Recommended Practice for the Design of Offshore Facilities Against Fire and Blast Loading

API RECOMMENDED PRACTICE 2FB
FIRST EDITION, APRIL 2006

REAFFIRMED, JANUARY 2012

AMERICAN PETROLEUM INSTITUTE

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FOREWORD

This recommended practice is under jurisdiction of the API Subcommittee on Offshore Structures. This Recommended Practice for the Design of Offshore Structures against Fire and Blast Loading is based on sound engineering principles and many years of experience gained by the owners, operators, designers, fabricators, suppliers, and classification/certification agencies of offshore facilities. In no case is any specific recommendation included that could not be accomplished by presently available techniques and equipment. Consideration is given in all cases to the safety of personnel, compliance with existing regulations, and prevention of pollution.

This recommended practice has been developed with the help and extensive contributions from industry experts of different areas of expertise. This recommended practice covers both fixed and floating structures that are in use by the industry as offshore oil and gas production systems. These include systems supported by column-stabilized units (semi-submersible vessels), ship-shaped vessels, Tension Leg Platforms (TLP), deep draft caisson vessels (also known as SPARs), and other hull shapes.

This recommended practice provides an assessment process for the consideration of fire and blast in the design of offshore structures and includes guidance and examples for setting performance criteria. This document complements the contents of the Section 18 of API RP 2A, 21st Edition with more comprehensive guidance in design of both fixed and floating offshore structures against fire and blast loading. Guidance on the implementation of safety and environmental management practices and hazard identification, event definition and risk assessment can be found in API RP 75 [51] and the API RP 14 series [52, 53]. The interface with these documents is identified and emphasized throughout, as structural engineers need to work closely with facilities engineers experienced in performing hazard analysis as described in API RP 14J [52], and with the operator's safety management system as described in API RP 75 [51].

This recommended practice provides general guidelines for incorporating hazard analysis output into the structural response assessment in determining whether the structure or its components meet the specified performance criteria.

This recommended practice includes code provisions and associated commentary. The commentary provides design guidelines for the evaluation of structural response to fire and blast loads. Nominal blast load cases are provided for certain classes of facilities. Guidance is also provided for the calculation of fire loads. Discussion of alternative methods for the calculation of blast loads, in lieu of applicable nominal load cases, is included with reference to sources of detailed guidance. The commentary also includes examples of good practice for fire and blast design including guidelines for facilities layout and structural connection detailing.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

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Suggested revisions are invited and should be submitted to the Standards and Publications Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

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0 Definitions

- **Blast Relief Panel:** Parts of a module wall, ceiling or roof, which are designed to increase the area of venting in an explosion by being opened or removed by the force of the explosion.
- **Blast Wall:** A structural barrier, which is designed expressly for the purpose of resisting blast loads.
- **Blow-down:** The rapid controlled or accidental depressurization of a vessel or piping network.
- **Cellulosic Fire:** A fire with a fuel source predominantly of cellulose (e.g. timber, paper, cotton). A fire involving these materials is relatively slow growing, although its intensity may ultimately reach or exceed that of a hydrocarbon fire.
- **Conduction:** The mode of heat transfer associated with solids. Each solid has a temperature dependent factor, which is a measure of the rate of conduction.
- **Convection:** Heat transfer associated with fluid movement around a heated body; warmer, less dense fluid rises and is replaced by cooler, denser fluid.
- **Ductility Ratio:** The ratio of the total deflection to the deflection at elastic limit. The deflection at elastic limit is the deflection at which strength behavior can be assumed to change from elastic to plastic.
- **Emergency Shutdown System:** A safety shutdown system comprising detection, signaling and logical control, valves and actuators, which can, in tandem with alarm and direct control mechanisms, enable the safe and effective shutdown of plant and machinery in a controlled manner.
- **Emmissivity:** A constant used to quantify the radiation emission characteristics of a flame. Emmissivity of a perfect black body is 1.
- **Fixed Platform:** A platform extending above and supported by the sea bed by means of piling, spread footings or other means with the intended purpose of remaining stationary over an extended period.
- **Heat Flux (heat density):** The rate of heat transfer per unit area normal to the direction of heat flow. A convenient unit is kW m^{-2} (1 kW m^{-2} = 317 Btu ft^{-2} h^{-1}). It is a total of heat transmitted by radiation, conduction and convection.
- **Hydrocarbon Fire:** A fire fuelled by hydrocarbon compounds, having a high flame temperature achieved almost instantaneously after ignition. A hydrocarbon fire will spread rapidly, burn fiercely and produce a high heat flux.
- **Mass Burning Rate:** The mass-burning rate of a pool fire is the mass of fuel supplied to the flame per unit time, per unit area of the pool. Units are typically $kg/m^2/sec$.
- **Mitigation:** Mitigation actions are defined as modifications or operational procedures that reduce loads, increase capacities, or reduce exposure.
- **Nominal Value:** The value assigned to a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions [ISO 32].
- **Operator:** The person, firm, corporation or other organization employed by the owners to conduct operations.
- **PFP:** Passive Fire Protection
- **Prevention:** The action that is taken to reduce the probability of an event in order to reduce the overall risk that the event poses to the platform.

- **Safety Critical Element:** Any component part of structure, equipment, plant or system whose failure could cause a major accident.
- **Specific Heat:** The amount of heat, measured in Joules, required to raise the temperature of one kilogram of a substance by one degree C. Units are Joules/kg/ºC.
- **Surface Emissive Power (SEP):** The heat radiated outwards from a flame per unit surface area of the flame. Units are kW/m^2.
- **Survival:** For purposes of fire and blast consideration, survival means demonstration that at least one escape route and the temporary refuge or safe mustering area are maintained for a sufficient period of time to allow platform evacuation and emergency response procedure, in accordance with the safety philosophy defined by the owner/operator of the platform.
- **Temporary Refuge (TR) or Safe Mustering Area:** An area of the platform that will enable the occupants to survive the defined fire or blast event. The area must also be safely accessible by personnel not in the immediate vicinity of the event and provide access to the primary escape route.
- **Unmanned Platform:** A platform upon which persons may be employed at any one time, but upon which no living accommodations or quarters are provided.
- **Utilization Ratio:** The ratio of actual stress to allowable stress.
- **AISC:** American Institute of Steel Construction
- **API:** American Petroleum Institute
- **ASCE:** American Society of Civil Engineers
- **ASTM:** American Society of Testing and Materials
- **AWS:** American Welding Society
- **ISO**: International Organization for Standardization
- **NFPA:** National Fire Protection Association
- **SFPE:** Society of Fire Protection Engineers
- **SCI:** Steel Construction Institute
- **SCE:** Safety Critical Element

1 General

This document provides guidelines and recommended practice for the satisfactory design of offshore structures against fire and blast loading. For guidelines and recommended practice and other requirements relating to planning, designing and constructing offshore structures relevant API recommended practices, such as API RP 2A, API RP 2FPS, etc., should be followed. The Section 18 of API RP 2A, 21st edition provided a brief overview of the issues associated with the design of fixed offshore structures against fire and blast loading. This document has no contradiction of the issues as identified in the Section 18 of API RP 2A, 21st edition, instead it expands on the details and includes various issues associated with floating structures previously not indicated.

The scope of this document is mainly directed to the new design of offshore structures against fire and blast, but is also widely recommended for use in verifying existing offshore structures against fire and blast loading if the operator so desires.

Fire and blast loading events can lead to partial or total collapse or sinking of an offshore platform resulting in loss of life and/or environmental pollution. Consideration shall be given in the design of the structure and in the layout and arrangement of the facilities and equipment to minimize the effects of these events. Implementing preventative measures has historically been, and will continue to be, the most effective approach in minimizing the possibility of occurrence of an event and the resulting consequences of the event. For procedures for identifying significant events and for assessment of the effects of these events from a facility engineering standpoint, guidance for facility and equipment layouts can be found in API Recommended Practice 75, API Recommended Practice 14G, API Recommended Practice 14J, and other API 14 series documents.

