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Revision Memo

12/99	This update reflects a major revision to the DP consistent with ASCE guidelines for blast design and revisions to the Blast Technology Manual, TMEE 065. Significant revisions include the following: Building Categories: decreased limit of building category 3 spacing from 800 ft to 700 ft consistent with DP XV-H. Building Function: revised terminology. Structural Damage Levels: new damage descriptions (high, medium, low) per IP 4-3-2 and ASCE. Structural Performance Goals: revised table to reflect new terminology. Special Structures: deleted provisions for cylinders, arches, domes, and earth embanked structures. Structural Design Requirements: deleted detailed structural provisions and provided reference to Blast Technology Manual.
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SCOPE

This section covers the special design considerations and requirements for blast-resistant process plant structures, focusing on buildings. Structural design requirements and analysis procedures are provided in [IP 4-3-2](#), [IP 4-3-4](#) and Section 3 of the Blast Technology Manual (**Reference 1**). Plant buildings requiring blast protection and the safety considerations involved in providing such protection are covered in [Section XV-H](#) of the Design Practices.

REFERENCES

DESIGN PRACTICES

[Section XV-H](#) Safety in Plant Design, Blast Protection and Fireproofing

INTERNATIONAL PRACTICES

IP 4-1-1 ,	Concrete Design and Construction
IP 4-1-2 ,	Structural Steel Design
IP 4-1-3 ,	Design Loads for Structures
IP 4-3-1 ,	Plant Buildings for Operations and Storage
IP 4-3-2 ,	Blast Resistant Buildings
IP 4-3-4 ,	Special Category 3 Blast Resistant Buildings
IP 4-6-1 ,	Reinforced Concrete Foundations and Anchor Bolts
IP 4-7-1 ,	Piles and Sheet Piles

OTHER REFERENCES

1. Blast Technology Manual, ER&E Report No. TMEE065, December, 1997.
2. *Design of Foundations for Blast-Resistant Structures*, ER&E Report No. EE.104E.73,
3. ACI Standard 318, Building Code Requirements for Reinforced Concrete.
4. AISC – Manual of Steel Construction, *Specifications for Fabrication and Erection of Structural Steel*.
5. ASCE – Manuals and Reports on Engineering Practice – No. 41, *Plastic Design in Steel*, 1971.
6. ASCE – Manuals of Engineering Practice – No. 42, *Design of Structures to Resist Nuclear Weapons Effects*, 1985.
7. ASCE – Petrochemical Energy Task Committee Report, *Design of Blast Resistant Buildings in Petrochemical Facilities*, 1997.
8. AIChE (CCPS) – Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVE's, 1994.
9. AIChE (CCPS) – Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires, 1997.
10. Department of Defense Manual, *Structures to Resist the Effects of Accidental Explosions*, TM 5-1300 / NAVFAC P-397 / AFM 88 – 22, June 1992.

BACKGROUND

Safety and economic considerations dictate that certain critical and/or normally occupied process plant buildings, should be made adequately blast-resistant to provide a reasonable level of protection against the effects of an accidental explosion. Such buildings normally include central control houses (CCH), main electrical substations (MES), critical remote instrument modules (RIM), and plant operation / office buildings, etc. [Section XV-H](#) provides information on when and why process plant buildings are to be blast-resistant. It also specifies the level of blast resistance appropriate for such buildings.

In general, critical or normally occupied process plant buildings located closer than about 700 ft (215 m) from a potential vapor cloud explosion domain are required to have some degree of blast resistance unless site specific conditions dictate otherwise. [IP 4-3-2](#) covers the basic structural design requirements for designing blast-resistant structures. Also, [IP 4-3-4](#) provides simplified design requirements for blast resistant buildings satisfying certain spacing and construction limitations. General guidelines and background data for blast-resistant design are provided in the Exxon Engineering *Blast Technology Manual*, TMEE065. **Section 3** of that manual is a guide covering the design method and calculation procedures to be followed for blast-resistant structures.

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DEFINITIONS

Blast-Resistant Structure

A blast-resistant structure is a process plant building, such as a central control house or critical substation, barrier walls, cubicles or other structures designed to withstand the effects of an accidental plant explosion with limited structural damage. The intent is that in the event of an explosion the facilities housed in such a structure remain operable and/or personnel are protected from injury and/or hazardous effects mitigated, depending on the facility functions.

Blast Wave

The blast wave is the pressure pulse which is propagated outward in all directions from an explosion source. It is characterized by a rapidly reached peak pressure (shock wave) or a more gradual pressure build up (pressure wave), accompanied by a decaying overpressure phase and then a negative pressure (suction) phase in some cases. The blast wave also produces a wind effect.

Critical Building

The building is required for continued operation of parts of the plant that are not affected by the VCE incident.

