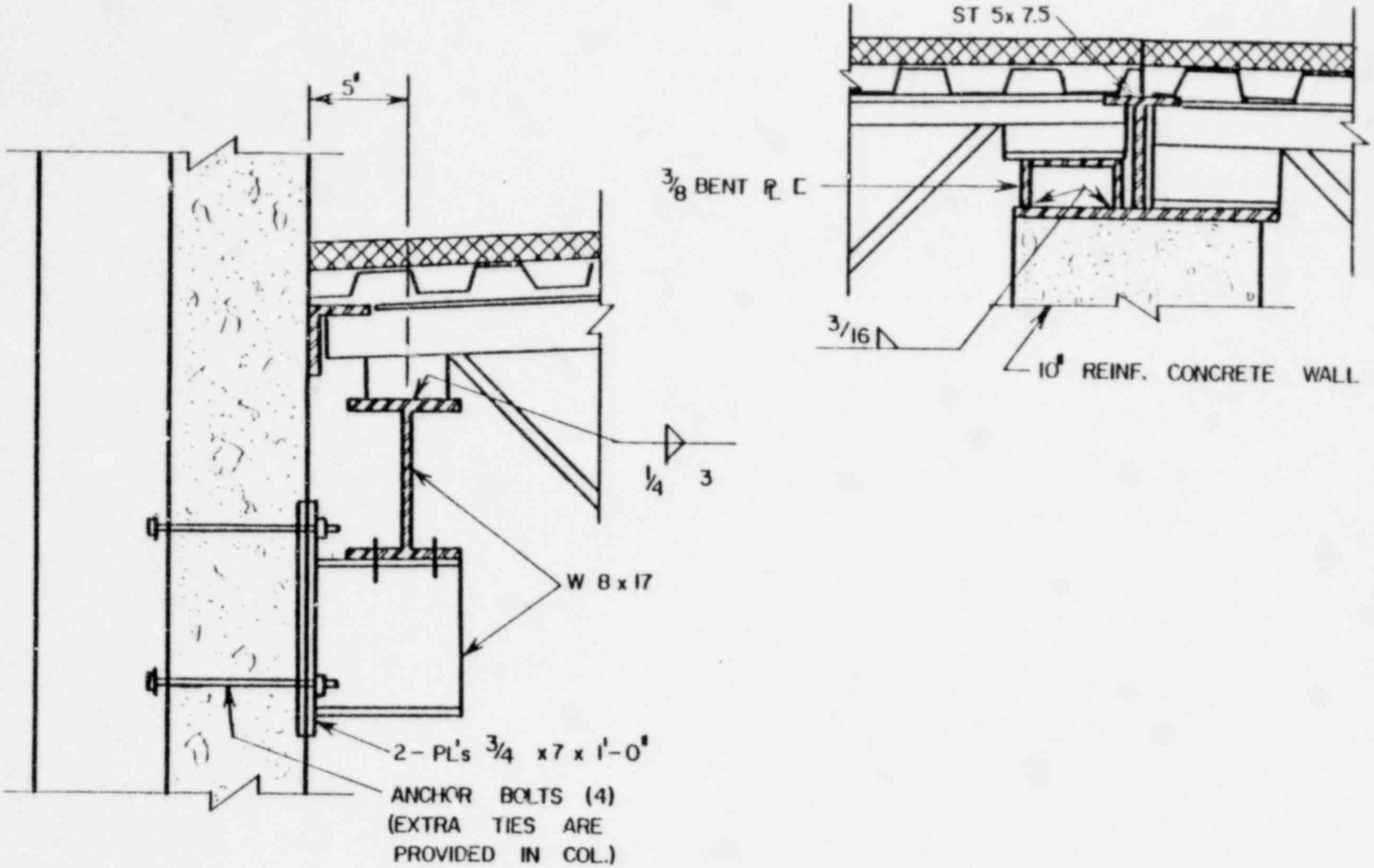
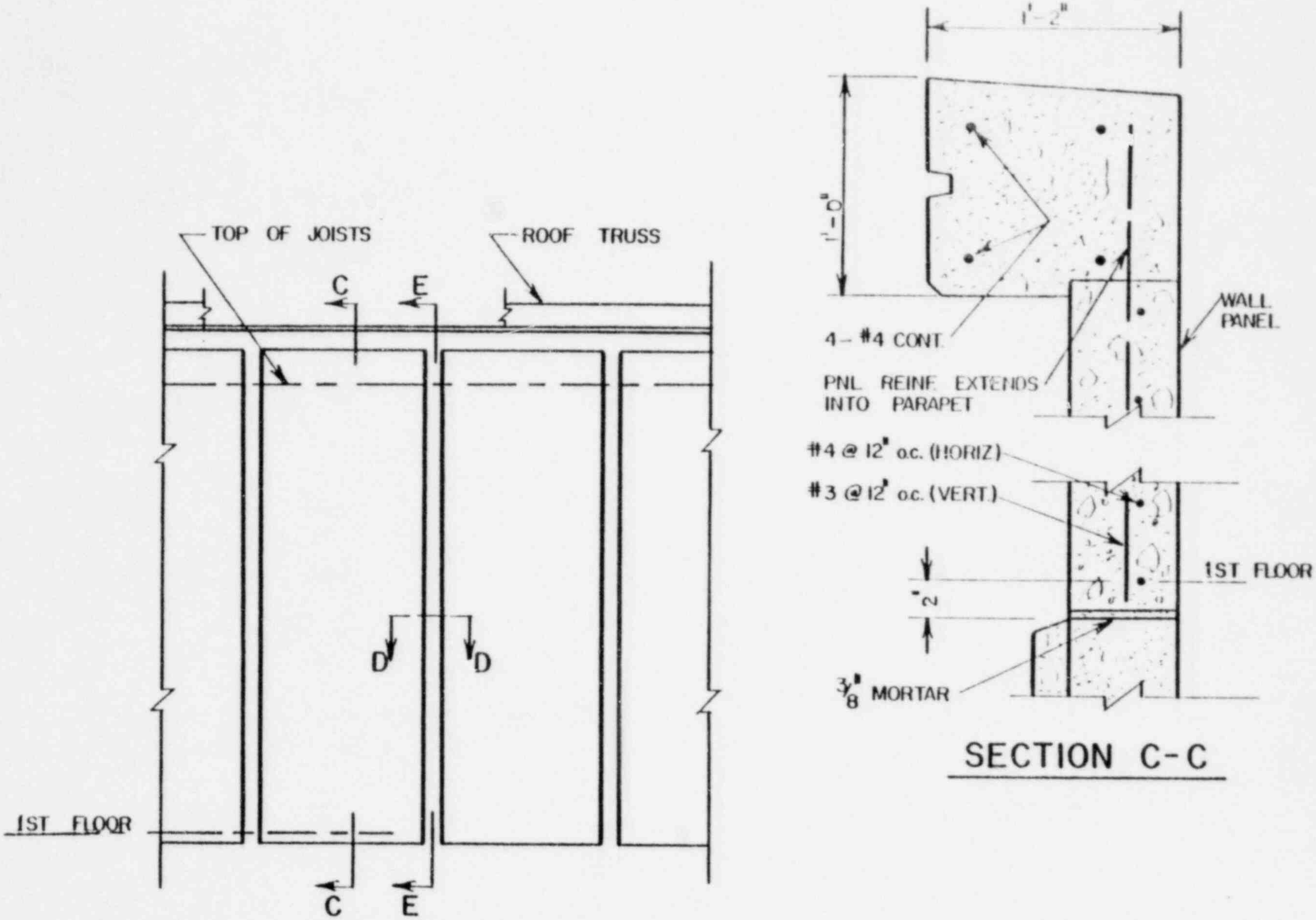