The operator is responsible for the overall safety of the facility. The structural engineer needs to work closely with facility engineers experienced in performing hazard analyses as described in API Recommended Practice 14J, and with the operator's safety management system as described in API Recommended Practice 75.

The probability of an event occurring that leads to a partial or total platform collapse and the consequence resulting from such an event vary with platform type. In the U.S. Gulf of Mexico, consideration of preventive measures coupled with established infrastructure, open facilities and relatively benign environment have resulted in a good safety history. Detailed structural assessment should therefore not be necessary for Gulf of Mexico-type platforms designated as low risk. A screening process is described herein to screen from further consideration those platforms considered to be at tolerably low risk from fire and blast events, and therefore not requiring specific structural evaluation for fire and blast. As discussed above, however, all designs should include consideration of facilities and equipment layout to minimize the effects of fire and blast events and the adoption of good practice in regard to structural detailing to optimize performance in the event of the occurrence of a fire or blast event.

2 Risk Assessment

2.1 GENERAL

The risk assessment process consists of three levels, as follows:

- **Screening**: The first level is a simple risk based screening process that establishes a class of un-manned fixed structures as low risk facilities for which specific consideration of fire and blast loading is not required beyond the adoption of good practice.
- **Nominal Loads**: The second level of assessment relates to those classes of facilities for which, nominal load cases are provided and require an assessment of the facility to meet the performance criteria for the nominal load cases.
- **Event Based**: The third level of assessment consists of a series of evaluations of specific fire and blast events that could occur for the facility over its intended life and service function(s). The risk associated with each event is defined as the product of the probability of the event occurring and the consequences of the event should it occur. Three risk levels are defined i.e. low-risk, medium risk and higher risk.

The event-based assessment will likely require a formal hazard identification study for the definition of credible events and assessment of the associated risk. More detailed guidance on hazard identification study is available in the API RP 14 series and other sources [7,16,24].

2.2 SCREENING

The screening process described is intended to identify those facilities considered to be at low risk from fire and blast events and therefore not requiring detailed structural assessment. The risk matrix shown in Figure 2.4-1 may be useful to help identify low-risk facilities. For low-risk platforms, qualitative assessment of consequence of events and likelihood of events may be performed by close examination of the facilities of the platform.

Low-consequence platforms will be characterized by low equipment counts, limited to wellheads and manifold with few vessels and little associated pipe work, which would lead to low congestion and inventory. The consequence could also be low if the confinement is low with no more than two solid boundaries including solid decks. For low consequence facilities, the manning would be consistent with normally unattended facilities with low maintenance frequency.

Likelihood considerations tend to align closely with the consequence factors in that the low consequence installations will tend to be small and therefore less complex. Larger installations will have higher potential for leak and ignition sources and therefore a greater requirement for intervention and maintenance.

For low-likelihood events, installations and compartments will have a low equipment count. The low frequency of intervention will contribute to low likelihood of events from the standpoint of maintenance risk.

2.3 NOMINAL LOADS

Nominal loads for fires have been in use since the publication of the Interim Guidance Notes [24] in 1993, and have been updated and extended in more recent references [16]. For fires, these take the form of recommended radiation levels and flame temperatures for pool and jet fires in confined and open conditions. Jet fires may give rise to radiation levels up to 300 kW/m^2 in open conditions whereas in confined situations radiation levels may rise to 400 kW/m^2 where re-circulation of the flow occurs. Pool fires generally give rise to lower radiation levels of the order of 100-160 kW/m^2.

For blast considerations, the nominal loads are space averaged peak blast overpressures determined for specific platform types from a set of data. The details are provided in the section C6.3 of the Commentary. If available and considered suitable for use for the particular facility, these nominal loads may be used for the assessment of the platform. The sensitivity of the available data set will determine whether assessment using nominal load cases should be restricted to preliminary design only.

Nominal loads are intended for use at an early project phase where Safety input is most effective and detailed geometry of the layout, particularly small bore pipe work, is not known. They may be applied as static loads if this can be justified. Each element of the structure will respond according to its natural period and resistance. An alternative method presently under development [46], the response spectrum method takes into account variations in natural periods and allowable plastic deformations (ductilities). The method is briefly described in the section C6.3 of the Commentary.

2.4 EVENT BASED

Fire and blast events originate from the release of hydrocarbons. Causes of release may include dropped objects, ship impact, intervention, fatigue, corrosion, wear, vibration, extreme environmental conditions, imperfections and/or faulty equipment, exceedance of design conditions and human error [37]. Generic release scenarios based on historic evidence in the Gulf of Mexico [35] and the UK sector of the North Sea [36] can be found in the references cited. The event based assessment process is intended to be a series of evaluations of specific events that could occur for the selected platform over its intended service life and service function(s).

For facilities not considered as low-risk (see Section 2.2) and where nominal loads (see Section 2.3) are not considered applicable, the risk assessment process should identify the risk levels for each credible fire and blast event. A formal hazard identification study will usually be required for the definition of credible events and assessment of the associated risk. More detailed guidance on hazard identification is available in the API RP 14 series and other sources [7,16,24].

For each credible event, the need for consideration within the structural design of the facility should be determined using the flow chart shown in Figure 2.8-1.

Low Risk: Insignificant or minimal risk that can be tolerated because of low potential for escalation and no significant impact on either life safety or the environment. This level of risk need not be considered further for structural design purposes.

Medium Risk: The risk level requiring further study or risk assessment may be needed to better define the risk level, consequence and cost of mitigation. In some instances, medium risk may be deemed acceptable as low as reasonably practicable (ALARP) when the effort and/or cost of mitigation become disproportionate to the benefit.

Higher Risk: This risk level must be reduced by implementation of prevention and/or mitigation measures or through change(s) in layout and/or structural design. Alternatively, more rigorous assessment of probability and/or consequence of the event may be undertaken.

The risk matrix shown in Figure 2.4-1 is a 3 x 3 matrix that compares the probability of occurrence of a defined fire or blast event with the consequence of its occurrence.

Probability of Occurrence				
	High	Medium Risk	Higher Risk	Higher Risk
	Medium	Low Risk	Medium Risk	Higher Risk
	Low	Low Risk	Low Risk	Medium Risk
		Low	Medium	High
		Consequence of Occurrence		

Figure 2.4-1—Risk Matrix

2.5 PROBABILITY OF EVENT

The probability of occurrence of a fire or blast event is associated with the potential of the origin of the event. The type and presence of a hydrocarbon source can also be a factor in event initiation or event escalation. The significant events requiring consideration and their probability of occurrence levels (that is low, medium or high) are normally defined from a fire or blast process hazard analysis.

2.5.1 Factors Affecting Origin of Events

Factors affecting the origin of the fire or blast event can be as follows:

- **Storage**: The number and size of isolatable hazardous inventories is important.
- **Equipment type**: The complexity, amount, and type of equipment are important. Separation and measurement equipment, pump and compression equipment, fired equipment, generator equipment, safety equipment, and their piping and valves should be considered.
- **Risers and wells**: The location and number of risers and wells will affect the probability of certain events including blowouts and riser failure.
- **Product type**: Product type (that is, gas, condensate, light or heavy crude) should be considered.
- **Ignition sources**: The presence and location of exposed ignition sources should be considered in determining the probability of the event occurring.
- **Operations type**: The types of operations being conducted on the platform should be considered in evaluation of the probability of occurrence of an event. Operations can include drilling, production, re-supply, and personnel transfer.
- **Production operations**: Production operations are those activities that take place after the successful completion of the wells. They include separation, treating, measurement, storage, pressure boosting, transportation, operational monitoring, lifting and handling, modification of facilities and maintenance. Simultaneous operations include two or more activities.
- **Deck type**: The potential of a platform deck to confine a vapor cloud is important. Whether a platform deck configuration is open or closed should be considered when evaluating the probability of an event occurring. Most platforms in mild environments such as the U.S. Gulf of Mexico are open allowing natural ventilation. Platform decks in more severe climates, such as Alaska or the North Sea, are frequently enclosed, resulting in increased probability of containing and confining explosive vapor and high blast overpressures. Equipment generated turbulence on an open deck can also contribute to high blast overpressures.
- **Structure Location**: The proximity of adjacent platforms should be considered in the evaluation of the probability of certain events e.g. strong shock response or projectile impact.
- **Other factors**: Other factors such as the type and frequency of personnel training should be considered. The level of maintenance and the implementation of a fully functional safety management system will also affect the probability of occurrence of a fire or blast event.