Design Vapor Cloud Explosions

For the purpose of design, three vapor cloud explosions (VCE #1, VCE #2 and VCE #3) have been established by the Safety and Risk Section of EETD. These are defined in [DP XV-H](#).

Drag (Dynamic) Pressure, P_d

A drag or dynamic pressure is exerted on any object in the path of the blast wave due to the induced air motion. This wind effect is in addition to the overpressure.

Dynamic Design

A dynamic design procedure is one which takes into account the dynamic response of a structural element to the transient blast loading.

Effective Positive-Phase Duration, t_0

To simplify the design procedure, the positive-phase pressure time curve is approximated by a straight line so that the peak overpressure and positive-phase impulse are unchanged. The decay time of this simple pulse is referred to as the effective positive phase duration. It is usually about 80 percent of the actual duration.

Energy Absorption Capacity

The energy absorption capacity of a structural member is its ability to support blast loading without rupture or collapse. This capacity is quantified by the area under the resistance-displacement curve for the structural member.

Frame Building

A frame building is one in which the main structural system consists of a series of bents (columns and girders) in at least one direction. The bents support the wall panels and the roof / floor beams or slabs. **Figure 1A**.

Free-Field Overpressure, P_0

The free-field overpressure is the pressure above ambient in the blast wave. Free-field refers to the condition of the blast wave unaltered by any objects in its path. This is also referred to as "incident" or "side-on".

Front Wall

The front wall or face of a building is the side assumed to face an explosion source. For a blast-resistant process plant structure, it is generally assumed that each side is a front. This recognizes that an explosion could occur in any direction.

Impulse, I

The area under a particular phase of the pressure-time curve for the blast wave is referred to as its impulse.

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DEFINITIONS (Cont)

Normally Occupied Building

The occupancy level in the building meets the criteria defined by the local Safe Operations Committee requiring the building to be considered as occupied.

Reflected Pressure, P_r

When the blast wave impacts an object, the pressure pulse is reflected and the object is subjected to a pressure which could be several times the free-field overpressure, depending on the angle of incidence and the magnitude of the overpressure.

Resistance

The resistance of a structural element is the load it can support statically at a specified displacement and based on the dynamic strength of its material.

Shear Wall Building

A shear wall building is one in which the lateral loads are transmitted to the foundation through shear in the transverse walls. The roof and floor slabs act as diaphragms (deep beams). **Figure 1B.**

Time of Arrival, t_a

The time of arrival is the time it takes the blast wave to travel from the explosion source to a particular point.

DESIGN CONSIDERATIONS

BASIC REQUIREMENTS

The criteria for designing blast-resistant structures in process plants are covered in the Exxon International Practices, [IP 4-3-2](#) and [IP 4-3-4](#). These criteria reflect the following basic requirements:

- A blast-resistant plant structure should be capable of withstanding an explosion of realistic magnitude in order to protect the occupants and/or facilities from the damaging effects of a blast.
- Non-structural damage and some structural damage which are not detrimental to the protective function of the structure is considered acceptable.
- In the event of an explosion in excess of the "design" values, failure of the structure should preferably be by excessive deformation without significant loss of load-carrying capacity, thus providing for a margin of safety against a catastrophic failure.
- The structure is expected to resist a major explosion no more than once in its life, however, a critical facility should have the capacity to safely support the post-explosion loading without requiring major disruptive structural repairs.

For design, the standard vapor cloud explosions (VCE #1, VCE #2, and VCE #3) have been established as being near ground level at specified distances, as defined below. It is normally assumed that all sides of a building are vulnerable to such explosions.

The minimum spacing from an explosion source provides a safety buffer zone to minimize the risk of the building being engulfed in an explosive vapor cloud.

The incremental cost for blast resistance would be prohibitively high if some damage were not tolerated and conventional factors of safety were required; moreover, plant explosions are relatively rare in the petroleum industry and in Exxon affiliates' experience. This justifies lowering of the safety margin and accepting some level of structural damage consistent with the performance goals for the structure. For this tolerable damage level, the cost of a blast-resistant building should be only 10 to 25 percent higher than the cost of a conventionally-designed (non-blast) building of the same size and layout, depending on location, type of construction and level of blast resistance (building category).

S VCE-BASED DESIGN CRITERIA

Historically, blast resistant design of structures in process plant have been based on TNT-equivalence to represent the effects of vapor cloud explosions (VCE). For example, prior to 1993, blast resistant plant buildings, according to [IP 4-3-2](#), were designed for 1 ton TNT at 100 ft (30 m); however, since that time a more realistic VCE model (the multi-energy method) has been adopted as the basis for designing and evaluating structures for blast resistance. **Exxon Design Practice, DP XV-H**, and the **Blast Technology Manual, TMEE065**, provide an overview of the application of the multi-energy model to predict the blast effects from vapor cloud explosions.