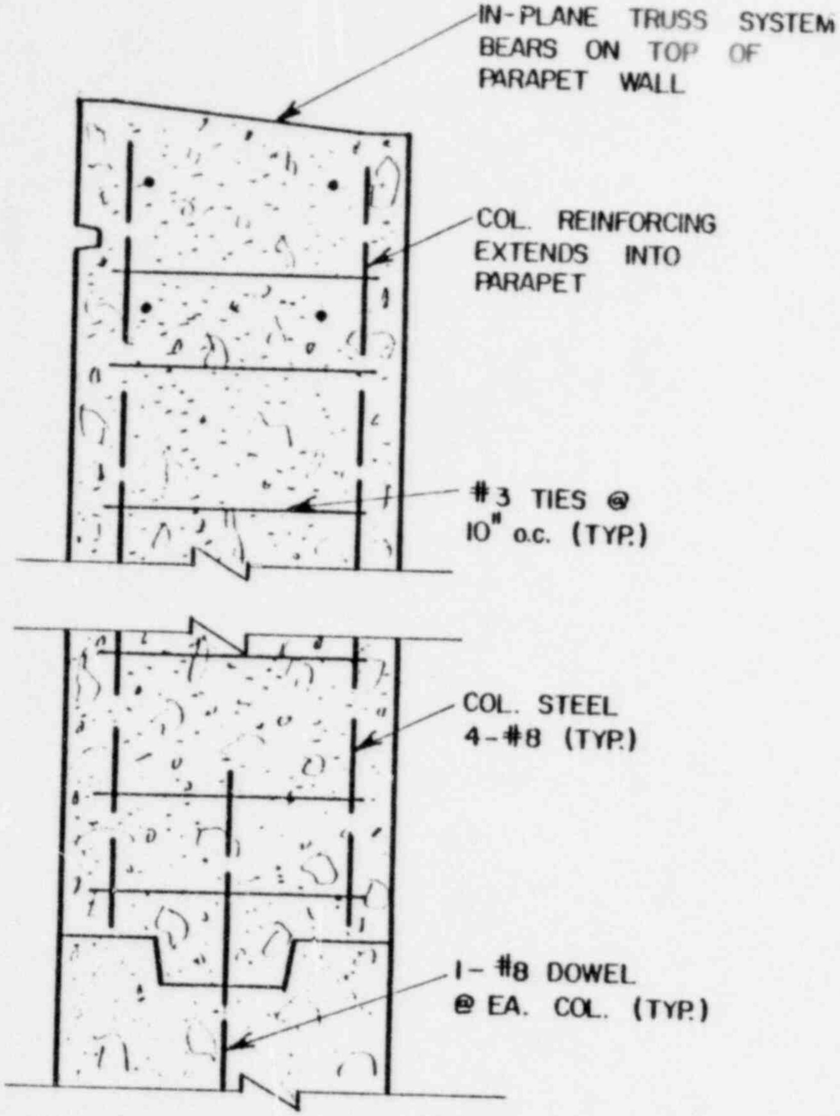