2.5.2 Probability Level

The determination of the applicable level for the probability of the event should consider the following definitions:

- High Probability: The event is likely to occur during the life of the platform and has occurred more than once on similar platform in the past.
- Medium Probability: The event is not expected to occur during the life of the platform, and the platform does not meet the criteria of High Probability or Low Probability.
- Low Probability: The event is extremely unlikely to occur during the life of the platform and no such occurrence of the event is reported in similar platforms.

2.6 CONSEQUENCE OF EVENT

The degree to which negative consequences could result from platform partial or total structural failure is a judgment, which should be based on the potential risk to life safety, the environment and to the level of economic losses that could be sustained because of the failure. In addition to loss of platform and associated equipment, and damage to connecting pipelines, the loss of reserves should be considered if the site would be subsequently abandoned.

Removal costs include the salvage of the collapsed structure, reentering and plugging damaged wells, and cleanup of the sea floor at the site. If the site is not to be abandoned, restoration costs must be considered, such as replacing the structure and equipment, and reentering the wells. Other costs include repair, rerouting, or reconnecting pipelines to the new structure. In addition, the cost of mitigating pollution and/or environmental damage should be considered in those cases where the probability of release of hydrocarbon or sour gas remains high. When considering the cost of mitigating pollution and environmental damage, particular attention should be given to the hydrocarbon stored in the topside process inventory, possible leakage of damaged wells or pipelines, and the proximity of the platform to the shoreline or to environmentally sensitive areas such as coral reefs, estuaries, and wildlife refuge. The potential amount of liquid hydrocarbons or sour gas released from these sources should be considerably less than the available inventory from each source.

The consequence level for a defined fire or blast event should be assigned as low, medium or high as applicable for either life-safety (see section 2.6.1), environmental (see section 2.6.2), or other (see section 2.6.3) consequences.

2.6.1 Life Safety Consequences

The life safety of personnel in the direct vicinity of the event is an issue for operational safety procedure and control and not of structural design and is outside the scope of this document. In the selection of life safety consequence for structural design, therefore, the user should be considering life safety consequence of personnel away from the immediate vicinity of the event.

The determination for the applicable level for life safety consequence should be based on the following descriptions:

- High Consequence: Occurrence of the event may result in loss of life for personnel and/or health/safety implications to the general public.
- Medium Consequence: Occurrence of the event may result in serious injury for personnel with limited or no health/safety implications to the general public.
- Low Consequence: Occurrence of the event may result in minor injury to personnel or no health/safety implications to the general public.

2.6.2 Environmental Consequences

The determination for the applicable level for environmental consequence should be based on the following descriptions:

- High Consequence: Occurrence of the event may result in environmental contamination as a result of well flow of either oil or sour gas or from oil stored for intermittent shipment.
- Medium Consequence: Environmental contamination resulting from the occurrence of the event is limited to process inventory, which includes large capacity containment vessels.
- Low Consequence: Environmental contamination resulting from the occurrence of the event is limited to process inventory where the continued integrity of most of the vessels, piping and valves is anticipated post-event.

2.6.3 Other Consequences

Other consequences of failure include anticipated losses to the owner, other operators, and/or to the public interest. The determination for the applicable level for these consequences should be based on the following descriptions:

- High Consequence: Occurrence of the event will likely result in significant business disruption to other operators (e.g. the event will result in shut down of major oil transport lines) or in the non-recovery of significant hydrocarbon reserves (e.g. decommissioning of the platform without replacement following occurrence of the event).
- Medium Consequence: Occurrence of the event will likely result in minor business disruption to other operators (e.g. the event will result in shut down of low volume in-field flow lines).
- Low Consequence: Occurrence of the event will not likely impact other operators or be detrimental to the public interest.

2.7 PERFORMANCE CRITERIA

In the structural evaluation of a defined fire and/or blast event, the structure should be designed to meet specific performance criteria. These criteria should be selected to ensure that the consequence of the event is consistent with the risk level assigned in the risk assessment for that event. The operator is responsible for the overall safety of the platform and performance criteria should be established consistent with the operators overall safety management philosophy.

In the selection of performance criteria consideration may be given to a number of issues as follows:

- For structural evaluation of loads associated with low probability, fire and/or blast events (infrequent occurrences) performance criteria should ensure defined ‘survival’ of the platform.
- Any blast walls and/or firewalls should remain in-place without rupture or disconnection from their supports. Deformations of the wall should be limited to avoid escalation.
- Safety critical elements (SCEs) that are designed to mitigate the effects of a major accident, such as, those necessary for (a) the safe shut down of the installation, (b) personnel protection and escape, (c) fire protection, suppression and control, (d) communications, and (e) hydrocarbon containment including transport and storage; should remain intact.
- For platforms with the potential to be manned during the defined event, performance criteria should ensure defined ‘survival’ of the platform.

For structural evaluation of loads associated with medium or especially high probability fire and/or blast events (more frequently occurring) performance criteria may be modified to limit damage to the facility consistent with the consequence assigned in the risk assessment. For example, the platform maybe designed to permit restarting of operations within a short time following appropriate integrity checks.