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DESIGN CONSIDERATIONS (Cont)

VCE Scenarios

DP XV-H specifies three (3) VCE scenarios for the purpose of blast resistant design of new plant buildings as follows:

- VCE #1 – a relatively small but strong explosion centered in a highly congested area of a plant. This incident results in a blast wave having high overpressure and short duration.
- VCE #2 – a large but average strength incident that covers an entire process block having equipment at standard spacing. This incident is likely to yield a blast or pressure wave of low overpressure but long duration.
- VCE #3 – an extreme (maximum credible) scenario resulting in multiple explosions within a single vapor cloud. This incident is likely to yield a high overpressure, long duration blast wave.

VCE #1 and VCE #2 are used to establish blast design criteria consistent with continued building use after the VCE event. Two separate events (VCE #1 and VCE #2) are considered in this case because the response of building components may be controlled by one or the other type of blast wave depending on the structural dynamic response. For example, a stiff component is likely to be governed by VCE #1, the high pressure short duration loading. On the other hand, a flexible component is more likely to be governed by VCE #2.

VCE #3 is expected to be less likely to occur than either VCE #1 or VCE #2. It is considered to be the most extreme event that can be credibly postulated for a particular plant and building. This event is used to establish the survival limit for certain buildings as discussed below.

Building Categories

Plant buildings are categorized for the purpose of blast resistant design based on spacing from a potential VCE domain and on its function or use, and on the required structural performance as follows:

A. Spacing

- Category 0 – 50 to 100 ft (15 to 30 m)
- Category 1 – 100 to 200 ft (30 to 60 m)
- Category 2 – 200 to 400 ft (60 to 120 m)
- Category 3 – 400 to 700 ft (120 to 215 m)

Spacing refers to the distance to the nearest edge (battery limit) of a potential explosion domain. The epicenter of the explosion is assumed to be about 60 ft (20 m) more than this distance, or along the center line of the domain if this distance is shorter.

The upper bound distance for Category 3 is set based on the distance where conventional non-blast resistant building construction is generally assumed to provide adequate blast protection. This usually corresponds to a free-field overpressure of about 1 psi (7 kPa); however glass breakage is expected to occur beyond this distance.

B. Function

- Critical and normally occupied** buildings such as multi-unit control centers.
- Critical**, but not normally occupied buildings such as main electrical substations and critical remote instrument modules (RIMs).
- Normally occupied**, but not critical buildings such as plant offices, unit control or operation buildings.
- Other** buildings not normally occupied and not critical for plantwide operation such as unit substations, analyzer shelters, etc.

KEY FACTORS

Several factors affect the response of a structure to an explosion. These factors relate to the nature of the blast wave and to the characteristics of the structural components. The blast wave is a time and spatially varying pressure pulse propagating outward in all directions from the explosion epicenter. The primary blast wave and structural parameters involved are as follows:

Blast Wave Parameters

- Maximum peak overpressure** (above the ambient atmospheric pressure) during the positive phase of the blast wave.
- Duration** of the overpressure or the time over which the positive phase of the blast wave lasts.
- Impulse** or the area under the pressure (or load) time curve for the blast wave. Impulse relates to both the peak pressure and duration.

DESIGN CONSIDERATIONS (Cont)

- **Shape** and rise-time of the blast wave pressure pulse. Generally the blast overpressure increases from ambient to some peak value then decays back to ambient conditions or sometimes to a negative pressure or suction phase. The pressure decay may be exponential or sinusoidal, but for simplicity a linear decay is normally assumed. The rise-time is the time for the pressure to reach the peak value. A zero rise-time or shock front is usually the most severe for structural or human response.

Structural Response Parameters

- **Resistance** or capacity (available strength) of each structural component subjected to the effects of the blast.
- **Mass and stiffness** of the structural component. These relate to the natural period or frequency of vibration of the component, which is key to its dynamic response to the transient blast effects.
- **Ductility** or the ability of the structural component to absorb the blast energy up to some tolerable deformation level. Ductility is the ratio at the maximum displacement to the displacement at material yielding.

In general, the overpressure level that a structure can withstand will depend on each of the other blast wave parameters, as well as on the structural response parameters of its components. Blast resistant design involves the determination of the capacity of each component of a structure so that the blast loading from an explosion will not cause it to lose its protective function; that is, to prevent collapse or excessive deformation resulting in disruptive building damage.