FIGURE 3. SECTION SHOWING JOIST BEARING DETAILS

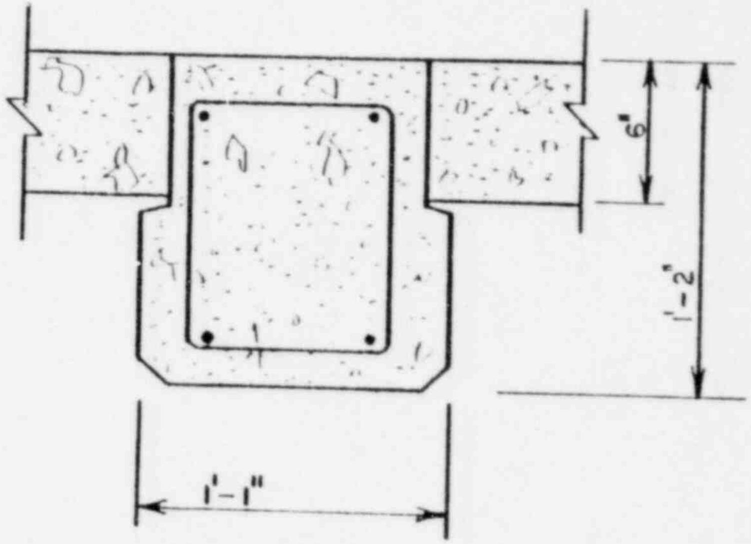


SECTION C-C

FIGURE 4. TYPICAL WALL PANEL CONSTRUCTION



SECTION E-E



SECTION D-D

FIGURE 5. TYPICAL COLUMN DETAIL

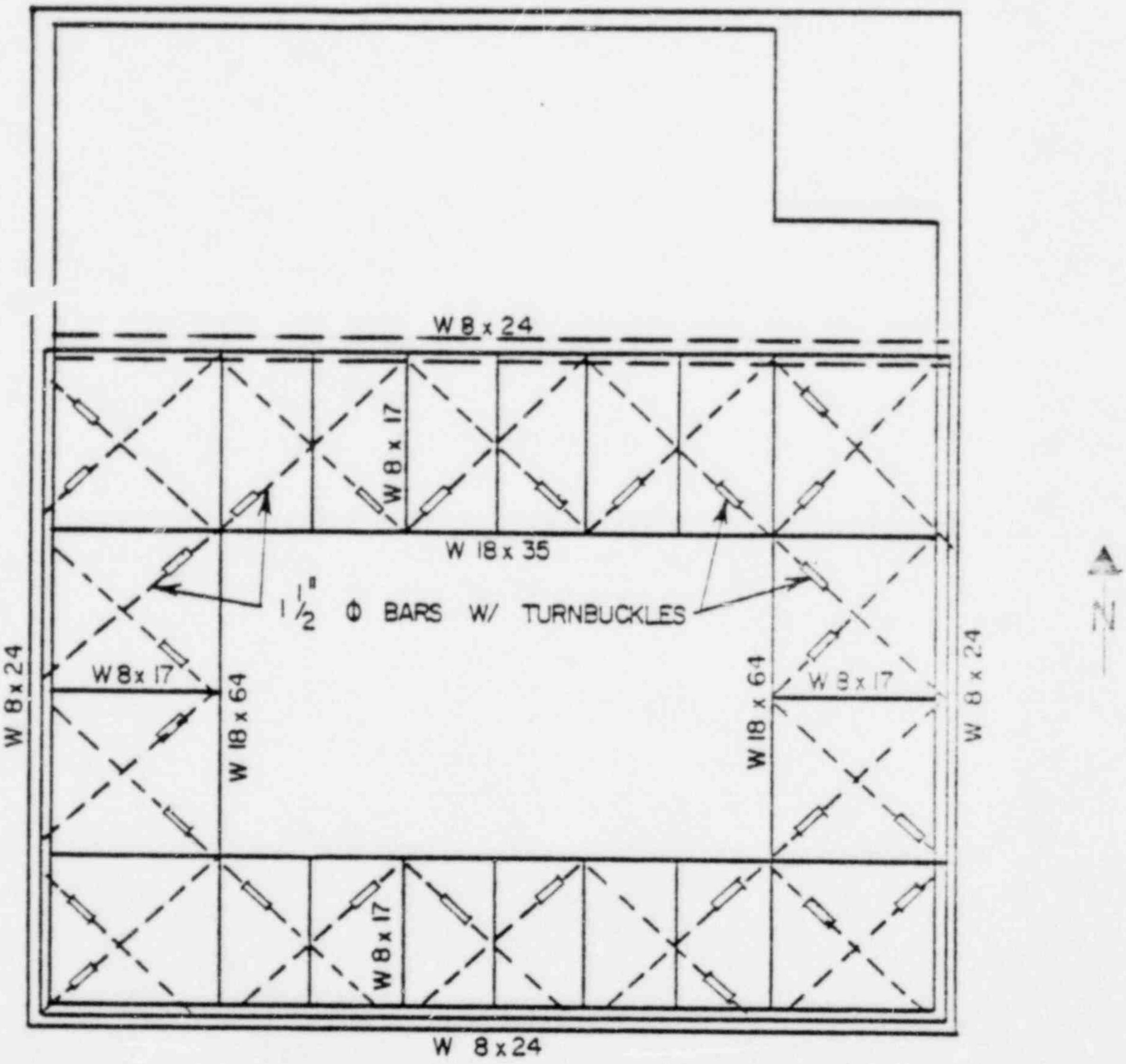


FIGURE 6. INPLANE ROOF TRUSS FRAMING PLAN

The vault is a massive cast-in-place concrete structure. Its exterior walls are 18 in. thick and its interior walls are 24 in. thick as shown in Figure 7. The vault roof is an 8 in. reinforced concrete slab with additional support provided by wide-flange steel beams. The steel beams are attached to the roof slab by bolts through the slab.

C. Material Properties

Properties of the building materials that are significant to wind damage assessment are listed in Table I. The table lists median values of material properties, and a range of low and high values. The variation of material property values is assumed to be log-normal; the magnitude of the ranges of strength are based on judgment. The primary source of material property values is EDAC Task I report [3]. In cases where material properties are not available in documents, judgments based on standard professional practice are made. In addition, if material properties for building components at the Exxon MOFP facility are not provided in reports such as Reference 3, the material property values are taken from the previous EDAC reports [6,7] to insure consistency among the different studies.

For steel and weld metals, the ultimate shear strength is taken as $1/\sqrt{3}$ times the tensile strength of the material. This relationship is based on the maximum distortion energy theory for ductile material [8].