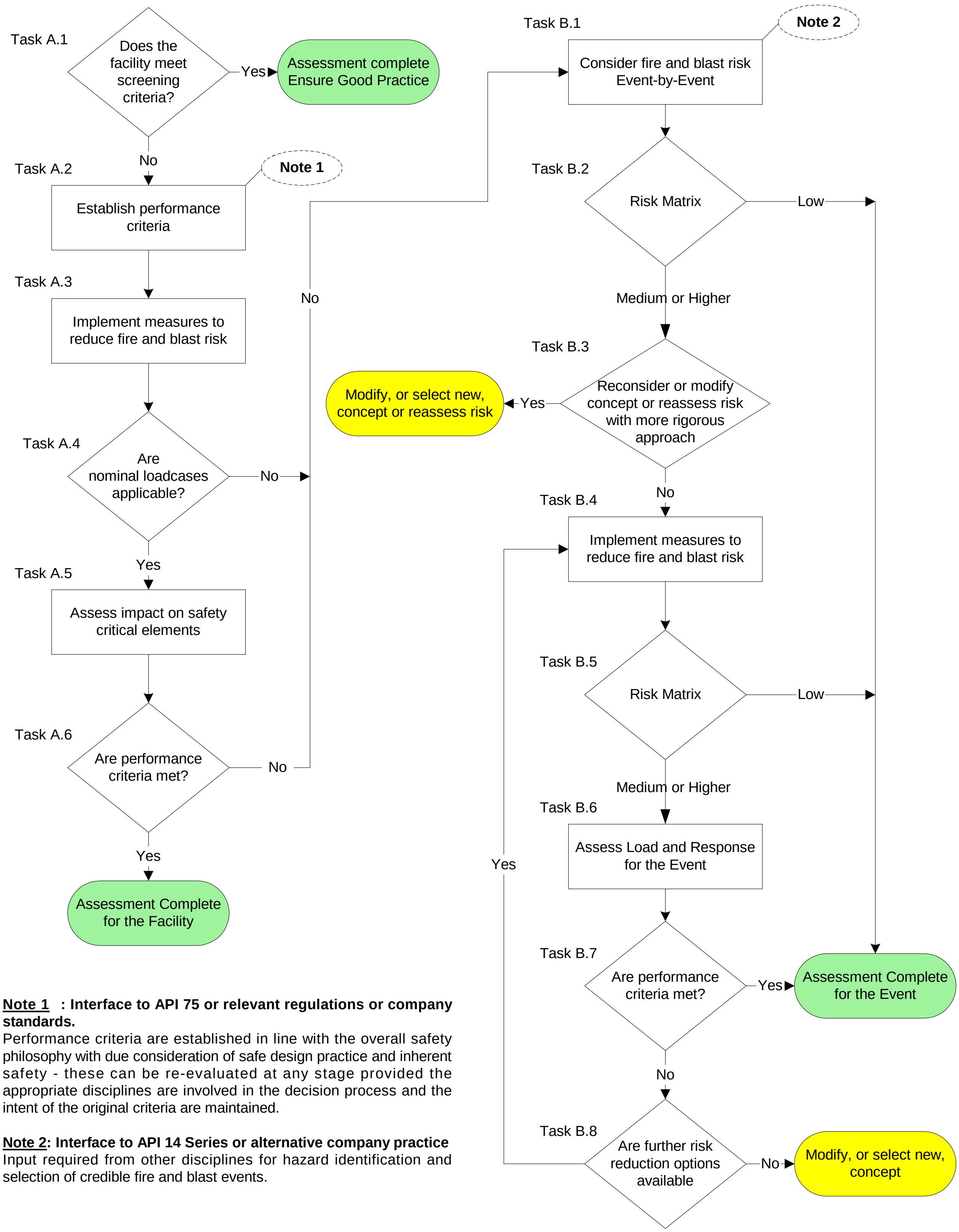
2.8 RISK ASSESSMENT PROCESS

The assessment process is illustrated in Figure 2.8-1 and comprises of a series of tasks to be performed by an integrated engineering team to identify facilities at significant risk from specific fire and/or blast events. The assessment tasks listed below should be read in conjunction with Figure 2.8-1 (Risk Assessment Process) and Figure 2.4-1 (Risk Matrix):

- Task A1: Determine whether the facility meets the definition of a low-risk facility as per the screening criteria, Section 2.2. If so, consideration of specific fire and blast loading in the design of the structure is not required.
- Task A2: Establish the performance criteria for the facility in accordance with Section 2.7. Performance criteria should comply with the overall safety and environmental management philosophy, guidance as provided in API RP 75, as well as relevant regulations and company standards.
- Task A3: Implement measures to reduce fire and blast risk in accordance with the guidelines for good design practice.
- Task A4: Establish whether nominal load cases for fire or blast loading are available for the facility. Nominal load cases are provided in the commentary for certain classes of facility for which a sufficient combination of analytical study and operational experience exists. If nominal load cases are not available for the facility, proceed to Task B1.
- Task A5: Evaluate the response of the critical structure and other key components to the nominal load cases. Critical structure and key components refer to elements of the facility that must survive for a specified duration of time following the occurrence of the event in order that the performance criteria for that event are met.
- Task A6: If the performance criteria set in Task A2 can be met for the nominal load cases the structural design for the event is complete for the facility.
- If it has been established from Tasks A1 to A5 that the facility does not meet the screening definition and that either nominal load cases are not available or structural evaluation indicates that the facility does not meet the performance criteria for the nominal load cases applied, it is necessary to consider fire and blast risk on an event-by-event basis.
- Task B1: Consideration of event-by-event fire and blast risk requires a formal hazard identification study for the definition of credible events (scenarios) and determination of their associated risk. Some guidance for the determination of the probability of events and their consequences is provided in section 2.5 and section 2.6 respectively. More detailed Guidance is available within the API RP 14 series and other sources [16,18].
- Task B2: Using the risk matrix, Figure 2.4-1, determine whether the level of risk associated with the event is low-risk, medium risk or higher-risk. If the risk is low, the assessment is complete for the defined event.
- Task B3: For events, where a higher-risk is identified, consideration may be given to modifying the design concept or adopting an alternative concept. This may be especially applicable during the early stages of a project. In this case, the assessment process is repeated from Task B1 for the modified or alternative concept. If ALARP is a part of performance criteria, the same would typically be assessed here.

The details of the assessment methods are given in the Commentary.

- Task B4: This task provides the choice for the engineering team to explore prevention and mitigation options to reduce the risk associated with the event.



Note 1 : Interface to API 75 or relevant regulations or company standards.
Performance criteria are established in line with the overall safety philosophy with due consideration of safe design practice and inherent safety - these can be re-evaluated at any stage provided the appropriate disciplines are involved in the decision process and the intent of the original criteria are maintained.

Note 2: Interface to API 14 Series or alternative company practice
Input required from other disciplines for hazard identification and selection of credible fire and blast events.

Figure 2.8-1—Risk Assessment Process

- Task B5: If the probability of the event or its consequence or both be reduced such that the risk, in accordance with risk matrix, Figure 2.4-1; becomes low-risk, the assessment is complete for that event.
- Task B6: This task involves the calculation of the fire or blast loads associated with the event and the evaluation of the ability of the critical structure and other key components required to meet the performance criteria set in Task A2.
- Task B7: If the performance criteria set in Task A2 can be met for the load cases for the specific event, the assessment is complete for the event.
- Task B8: In the case that the structural evaluation indicates that the performance criteria cannot be met, the engineering team must consider whether further risk reduction/mitigation options exist. If so, these should be implemented and the process reverts to Task B4. If no further risk reduction options are available, it will be necessary to modify the design concept or, adopt an alternative concept. In this case, the assessment process is repeated from Task A1 for the modified or alternative concept.

3 Fire as a Load Condition

If the risk assessment process described in Section 2 identifies that a significant risk of fire exists, fire should be considered as a load condition.

The treatment of fire as a load condition requires that the following be defined:

- The fire event or scenario, see section 2.4,
- Heat flow characteristics from the fire to the unprotected and protected steel members,
- Properties of steel at elevated temperatures, and where applicable
- Properties of fire protection systems (active and passive).

The fire scenario may be identified during process HAZOP (hazard and operational) analysis. The fire scenario establishes the fire type, location, geometry, and intensity. The fire type will distinguish between a hydrocarbon pool fire and a hydrocarbon jet fire. The fire's location and geometry defines the relative position of the heat source to the structural steel work, while the intensity (heat flux) defines the amount of heat emanating from the heat source.

Fire loading may be computed using the techniques presented in the Commentary.

4 Structural Response Assessment Against Fire

Structural assessment should ensure that the design meets appropriate performance criteria, as set forth in section 2.7. The structural response assessment against fire can be carried out using one, or a combination of, the following methods:

a. Zone (or screening) method
b. Strength level method
c. Ductility level method

Each of the analysis methods is successively more complex, requiring different analysis tools with increasing complexity.

Should a structure fail to meet the performance criteria in screening analysis then a strength level analysis should be carried out. If the structure fails in strength level analysis then a ductility level analysis should be performed.