S STRUCTURAL DAMAGE LEVELS

The levels of response (or damage) experienced by the structural components of a building or by the overall building subjected to an explosion can be classified as follows:

BUILDING RESPONSE LEVEL	DAMAGE DESCRIPTION
Low	Localized building / component damage. Building can be used; however, repairs are required to restore the integrity of the structural envelope.
Medium	Widespread building / component damage. Building cannot be used until repaired.
High	Building / component has lost structural integrity. Additional loading, subsequent to blast pressure, due to environmental conditions (i.e., wind, snow, rain) may lead to collapse.

S STRUCTURAL PERFORMANCE GOALS

Three structural performance goals are set for blast resistant design of buildings in terms of tolerable damage levels based on the blast protection objectives as follows:

1. Damage level consistent with continued use of building (Low Response).
A *damage-limited building* should *withstand* the effects of the design basis VCE's with only a slight to moderate amount of structural damage such that operations (functions) can continue during and after the incident.
2. Damage level consistent with protection of occupants (High Response).
A *collapse-limited building* should survive a maximum credible design VCE incident while tolerating severe damage without collapsing.
3. Damage level consistent with nominal blast protection.
An ordinary plant building, although not explicitly designed for blast resistance, should be designed and constructed to minimize the consequences from blast effects. Thus, **IP 4-3-1** prohibits the use of unreinforced masonry load bearing walls and specifies special glazing for windows to reduce the hazard of glass fragments.

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DESIGN CONSIDERATIONS (Cont)

The VCEs and structural performance basis for various classes of plant buildings are as follows:

FUNCTION	DESIGN VCE PER DP XV-H	BUILDING RESPONSE LEVEL	APPLICABLE INTERNATIONAL PRACTICE
Critical & Normally Occupied	VCE #1	Low	IP 4-3-2 for all spacing category buildings. IP 4-3-4 for spacing category 3 buildings.
	VCE #2	Low	
	VCE #3	High	
Critical (not normally occupied)	VCE #1	Low	IP 4-3-1
	VCE #2	Low	
Normally Occupied (not critical)	VCE #3	High	
Other ordinary plant buildings (not critical or normally occupied)	None, but use non-load bearing walls & limitations on window glass	Not Applicable	

In blast resistant design, damage to the building component is usually given in terms of the amount of permanent deformation expected under the blast loading conditions. Deformation limits are set by [IP 4-3-2](#) for each type of component and construction so that the building as a whole meets its structural performance objective.

SPECIAL FEATURES

The blast resistance of a building is influenced by its shape, layout and orientation to the potential explosion epicenters. In addition, certain types of construction are preferable for blast resistance while others should not be used. These special blast resistance features are discussed below.

Building Layout

Non-structural considerations such as safety, operation, architecture, cost and owner preferences may dictate the shape, orientation, and layout of a plant building. In establishing these, however, the requirements for blast resistance should be considered. Some of the factors affecting the protective function of a building are discussed below.

Designers commonly use rectangular box-like shapes for refinery buildings; however, to meet the structural requirements of blast resistance, other building design concepts may also be considered. Arch or dome-shaped igloo construction is particularly effective, since it possesses inherent structural strength and experiences a smaller blast loading than a rectangular building of the same size. Earth-mounded or partially buried structures are also effective in providing blast protection. These and other design concepts are illustrated in [Figure 1](#).

Generally, for a given building volume, the cost of blast resistance increases with the building height. A low profile building experiences lower blast loads and overturning effects compared with a tall structure. Buildings over two stories high are, therefore, not recommended as protective structures. Moreover, a one-story building is preferable to a two-story because foundation design is more troublesome with the increase in the building height due to the more severe overturning effects of the blast loading.

The plan outline and elevation profiles of a blast-resistant building should be as "clean" and simple as possible. Reentrant corners and offsets, in particular, should be avoided. Such features, beside being difficult to detail, create local high concentrations of blast loading. This requires that as small an area as possible face the most probable source of an explosion.

Control room layout considerations often require a large floor area unobstructed by structural walls or columns. There is, however, an increase in cost for large-span structural framing. Interior columns should, therefore, be used where feasible so that the maximum span does not exceed about 50 ft (15 m) in either frame or shear wall type buildings. Arches and igloo type structures ([Figure 1D](#)) are very effective for larger spans. These structures, when used for clear spans greater than 50 ft (15 m), usually require much less structural material, compared with conventional frame or shear wall buildings. However, the cost saving in material must be compared against the cost of the special shell construction.

Another factor affecting the selection of a structural concept for a blast-resistant building is the need for future expansion. Generally, a frame type building can be readily expanded in a direction perpendicular to the bents by simply erecting additional bents, as indicated in [Figure 1A](#). An arch or cylindrical-shaped building can also be extended in the direction of its axis. On the other hand, a two-story shear-wall building or an igloo structure cannot be conveniently enlarged to provide floor space without obstructions. If these concepts are to be used and a future expansion is likely, they should be pre-engineered to account for the effect of possible removal of structural walls.