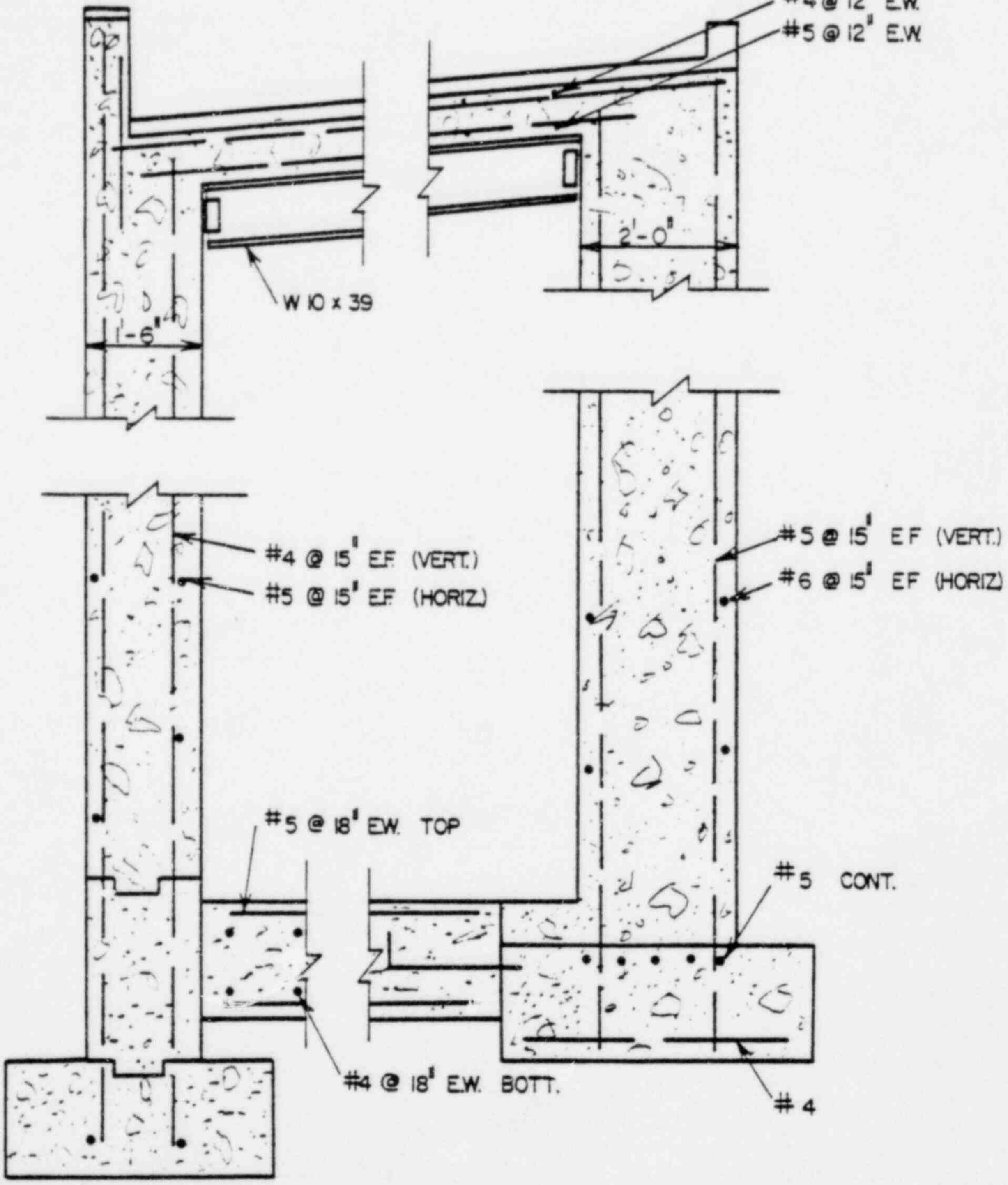


FIGURE 7. TYPICAL SECTION THROUGH VAULT

TABLE I

MATERIAL PROPERTIES

Material	Property	Median Value	Range Low	Range High	Source
Weld Metal	shear strength	47 ksi	40 ksi	56 ksi	E70 electrodes
A36 Structural Steel	tensile strength	68 ksi	64 ksi	73 ksi	EDAC [3]
Steel Roof Deck (ASTM A570 Gr.C)	tensile strength shear strength	60 ksi 34.6 ksi	56.5 ksi 32.6 ksi	64 ksi 37 ksi	EDAC [3]
Reinforcing steel (ASTM 615 Gr.60)	tensile strength yield strength	102 ksi 66 ksi	97 ksi 62 ksi	109 ksi 70.5 ksi	EDAC [3] EDAC [3]
Structural Bolts < 1" ϕ, ASTM A325	tensile strength	130 ksi	125 ksi	136 ksi	EDAC [3]
3/4"ϕ Stud Anchor "Redhead"	Pullout strength shear strength	10.1 kips 14.4 kips	8.5 kips 12.0 kips	12.2 kips 17.0 kips	EDAC [3]
Structural Concrete at 28 days	Compressive strength	4.0 ksi	3.4 ksi	4.7 ksi	EDAC [3]

III. STRUCTURAL RESPONSE AND DAMAGE CONSEQUENCES

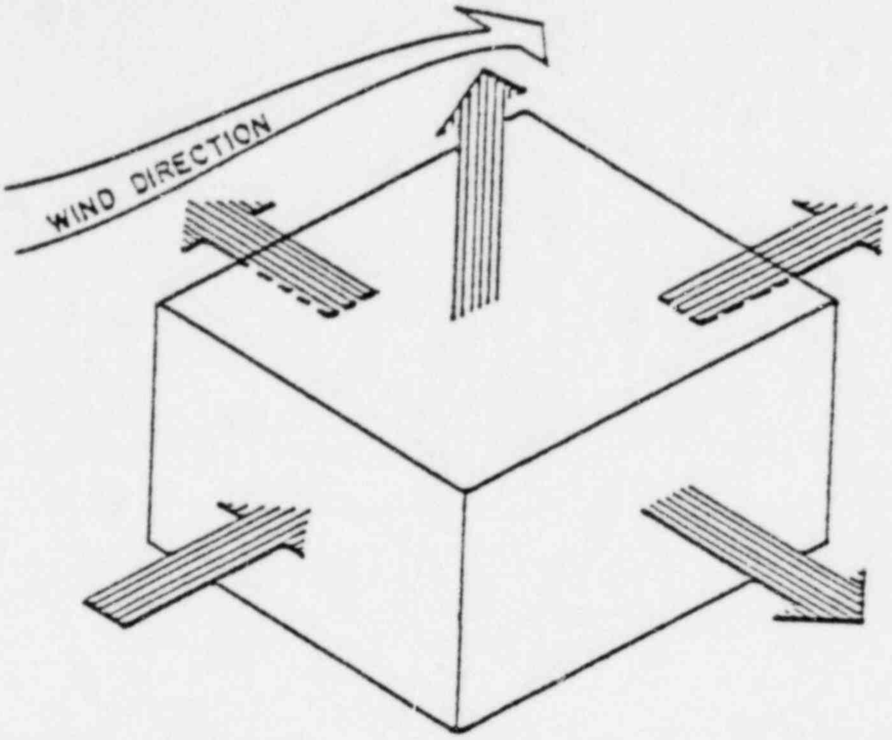
The effect of wind loads on a building and its components is referred to herein as structural response. This section presents a generic discussion of structural response and damage consequences. In order to predict damage to glove boxes containing plutonium as well as to filters, the structural response of the building and its components due to three effects of windstorms, namely, wind, atmospheric pressure change (only in case of tornadoes), and windborne debris must be evaluated. The wind and atmospheric pressure change effects may be combined under specific circumstances. The general analytical approach for determining a threshold value of windspeed that will produce significant damage to a building or its components is presented in this section. In addition discussions concerning damage from windborne debris is also presented. The structural damage to the building and its components is then translated into subsequent damage to glove boxes and filters. Because the consequential damage to glove boxes and filters is random, rational judgments regarding glove box and filter damage are made.