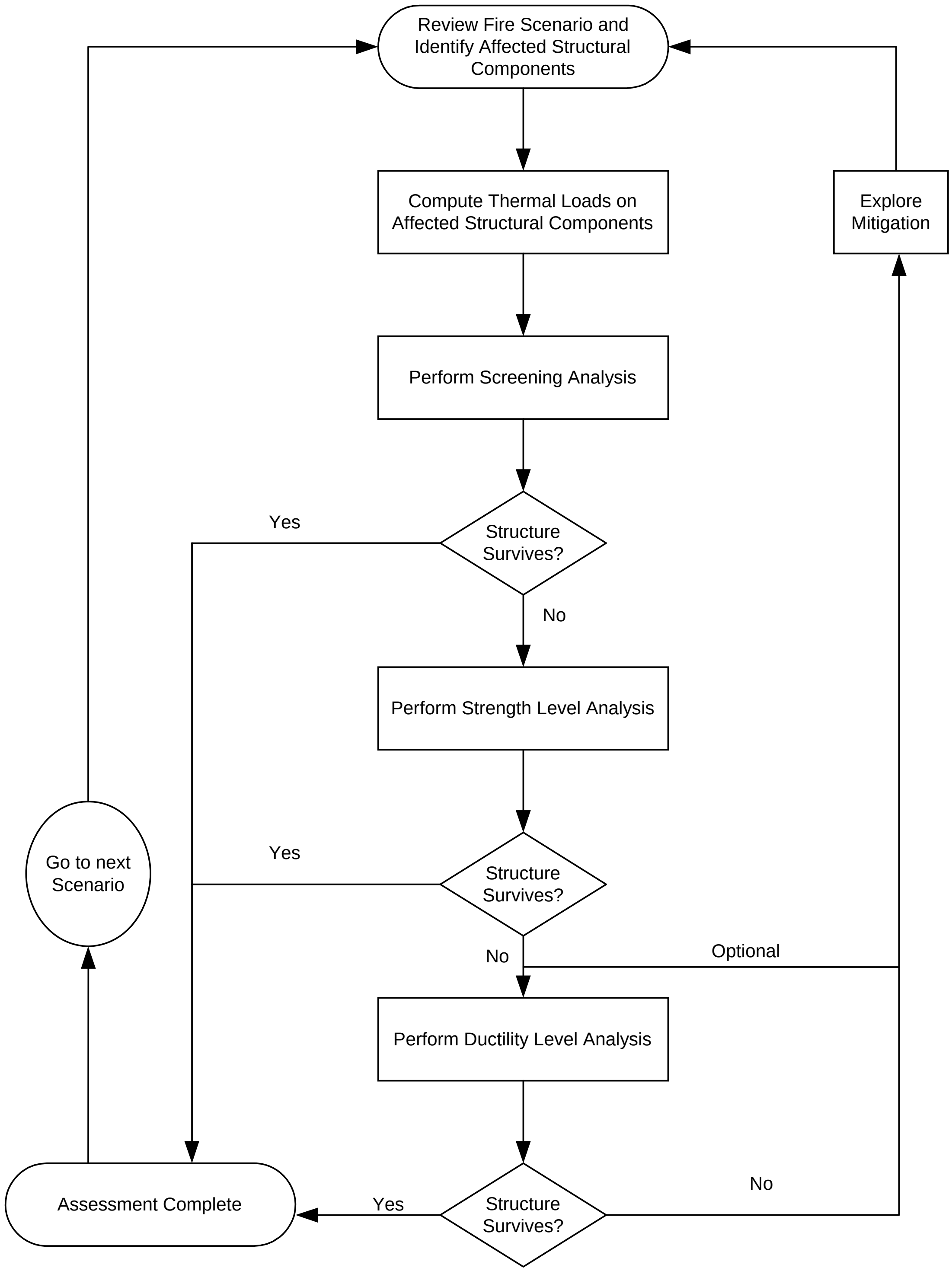


Figure 4-1—Process of Structural Assessment Against Fire

5 Fire Mitigation

Consideration of fire mitigation includes breaking the chain of events leading from the initial release to the full development of a fire scenario, reducing intensity and duration of fire, and provision of protection for structural members from fire.

5.1 GENERAL

While protection of structural members from fire remains the primary concern of the structural discipline, other means of fire mitigation may be considered by process and safety disciplines. These means of fire mitigation include, installation layout, process design, module layout, ventilation, cladding and decking details, drainage, vulnerability of equipment, pipe work and cabling, flame detection, fire detection, heat detection, smoke detection, gas detection, emergency shut down (ESD), de-pressurization, liquid inventory disposal, bunding drainage, and active fire suppression (deluge, halon, foam, CO2 and sprinkler systems, etc.).

Generally, layout may be optimized to minimize flame length and complexity of flame paths. Escalation may be prevented by the introduction of barriers and by the use of separation by distance where possible.

Experiments described in [18] state that deluge system has a negligible benefit when dealing with natural gas and propane jet fires. More recent experiments (37) have shown that there is a small probability that jet fire may be extinguished by deluge leading to the possibility of an explosion, indeed jet fires may become unstable and self extinguish.

Pool fires are usually extinguished by deluge. Water curtains are effective against pool fires in reducing radiation levels on escape ways and limiting extent of the flame.

While active fire suppression may be most effective against pool fire, the effective protection of structural members from hydrocarbon jet fire may be possible by appropriate positioning of firewalls, and/or application of passive fire protection (PFP) to the affected structural members.

Additional information on control and mitigation of fire events in offshore installations may be obtained from ISO 13702 [34].

5.2 FIREWALLS

The ratings for firewalls were originally developed for cellulose fires rather than hydrocarbon fires, which are more severe. The type of fire is represented in a furnace test where the firewall is in contact with a furnace with a well-defined temperature-time relationship. The hydrocarbon fire curve has a higher rate of temperature rise and attains a higher peak temperature than a cellulose fire curve.

The following equation is used to generate hydrocarbon temperature-time curve for furnace testing of steel structures designed to resist a hydrocarbon fire [17]:

$$T := 1100\cdot\left(1 - 0.325\cdot e^{-0.167\cdot t} - 0.204\cdot e^{-1.417\cdot t}\right) - 0.471\cdot e^{-15.833\cdot t}$$

where

T is the furnace temperature in °C at time t, minutes

The following equation is used to generate cellulose temperature-time curve for furnace testing of steel structures designed to resist a cellulosic fire [17]:

$$T := 345\cdot\log(8\cdot t + 1) + T_0$$

where

T_0 is the initial furnace temperature in °C at the start of testing.

In the offshore industry, the three ratings used are as follows [5]:

- B Class – maintains stability and integrity for 30 minutes when exposed to a cellulose fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period in minutes specified in the rating, i.e., B15 rating has a 15-minute time-period during which temperature rise is below 140°C (284°F) for maintaining insulation performance [2].

- A Class – maintains stability and integrity for a period of 60 minutes when exposed to a cellulose fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period specified in the rating.
- H Class – maintains stability and integrity for a period of 120 minutes when exposed to a hydrocarbon fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period specified in the rating.

In these definitions for the ratings for A-Class and H-Class, maintaining stability and integrity means that the passage of smoke and flame is prevented and that the load bearing components of the fire boundary, preferably do not reach a temperature in excess of 400°C (752°F) [2].

Table 5.2-1 outlines the performance standards for firewalls according to their ratings and applies to a pool fire. The rating of firewalls against jet fires gives about half the endurance times of those given in Table 5.2-1.

The positioning of firewall and its rating are critical in determining its effectiveness in providing adequate protection of the structural components from a particular fire scenario for the duration of the fire.

Structural assessment of a firewall should be considered when designing the division to meet the desired performance standard or rating of the firewall.

The erosive and momentum effects of a jet fire must also be considered. See Commentary for details.

5.3 PASSIVE FIRE PROTECTION (PFP)

The determination of PFP requirement may be made after completion of appropriate level of structural analysis and after consideration of all possible fire mitigation measures.

The application of PFP on to the exposed surface of the steel work restricts the temperature rise in the protected steel structure for the defined duration of the fire scenario. The PFP thus limits the thermal stress levels in structural steel so that its load-bearing ability is not compromised.

Amongst available PFP materials and systems are mineral wool, ceramic fiber, concrete and vermiculite-based materials, phenolic syntactic foam, and epoxy intumescent materials. Intumescent materials are thin coatings, generally between 5mm to 15mm thick. When exposed to fire this material forms a thick char preventing heat transfer. These materials provide protection against hydrocarbon pool and jet fires, and retain their fire performance throughout the life of an application, subject to material characteristics, surface preparation and specified application.

Care should be taken to protect structural steel from corrosion under certain PFP materials.

The materials for the PFP must be tested and certified by competent authority. The application of PFP must conform to the manufacturer’s specifications.

The thickness of the PFP would depend upon the performance standards.

The erosive and momentum effects of a jet fire must also be considered to prevent scaling of PFP materials.

Table 5.2-1—Performance Standard for Fire Walls by Rating (For Pool Fire)

Wall Rating	Stability and Integrity (Minutes)	Time for the Temperature to Rise to 140°C on Cold Face (Minutes)
H120	120	120
H60	120	60
H0	120	0
A60	60	60
A30	60	30
A15	60	15
A0	60	0
B15	30	15
B0	30	0

6 Blast as a Load Condition

If the risk assessment process described in Section 2 identifies that a significant risk of blast exists, blast should be considered as a load condition.

A blast scenario developed as a process HAZOP (hazard and operational) analysis establishes the make up and size of the vapor cloud, and the ignition source for the area being investigated.

The loading generated by a blast depends on many factors, such as the type and volume of hydrocarbon released; ignition source, type and location; the amount of congestion in a module; the amount of confinement; and the amount of venting available. Additional details on blast loading are presented in the Commentary.

Blast loading can be categorized in four components:

- Overpressure loads which result from increases in pressure due to expanding combustion products
- Drag loads which result from the flow of air, gases, and combustion products past an object.
- Shock loads have a very small duration compared to the whole blast.
- Global reaction loads, which result from differential pressure loading, have same time scale as the pressure variation.

6.1 BLAST OVERPRESSURE

There are no simple calculation methods for determining blast loads for offshore structures. A number of predictive approaches are currently being applied to generate blast overpressure from explosions in congested volumes. These are:

a. Empirical Models based on the correlation of experimental data and the models' accuracy and applicability relating to the experimental database
b. Phenomenological Models based on modeling the underlying physical processes, interpolating more accurately between data and extrapolating with more certainty to situations not addressed by experimental work
c. Numerical Models which solve the underlying equations describing gas flow, turbulence and combustion processes

Numerical models following the principles of Computational Fluid Dynamics (CFD) have the potential for providing a higher predictive accuracy and a greater potential of addressing any blast scenario [24].

In addition, there is a reasonable experience base across industry from which 'nominal overpressures' have been established for certain classes of structures. Nominal overpressures and their application are discussed in the commentary Section C6.3. In lieu of the availability of applicable nominal overpressures, some level of blast simulation modeling, as described above, is recommended for computation of blast loading on offshore structures.

6.2 DRAG LOADS

If a body is subjected to a blast induced wind, then it will experience a directional loading due to the passing air/gas flow, known as the drag load. See commentary for further details.

6.3 SHOCK AND GLOBAL REACTION LOADS

The two major sources of loads from blasts are:

- Reaction loads from the expulsion of vented gases.
- Side loads due to the ignition of an external gas cloud, which has drifted to one side of the platform – the external blast.

A structure, which is subjected to a blast, may experience differential pressure loading. The duration of the loading is typically only a fraction of the blast. In this case, the relationship between the load experienced by the structure and the overpressure in the incident wave is much more complicated. If the pressure wave is normally incident on a closed wall then all the blast energy is reflected and the peak overpressure on the impacted surface is amplified. This results in a peak net directional loading greater than that of the incident wave.

When the blast wave propagates past or through openings in the structure, more complex interaction occurs giving rise to reflected and diffracted components. See commentary for additional details.

7 Structural Response Assessment Against Blast

Structural assessment should ensure that the design meets appropriate performance criteria, as set forth in Section 2.7.

7.1 DYNAMIC EFFECTS

When computing structural response against blast loading, the duration of the loading is important as it determines whether the loading is impulsive, dynamic or quasi-static. The duration of a typical hydrocarbon blast is often close to the fundamental natural period of the structural members, which would call for a dynamic analysis. The details of computing dynamic effects may be seen in the commentary.

7.2 STRUCTURAL ASSESSMENT FOR BLAST

The treatment of blast as a load condition can be addressed using one of the following methods:

a. Screening check

b. Strength level analysis which considers a more frequent design event where it is required that the structure does not deform plastically and that the SCEs remain operational

c. Ductility level analysis which considers the extreme design event and utilizes reserve strengths of the structure

A screening check may be used as a conservative design basis or to assist in the identification of structural components for further response assessment to ensure compliance with performance criteria. The strength level analysis is a linear elastic analysis with modified code checks, which provides a less conservative basis for the design. If the strength level analysis fails to satisfy the performance criteria, a ductility level analysis may be performed. If the ductility level analysis fails to meet the performance criteria, then blast mitigation and/or structural modification should be considered.

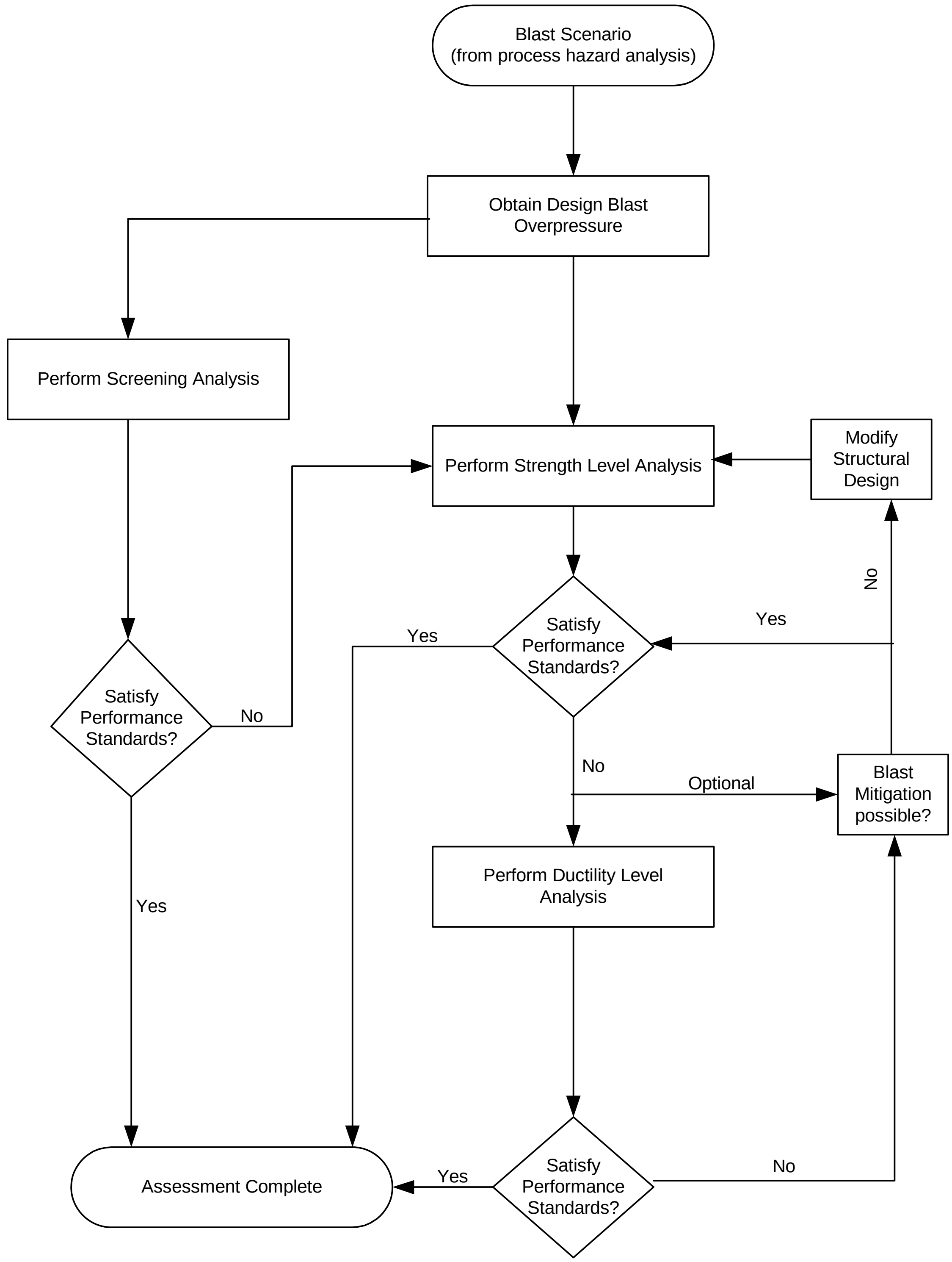


Figure 7-1—Process of Structural Assessment against Blast

At any stage of the process, mitigation measures may be considered. This may include measures for elimination of the initiating event, reduction of the severity of the event, and/or structural modification. If none of the mitigation options is feasible, structural modification/strengthening measures should be considered to satisfy the performance criteria. The assessment process is shown in Figure 7-1. The details of the assessment methods are given in the Commentary.