Fire, as a consequence of windstorm damage, does not appear to be a pertinent hazard. In more than 40 major windstorm events investigated by the authors, not a single one produced a fire as a consequence of windstorm damage.

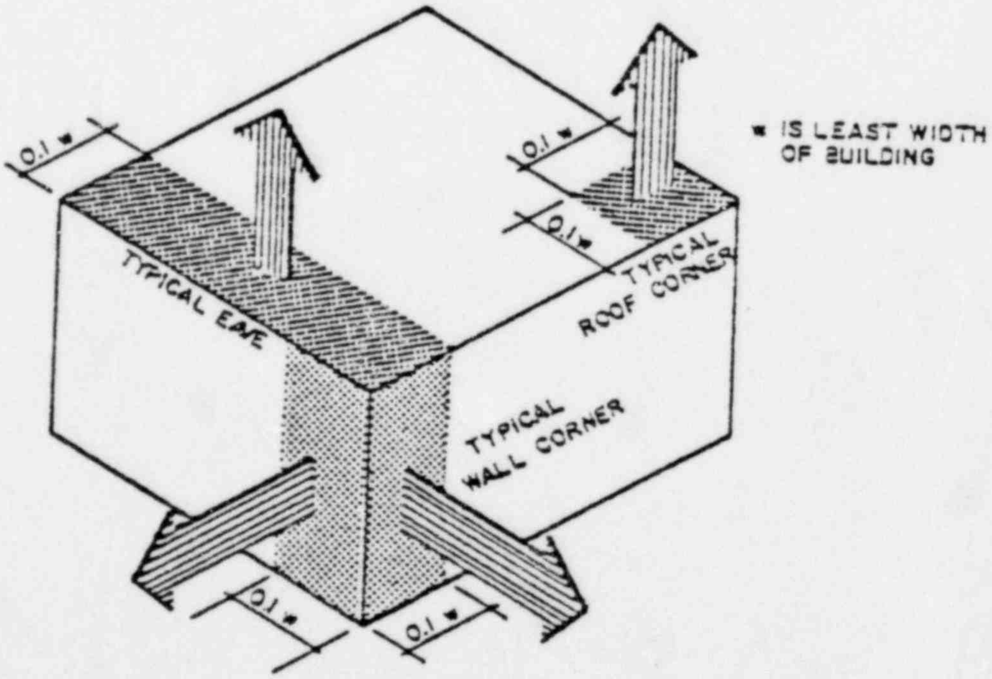
A. Threshold Windspeeds to Produce Damage

Threshold values of windspeed to produce damage to a building and its components are obtained by applying basic techniques of structural analysis. These techniques are utilized by the authors to determine windspeeds in tornadoes [9]. Damage, as used here, implies the removal of a component due to outward acting forces or the total collapse of a member due to outward or inward acting forces.

Wind interacts with a flat-roofed building and produces inward acting external pressures on the windward wall and outward acting external pressures on the sidewalls, the leeward wall, and the roof (Ref. Figure 8). In addition, relatively high outward acting external pressures are produced on localized areas at wall corners. roof corners



EXTERNAL WIND PRESSURES



LOCALIZED WIND PRESSURE

FIGURE 8. WIND PRESSURES ON A BUILDING

and eaves (Ref. Figure 8). In cases where there are openings in the walls or the roof of a building, internal pressures are also produced. These internal pressures may combine with external pressures to produce a more severe loading condition on a building component. Since wind can come from any direction, the failure mode of a building component should be evaluated for the inward acting pressures as well as the outward acting pressures.

Knowing the strengths of the materials and the type of structural system, principles of mechanics are applied to determine structural response and the wind pressure to produce a postulated failure. The structural response of a building component is made up of a static and a dynamic part. For low-rise buildings and relatively stiff components the contribution of the dynamic part of the response can be neglected. The fundamental frequencies of low-rise buildings or their components such as masonry walls or metal roof decks have fundamental frequencies greater than 3 Hz, while most of the free field wind gust spectrum energy is in the frequency range that is less than 0.5 Hz[10,11]. The disparity between fundamental frequencies of building components and gust frequencies of the wind suggests that the dynamic part of the response is negligible for ordinary structures.

Once the wind pressure required to produce the postulated failure mode is obtained, the corresponding windspeed V is calculated using appropriate equations that relate windspeed to aerodynamic pressure. The general form of the equation is

$$p = 0.00256V^2C \qquad (1)$$

where

p is the wind pressure in psf

V is the windspeed in mph

C is a shape factor or pressure coefficient

Equation (1) is the stagnation pressure multiplied by an appropriate pressure coefficient. Pressure coefficients are obtained primarily from wind tunnel tests of model structures. Coefficients from the

American National Standards Institute Standard A58.1-1972 [12] are used in this study.

The ANSI A58.1 Standard [12] defines three types of pressure coefficients:

(1) External pressure coefficient, C_p
(2) Internal pressure coefficient, C_{pi}
(3) Net pressure coefficient, C_f

External pressure coefficients are applicable for external wind pressures acting on enclosed buildings. The equation for externally acting wind pressure is:

$$p = 0.00256V^2 (C_p) \qquad (2)$$

If the building has windows, doors or other openings that allow the wind to get inside the building, internal pressures act on the walls and roof in addition to the external pressures. The equation for combined external and internal wind pressure acting on a building component is:

$$p = 0.00256V^2 (C_p - C_{pi}) \qquad (3)$$

The sign of the internal pressure coefficient C_{pi} is a function of wind direction and opening locations in a given building.

Net pressure coefficients are used for structures such as chimneys or towers. The wind pressure is the net horizontal pressure and is obtained from the equation:

$$p = 0.00256V^2 (C_f) \qquad (4)$$

With knowledge of the wind pressure p calculated from structural mechanics procedures, and with appropriate pressure coefficients determined from the literature, the threshold windspeed V can be calculated utilizing the above equations.