7.3 BLAST LOAD LEVELS

For higher consequence facilities operators may, optionally wish to consider two levels of explosion loading by analogy with earthquake assessment, i.e., the ductility level blast and the strength level blast.

The design level blast load is referred to as the Ductility Level Blast (DLB); defined as a low-probability high-consequence event, which must be investigated for at least retaining the integrity of the temporary refuge, safe muster areas and escape routes. The ductility level blast is the design level overpressure used to represent the extreme design event

A reduced blast load, sometimes referred to as a Strength Level Blast (SLB) by analogy to earthquake design, is defined as a higher-probability, lower-consequence event. Performance criteria associated with the SLB may include elastic response of the primary structure, with the safety critical elements remaining functional, and with an expected platform restart within a reasonable period.

The SLB load case may be desirable for the following reasons:

a. The SLB may detect weaknesses in the structure at an early stage of the design improving the likelihood of meeting performance criteria for the DLB.
b. The prediction of equipment and piping response in the elastic regime is better understood than the conditions that give rise to rupture. The SLB enables these checks to be made at a lower load level often resulting in good performance at the higher level.
c. It is quicker to perform SLB load case. If performed correctly, the assessment will provide good assurance of adequacy of structure under DLB loads.
d. The SLB load case provides a degree of additional asset protection.

Overpressures computed from the extreme design event are used as blast loading for ductility level analysis. If computations are not available for overpressures for frequent design events, then 1/3rd of the blast loading from the extreme design event may be used for strength level analysis.

8 Blast Mitigation

8.1 MITIGATION OF THE CONSEQUENCES OF BLAST

Blast mitigation measures may include one or more of the following:

a. Measures to reduce the probability of formation of a gas cloud,
b. Upgrading the emergency shut down equipment,
c. Introduction of blast relief panel to alleviate peak pressure,
d. Modification to equipment layout,
e. Provision of deluge
f. Providing/strengthening blast walls, and
g. Removal or isolation of ignition sources.

Mitigation measures should address the chain of events that occur in the lead up to a vapor cloud explosion incident such as, prevention or reduction in the size and concentration of a vapor cloud, measures to prevent ignition and/or combustion, followed by measures to alleviate blast severity and finally strengthening of the structure.

Additional information on control and mitigation of blast events on offshore installations may be obtained from ISO 13702 [34].

8.2 VENTILATION

Open vent areas improve the ventilation and airflow paths in the event of a gas release. This helps in reducing the probability of gas build-up due to free expansion of gas and hence occurrence of blast.

Open vent areas may be provided in the form of grating floors or mesh walls. In general, these provisions may reduce the blast overpressure. However, if the ignition source is some distance away from the vent and the blast is congestion controlled, then it is likely to have little effect on the blast overpressure [24].

Venting is most effective when the obstacles are evenly distributed. For the same blockage ratio (volume occupied by the obstacles to the total volume), several obstacles create a higher overpressure than a smaller number of big obstacles. Normal louvers create sufficient obstruction to cause increased overpressures.

8.3 BLAST RELIEF PANELS

Blast relief panels, which open quickly during a blast event in order to reduce peak overpressures, must be carefully designed. It is unlikely that loosening of cladding panels will have the desired effect.

A typical blast relief panel should have the following properties:

a. To be lightweight construction, may be of aluminum

b. To start opening at 50 millibar overpressure

c. To open within about 50 milliseconds (ms) and to stay open

d. To be located to open a clear vent path

More details can be obtained from ref. [12,26].

8.4 BLAST WALLS

Blast walls may be either bulkhead walls or proprietary walls.

Bulkhead walls are integrated with the general structural form like ship bulkheads and are usually built at the same time as the rest of the structure.

Proprietary walls are usually lightweight structures fitted later in the construction phase. They are often made up of stainless steel, carbon steel, aluminum or fiberglass.

Blast walls usually are designed to deform plastically and act predominantly in bending to minimize the reactions on the primary structural members of the platform. Edge connections shall be so detailed that the reaction loads are transmitted to the supports without damage to the supporting steel work. Because of the inertia of the wall, it is possible to design these connections such that the transmitted shear forces and moments are much lower than the peak overpressure force on the wall.

The capacity of a blast wall with stiffened plate construction may be estimated using yield line analysis for the plate sections [28]. The possible failure modes of the wall may include panel failure, stiffener failure, and whole wall collapse. Tension and membrane effects may have limited advantage as the restraint from the surrounding structure through inertia or stiffness may not be sufficient for these effects to be fully mobilized.

9 Fire and Blast Interaction

Fire and blast are often synergistic. Fires may occur after a blast has occurred and a blast may be one of the escalation consequences of a fire. The consequences of combined fire and blast scenarios with either component occurring first should be considered in the structural design or assessment. The fire and blast analyses should be performed together and the effects of one on the other carefully analyzed. See Commentary for further discussion.

10 Floating Structures

The extension of oil and gas production into deep water has brought about the use of floating structures. Increasing number of large floating structures with high inventories, storage and/or throughput are operated and being planned around the world including the Gulf of Mexico. The type of floating structures include but is not limited to (a) Floating Production System (FPS), (b) Floating Production Storage and Offloading System (FPSO), (c) SPAR, (d) TLP, (e) Semi-submersible, and (f) deep-draft floating structures.

There are several special features associated with floating structures, which cannot be dealt with by simple extrapolation of current practices in use on fixed platforms. These features relate to the different geometry, methods of construction, compartmentation, operations, fire and blast scenarios, response characteristics of marine construction to fire and blast, and special features associated with the motion, station keeping, marine systems and stability of the structure.

Special attention is drawn on the need to check on stability of the structure due to the effect of any fire or blast event, which has the potential to bring on the instability of the floating system. The other considerations would include structural integrity of the hull, maintenance of evacuation capabilities, and prevention of secondary dimensioning events.

10.1 CHARACTERISTICS OF FLOATING STRUCTURES

The design of floating structures differs from fixed platform, as these units require the use of stiffened plate construction, Marine Systems, Marine Operations Manuals and personnel such as Ballast Control Operators for safe operations. Floating Facility Systems, including risers, Marine Systems, Station Keeping are made up of a number of sub-systems, which are important in evaluation of safety against fire and explosion events. Examples of such sub-systems or marine operations systems together with their incident potentials are listed in Table 10.1-1:

Table 10.1-1—Floating Installations Sub-systems

Sub-system	**Probable Incident**
Drilling	Well control failure
Catenary risers	Rupture leading to release of hydrocarbon
Production and drilling risers	Rupture leading to release of hydrocarbon
Station-keeping	Riser damage leading to release of hydrocarbon
Wellheads, X-mass trees	Pressure leakage
Process facilities	Equipment failure leading to fire and blast
Marine systems	Pump failure leading to ignition and blast in confined space
Storage/Offloading	Malfunction of inert gas system

The assessment of risks related to fire and blast on floating structures should be performed after identifying risks in the following two (2) categories:

1. Fire and blast risks that may impact the integrity of the floating structure or are related to marine systems, such as engine room incidents that may impact the topside.
2. Fire and blast risks that have an impact on the topside evacuation, rescue, living quarters, and temporary refuge. Such scenarios should be treated similarly as they are treated on fixed platforms, but need to include the following effects and characteristics:
    - General layout (separate modules/sections and relative position of modules/sections)
    - Movement of topside (waves etc.)
    - Weathervaning (wind direction is often constant)
    - Any roll, pitch, or trim of the vessel due to damage

10.2 SPECIFIC ISSUES WITH FLOATING STRUCTURES

The major differences in the case of floating structures including FPSOs, TLPs, SPARs, and Semi-submersibles compared to fixed platforms are deck layout, hull compartmentation and marine systems operations. Floating structures thus present different risk scenarios compared to fixed platforms.