The threshold windspeeds that produce damage as determined using the above equations include wind gusts. The calculated windspeeds are equivalent to "gust speed" given in Column B, Table 14 or "tornado windspeed" given in Column D, Table 14 of Reference 2. Whether the threshold windspeeds are straight-line winds or tornadic winds depend on the probability of occurrence of that intensity wind.

B. Atmospheric Pressure Change (APC)

If a tornado is the windstorm hazard, then the effect of atmospheric change (APC) may also contribute to the damage. A region of reduced pressure exists near the core of a tornado. As the tornado passes over a building the pressure inside a building becomes greater than that on the outside, thus producing a differential pressure across the walls and the roof of the building. Table II gives the APC values associated with tornadic windspeeds for different probabilities of occurrence at the Exxon Nuclear MOFP facility. The probabilities of occurrence of tornadic windspeeds at the Exxon MOFP facility are obtained from Reference 2. The APC values are calculated using the cyclostrophic equation [13].

If a building is sealed, it will experience the effect of APC as the tornado passes over it. However, most industrial buildings are not totally sealed (air tight). If there are enough openings in the walls or the roof to allow air inside the building to escape, the differential pressure will be equalized. The venting areas per cubic ft. of building are given in Table II for different values of APC.

TABLE II

Tornadic Windspeeds, Atmospheric Pressure Change and Venting Requirements

Probabilities of Occurrence per year	Straight Line[a] Windspeeds, mph	Tornadic[b] Windspeed, mph	Atmospheric Pressure[c] change, psf	Venting Area[d] sq.ft/cu.ft
10	44	-	-	-
10^{-1}	65	-	-	-
10^{-2}	88	-	-	-
10^{-3}	109	-	-	-
10^{-4}	128	-	-	-
10^{-5}	143	-	-	-
10^{-6}	155	-	-	-
10^{-7}	-	167	91	0.17×10^{-3}

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[a] Includes gusts; Column B of Table 14 from Reference [2]

[b] Column D of Table 14 and Figure 6 from Reference [2]

[c] Determined using cyclostrophic equation Reference [13, 2]

[d] Escaping air is limited to 25 mph

C. Combination of Wind and Atmospheric Pressure Change

For buildings which are sealed, the combined effects of wind and atmospheric pressure change may produce the most critical loading condition on the building components. The highest load could be due to outward acting pressure caused by the maximum windspeed in a tornado and the associated atmospheric pressure change at the location of the maximum windspeed. It is possible to express the value of the atmospheric pressure change in terms of maximum windspeed if certain assumptions are permitted. This information is given below.

The maximum windspeed, V, in a tornado is a combination of the tangential, V_t and translational, V_{tr} windspeeds:

$$V = V_t + V_{tr}$$

Fujita [2] assumes that translational windspeed is 20% of the maximum windspeed, hence

$$V_t = 0.8V$$

The cyclostrophic equation suggests that atmospheric pressure change at the point of maximum windspeed in a tornado is:

$$APC = 0.5 \rho V_t^2$$

Where ρ is mass density of air. The total outward acting pressure due to combined effect of wind and APC on a building component would be

$$p = 0.00256V C_p + 0.5 \rho V_t^2$$

Substituting the value for ρ and utilizing $V_t = 0.8V$, the total outward acting pressure will be

$$p = V^2 (0.00256C_p + 0.00164)$$

The value of C_p would depend on the type of component such as side wall, roof, roof corner, etc. For example, the pressure coefficient for the roof is $C_p - 0.7$, hence the uplift pressure would be

$$p = 0.00343V^2$$

A threshold value of a tornadic windspeed can be determined that would fail a building component. Two requirements are essential to consider combined effects of wind and APC; they are (1) the building is sealed, and (2) the threshold windspeed is in tornadic windspeed range as specified in Table II.

D. Windborne Debris

Windstorms tend to pick up and transport various types of loose debris. The kinds of debris range in size from roof gravel to automobiles. Most of the debris consists of objects such as sheet metal, timber from damaged houses or other light weight objects. In a very intense tornado (windspeeds greater than 200 mph) debris can be propelled to high velocities to become damaging missiles. Velocities attained by typical pieces of debris which can cause damage are shown in Table III. Missiles which impact exterior walls may not pose danger to glove box integrity or to HEPA filters if much of the missile energy is absorbed by the wall. The walls of the Exxon MOFP are reinforced precast concrete panels and columns. Hence, windborne debris damage is not likely to be critical at this facility.

E. Damage Consequences

The building damage and damage consequences discussion presented here are generic in nature. Structural response, component damage and missile impact translate into damage to glove boxes, filters, or other containments of plutonium. The consequences of building damage or missile impact to glove boxes and other containments can be catastrophic or can be negligible depending on the potential to release plutonium. The damage to glove boxes and the subsequent plutonium release potential are defined as follows:

> Crushing of Glove Box: If a heavy object falls on the glove box, structural members of the box may collapse resulting in the glove box being crushed. This event could occur if a load-bearing wall or building frame should collapse thus allowing the roof structure to fall downward. In this case the integrity of the glove box would be violated. The material inside the glove box would be exposed to the atmosphere.

TABLE III

Windstorm Generated Missile Velocities [13]

Missile	Weight (lb)	Impact Area (ft^2)	Missile Velocities, mph Windspeed, mph (V)				
			100	150	200	250	300
Timber Plank 2 in. x 4 in. x 15 ft	28	0.04	*	70	98	124	160
Timber Plank 4 in. x 12 in. x 12 ft	115	0.29	*	60	90	100	125
Standard Steel Pipe 3 in. dia x 15 ft	76	0.067	*	*	65	85	110
Utility Pole 13.5 in. dia x 35 ft	1490	0.99	*	*	*	60	100
Automobile	4000	20	*	*	*	25	45

Note 1. Interpolation of windspeed is reasonable and consistent with the current state-of-the-knowledge on missile generation.

Perforation of the Glove Box: Pieces of timber, concrete blocks, loose pieces of pipe or equipment could strike a glove box causing an opening in the glove box window. Plutonium stored in canisters is not likely to be released in this case, but loose material in powder form could possibly escape the confines of the glove box. Failure of an exterior wall could allow the wind to circulate throughout the building, causing loose objects to be thrown against the glove boxes. Windborne debris could cause missile impact on the glove box and may cause perforation of the glove box.

Tear in Glove: The gloves are the weakest elements with respect to the glove box integrity. Flying or moving debris could strike and tear a glove. Some of the material in powder form could be pulled or blown from the glove box should the ventilation system be altered by the effects of the wind. Containerized material or material in pellet form is not likely to escape.

These three definitions of glove box damage are correlated with extent of damage to the building and its components, and are shown in Table IV. Damage scenarios in Section V present actual damage consequences.

TABLE IV.

Damage Consequences

Building or Component Damage	Glove Box or Filter Damage	Remarks
1. Mechanical equipment on roof topples but does not penetrate roof	Filters in ventilation equipment crushed	
2. Collapse of mechanical equipment through roof	Glove box crushed under equipment; filters crushed	Only the box underneath the equipment damaged
3. Uplift of small portion of roof corner or eave	Perforation of a few glove boxes; a few filters crushed	Items may fall through roof opening
4. Uplift of entire roof deck	Perforation of a few glove boxes; a few filters crushed	Items may fall through opening
5. Failure of doors or windows	Tear in several gloves; glove box close to opening may be perforated, a few filters outside of boxes crushed	Wind and windborne debris cause damage
6. Wall corner failure	Perforation of glove boxes located near the wall corner	
7. Loss of wall siding	Filters crushed; perforation of a few glove boxes	Windborne debris can enter the building
8. Outward collapse of nonload-bearing wall	Filters crushed; perforation of a few glove boxes	Windborne debris can enter the building
9. Inward collapse of non-load-bearing masonry wall	Glove boxes in the vicinity of walls crushed; filters crushed	
10. Collapse of load-bearing wall	Glove boxes crushed; filters crushed	Roof collapses downward
11. Lateral collapse of building	Glove boxes crushed; filters crushed	

IV. THRESHOLD WINDSPEEDS AND FAILURE MODES

The threshold values of windspeed that cause failure of building components have been calculated. Detailed calculations are contained in Volume II of this report [4]. Each postulated failure mode has potential for damage to glove boxes and HEPA filters. The failure mode that occurs at the lowest windspeed is the critical failure mode for a given building component. Critical failure modes of components and their associated windspeeds are summarized in this section. These data are then used to formulate damage scenarios in Section V for selected windspeeds and associated probabilities of occurrence.

Calculated threshold windspeeds are considered gust speeds or tornadic windspeeds which include gusts. In addition, the threshold windspeeds to produce damage are also considered to be nominal windspeeds since they are based on median strengths of materials. Windspeed ranges are provided for each calculated threshold windspeed to reflect variation in material properties. In cases where the material properties are not the governing failure criteria, windspeed ranges are based on subjective engineering judgments. All windspeed ranges are assumed to have a log-normal distribution.

Critical failure modes, threshold windspeed values for wind damage, atmospheric pressure change effects, and missile impact damage are described below.

A. Wind Damage at MOFP Facility

The framing and construction details of the Exxon Nuclear MOFP facility are discussed in Section II. A 10 in. reinforced concrete wall (Ref. Fig. 1) separates the building into an office area and a laboratory area (high bay area). All the areas of concern except the vault are in the laboratory area. Calculated threshold windspeeds to fail roof components, wall components, and the structural frame are shown in Table V and discussed below.

The door in the east wall at the southeast corner of the building

TABLE V

Threshold Failure Windspeeds For Exxon MOFP

Building Component	Nominal Threshold Windspeed mph	Windspeed Range mph		Remarks
		Low	High	
Doors:				
Southeast Corner	88	83	92	Collapses outward
Other Exterior Doors	140	133	147	Collapses inward; alleviates effects of APC.
Roof:				
West Eave Area	167	154	182	Failure of bearing connection of joist due to uplift; 10 ft wide section collapses downward.
East Eave Area	189	174	206	7 ft wide section collapses downward
Other Areas	231	213	252	Several joists could fail.
Walls:				
Corners (except vault)	184	170	199	Failure of column and parapet beams; outward collapse of 20 ft wide section.
Other Areas	204	188	221	Inward collapse of walls
Lateral Collapse	>300	–	–	Failure not feasible.
Vault	>300	–	–	Structure is able to resist the loads

could fail at 88 mph. Other doors located in the exterior walls of the lab area could fail at 140 mph. Failure of the exterior door in the south wall could result in the collapse of the interior unreinforced concrete block walls located in the vicinity of the door.

The roof joist located close to the west wall could be uplifted due to a failure of the weld between the joist bearing plate and the support beam at windspeed of 167 mph. A 10 ft. wide section of the roof in that area would tend to uplift, but would be prevented by the presence of the inplane roof truss. The roof section would likely collapse to the floor after reduction of the uplift forces. The roof joist located close to the east wall could fail at windspeed of 189 mph. The failure is due to failure of weld between the joist bearing plate and the support beam. A 7 ft. wide section of the roof next to the east wall could collapse downward. Critical failure windspeed for the remaining roof joists is 231 mph.

A 20 ft. wide section of the wall corners (except at the vault) could collapse outward due to failure of the first column from the corner and the parapet beam at windspeed of 184 mph. This opening in the wall would permit development of internal pressure inside the building which will contribute to subsequent additional failures in the roof. Exterior walls subject to windward (inward) pressures could collapse at 204 mph. Failure of the south wall, which indirectly supports the roof joists, results in collapse of the roof also.

Lateral collapse of the building could occur at windspeeds greater than 250 mph. This is not a feasible failure mode, because the individual components (wall corners, roof areas and walls) fail at windspeeds considerably less than 250 mph.

Calculations show that no damage to the vault occurs at windspeeds of 300 mph. The rest of the building could be lying in rubble, but the vault will remain intact.

B. Atmospheric Pressure Change (APC) Effects

Tornadic winds would be the controlling windspeeds rather than straight-line gust winds for windspeeds higher than 155 mph (Ref. Table II). For tornadic loading, atmospheric pressure change effects should be considered, if sufficient venting area as shown in Table II is not available. In the lab area, the doors to the exterior are expected to fail at windspeed of 140 mph. These openings through the doors provide opening areas sufficient for adequate ventilation to take place. Thus, APC pressure is not likely to contribute to damage in the lab area. The vault is capable of withstanding the maximum APC effects postulated for the site.

C. Damage from Windborne Debris

Extreme winds tend to pick up and transport various types of debris that range in size from roof gravel to automobiles. Windborne debris is of secondary concern for the MOFP facility. The energy which a missile may possess as it approaches this building will be dissipated upon impact with the exterior precast concrete walls. When the exterior walls fail, the equipment is likely to be crushed underneath the walls. Therefore, missiles entering the MOFP facility subsequent to the wall collapse cause little additional damage. The massive walls and roof of the vault are able to resist any missile impact postulated in this study.

D. Summary of Failure Modes

Calculations of threshold values of windspeed that cause damage suggest the following sequence of failure modes:

88 mph	The exterior door at the southeast corner of the building could fail.
140 mph	Other exterior doors could collapse inward, resulting in some wind circulation through the building. The west interior wall of the Poison Rod Fab Area could collapse.

167 mph	A joist anchorage failure occurs along the west eave of the lab area. A 10 ft. wide strip of roof along the west wall will tend to uplift, but will be restrained by the inplane roof truss. The joists and roof decking will subsequently collapse downward to the floor.
184 mph	A twenty ft. wide section of the exterior wall could collapse at the wall corners (except at the vault) due to failure of the first column from the corner or due to the formation of a mechanism in the parapet beam. If this failure occurs in the south wall at the southeast corner, the joists bearing on this wall (through the brackets attached to the column) and the 20 ft. wide section of roof will collapse downward.
204 mph	Exterior walls collapse inward due to windward pressures. If this occurs in the south wall, joists bearing on the wall will collapse downward. All the walls are not likely to collapse but rather portions of the walls would be affected.
231 mph	Additional joist anchorage failure could occur resulting in portions of roof collapsing to the floor.
250 mph	At these windspeeds, the integrity of the laboratory building is expected to be lost. Most of the walls will collapse along with the inplane roof truss. The vault is not likely to sustain damage at this windspeed.

V. DAMAGE SCENARIOS

Damage scenarios for selected probabilities of occurrence of windspeed are formulated from the calculated threshold windspeeds presented in Section IV. The damage scenarios are used for subsequent identification of source terms.

Four damage scenarios for selected windspeed values are presented to formulate a trend of increasing damage with reduced probability of occurrence. Fujita [2] developed the relationship between windspeed values and their probability of occurrence at the Exxon MOFP facility. The values used here and presented in Table II are taken from curves B and D of Figure 6 in Reference 2. The windspeed values are gust speeds in the case of straight line winds and maximum tornadic windspeeds in the case of tornadoes. Damage causing threshold windspeeds are either gust speeds or maximum tornadic windspeeds. Since damage is based on median material strengths, the threshold windspeeds are termed nominal windspeed. Variation in material properties, or subjective engineering judgement, based on the type of damage, establishes the windspeed range for each damage scenario. These windspeed ranges may be used to provide error bands on potential damage to the facility.

A. Damage Scenario for Nominal Windspeed of 95 mph

Probability of Occurrence: 6×10^{-3}

Windspeed Range: 83 mph to 109 mph, based on failure of door.

Mixed Oxide Preparation Area: The small door at the southeast corner of the building could fail outward. Wind circulation in the vicinity of the failed door could damage the exterior filters on glove box 4a. The other glove boxes or filters in the Mixed Oxide Preparation Area are not likely to sustain damage. No significant missile induced damage is expected at this windspeed.

Cold Lab Area: No damage of consequence.

Mass Spec Area: No damage of consequence.

Poison Rod Fab Area: No damage of consequence.

Vault: No damage of consequence.

B. Damage Scenario for Nominal Windspeed of 150 mph

Probability of Occurrence: 3×10^{-6}

Windspeed Range: 133 mph to 169 mph, based on failure of doors.

Mixed Oxide Preparation Area: Failure of the small door in the southeast corner of the building would permit some wind circulation in the area. Since the opening is small, only the glove box closest to the door is likely to be affected. The filter outside the glove box is likely to be damaged and the glove box could be perforated by a small wooden plank.

Cold Lab Area: No damage of consequence.

Mass Spec Area: No damage of consequence.

Poison Rod Fab Area: Outside door in south wall could fail allowing wind to circulate in that area of the building. The interior wall could collapse in the poison rod fab area, causing damage to equipment located within 15 ft. of the wall. Best estimate of the number of pieces of equipment crushed is one-third as median value with upper and lower bound values being one-half and one-fifth, respectively.

Vault: No damage of consequence.

C. Damage Scenario for Nominal Windspeed of 190 mph

Probability of Occurrence: 6×10^{-8}

Windspeed Range: 170 mph to 212 mph, based on failure of walls.

Mixed Oxide Preparation Area: A 20 ft. section of south wall at the southeast corner can fail. This failure will cause 20 ft. section of the roof to collapse downward. Roof joists and metal deck are likely to remain together and the north end of the roof may not slip from its support. The best estimate is that three-fourths of the glove boxes in this 20 ft. wide section close to east wall will be crushed; upper and lower bound values of the glove boxes crushed are all and one-half, respectively. In the remaining area, one-half of the glove boxes may be perforated by debris; upper and lower bound values for the glove boxes affected are three-fourths and one-third, respectively.

Cold Lab Area: No damage of consequence since it is at a fair distance away from the wall opening.

Mass Spec Area: No damage of consequence since it is at a fair distance away from the wall opening.

Poison Rod Fab Area: Portions of west and east interior walls are likely to collapse and could cause damage to equipment located within 15 ft. of the walls. Best estimate of the number of pieces of equipment crushed is one-half as median value with upper and lower bound values being three-fourths and one-third, respectively.

Vault: No damage of consequence.

D. Damage Scenario for Nominal Windspeed of 250 mph

Probability of Occurrence: 3×10^{-9}

Windspeed Range: 200 mph to 312 mph, based on collapse of walls.

Mixed Oxide Preparation Area: Portions of the outside walls collapse. The interior wall between Poison Rod Fab Area and MOP collapses allowing wind to circulate through the building. The roof collapses downward along with the inplane truss. All glove boxes and filters are likely to be crushed. The roof deck and the inplane truss cover the glove boxes and prevent some material from being blown from the building.

Cold Lab Area: Interior walls collapse. The roof and the inplane roof truss collapse downward. The 10 in. concrete wall is likely to remain standing. All glove boxes and filters will be crushed. The roof deck is likely to cover the crushed boxes and prevent some material from being blown from the building.

Mass Spec Area: Damage similar to Cold Lab Area.