Examples of specific issues, which are required to be considered during risk assessment and design of floating structures against fire and blast events, are identified as follows:

1. Considerable movement of floating system hull with potential to:
   - Contribute to increased spreading of pool fires.
   - Control the natural ventilation in case of turret-moored FPSO with weathervaning capability
2. Potential of high congestion/confinement of gas, with increased potential for blast events, in areas such as:
   - FPSO turret, process area, cargo tanks and pump room.
   - SPAR moonpool machinery or storage spaces inside hulls
3. Increased number of potential hydrocarbon releases, such as leakage from:
   - FPSO swivel unit
   - Piping due to hogging and sagging of deck structure
   - FPSO cargo tanks due to fire and explosion events
4. Equipment spacing and layout variation, such as:
   - Closer equipment spacing on Semi-submersibles, TLPs and SPARs
   - Spread out spacing between equipment and utilities on a tanker type FPSO
5. Potential for spread of fire to multiple decks or compartments, such as:
   - Presence of grated deck
   - Layouts involving proximity of process area with living quarters.
6. Potential for larger blast and fire events due to:
   - Storage tanks of crude oil or methanol tanks in FPSO and their possibility in other FPS units
   - Gas cloud accumulation on FPSO from the cargo vent pipes
   - Blast/fire in engine room
7. High consequence events with possibility of losing the unit, due to:
   - The stability of the vessel may be compromised during fire or blast events including any subsequent blasts as a result of escalation.
   - Loss of buoyancy from significant leakage from riser and subsea equipment reaching underneath the floating unit
   - Flooding of a riser or tendon could result in reduced buoyancy of hull
8. Tie-in of satellite wells increases the risk level by increasing the production throughput
9. Environmental pollution from loss of hydrocarbon from floating installations.

It must be understood that the data on frequencies of fire and blast events in floating installations are limited and careful considerations must be made to allow significant uncertainty in estimation of risk measures.

The impact of above specific features of floating structures on initiation of fire and blast events and their propagation into severe and catastrophic events is controlled through various rules and regulations of certifying agencies as well as SOLAS [51]. Some examples of measures, which may be taken during design phase to reduce risks from fire and blast events associated with specific features of floating structures are given as follows:

a. Reducing frequency of events from floating installation specific design and equipment layouts, such as:
   - It is recommended that the hull compartments shall not be used for the storage of un-processed oil, which increases blast risk.
   - Secure connections and improved fuel gas piping reduces risk of leakage and ignition.
   - Routing of hydrocarbon piping to or through the utility area shall be minimized and flanges avoided.
   - Hydrocarbon pressure vessels and heavy-duty equipment, such as generators shall not be located within main hull structure.
   - Depending on the amount of ventilation required by the process facilities design, effective placement of fire walls and/or blast walls can provide adequate protection to quarters, temporary refuge, and escape routes and embarkation stations.
   - Effective placement of production equipment, such as the orientation of pressure vessels to reduce blast and fire effects plays an important role in reducing the amount of damage caused by fire and blast.

b. Implementation of operational and safety measures to reduce or to eliminate spread of an initiating event into a hazardous event with potential negative consequences:
   - Provision of effective gas detection system in areas with potential of high congestion/confinement of gas. An effective gas detection system plays important role in reducing risk of ignition.
   - Draining of oil spills from process deck to prevent escalation to tank deck and cargo tanks.
   - Location of cargo tank vents away from hot surfaces and ignition sources.
   - Longitudinal shape of FPSO enables good separation distance between process areas and accommodation area.
   - A weathervaning FPSO with deck layout keeping the accommodation area upwind of any hydrocarbon event enable enhance the integrity of accommodation and lifeboats.
   - Process deck should be continuous (solid deck plating) with sills/bunds provided around openings such as stairwells and penetrations, and on the perimeter of the solid part of the deck to prevent fire escalation caused by run-off on to lower decks
   - Good natural ventilation of process areas and turret area above deck level due to open design reduces probability of ignition and explosion overpressures. Enclosed mechanically ventilated areas shall be restricted to containers or small rooms. Equipment that may present source of ignition shall not be arranged in the moonpool area.
   - Isolation of process stream segments prevents escalation.
   - Cold flare philosophy implemented to decrease probability of igniting riser/turret releases.
   - Location of crude oil pumps shall be made based on hazard evaluation for operation and maintenance of pumps. Submerged pumps should be preferred.

c. Control of consequences from hazardous events could be achieved through the following:
   - Segregation of cargo tanks by using ballast tanks or void tanks can provide a structural double barrier to prevent the possibility of environmental pollution.
   - Production or export/gas injection risers shall be protected against fire in the turret
   - Protected escape routes along the length of the installation capable of withstanding fire and blast in process and turret areas.
   - Reducing duration of a fire scenario reduces heat load on primary structural members supporting decks located at or above fire source.
   - Route any potential overpressure away from adjacent cargo tank.
   - Rapid blow-down beyond recommendation of API RP 521 reduces risk and reduces/eliminates structural fire protection
   - Uses of an emergency disconnect system for emergency abandonment of field.

10.3 SPECIFIC DESIGN ISSUES

The design of the hull against blast overpressure shall ensure that the hull sustains only local damage, which is not detrimental to the integrity of the whole unit at least for the period of evacuation.

The hull compartment design shall consider potential for containing damage within the same compartment and eliminate the chain of events leading to spreading the damage to the adjacent compartments or to deck, so that significant loss of buoyancy and instability of the overall unit and failure of the mooring system is not compromised. Thus, the compartment with potential for initiating or escalating fire or blast events shall be designed appropriately.

The design of piping in hull compartments shall be appropriate to eliminate potential for spreading damage to multiple compartments; design considerations may include provision of ‘pipe chamber’ or ‘pipe chute’ to limit damage and eventual flooding of multiple damaged compartments.

The upper hull design shall account for impact of fire events from topsides or moonpool with potential of deteriorating structural capacity of the hull and thereby reducing stability. Special attention shall be given to concentrated load areas such as topsides connections, or mooring chain-jack foundations.

Additional guidance on fire and blast considerations in floating structures is available in API Recommended Practice for Planning Designing and Constructing Floating Production Systems (API RP 2FPS).

11 Material

For materials specification, reference should be made to Section 8 of API RP 2A [2].

Fire or blast events may substantially alter the material behavior due to changes in thermal properties with increased steel temperature and due to strain rate enhancement and plastic capacity considerations.

For material behavior in fire and blast loading, see Commentary.

12 Limited Construction Guidance

12.1 PLATING

The size of connection welds in the deck plates where membrane stresses occur in blast loading shall be at least sufficient to transmit the plate membrane forces. The welds may be oversized to have a large reserve capacity.

The welds between the deck plating and supporting beam should be subjected to detailed strength check to withstand blast loading.

The penetrations through plate in areas where high in-plane stresses or strains can occur should have a compensation plate with cross-sectional area not less than the diameter of the cut-out in the plate multiplied by its thickness.

12.2 BRACES AND STRUTS TO CEILING TIES

The connections between the braces, struts and ties should have strength substantially above the design loading for the structure and should develop the strength of connected elements.

The connections should be detailed so that buckling or overstressing of one member does not weaken the member to which it is connected.

12.2 BEAMS

In long span beams above a potentially hazardous area where credible blast event may occur, nominal bottom flange restraints should be provided to counter lateral torsional buckling.

Design of continuous span beams should consider load reversal in adjacent spans due to blast.

To have improved blast resistance capacity, continuous construction of primary deck beams are preferred.

In potential high blast areas, all end connections to stringers should be provided with end fixity and gussets.

13 Good Practice Detailing

Dispersal of blast overpressure may be most effectively achieved through careful consideration of venting details in layout of equipments, partitions, firewalls, piping, etc. Some guidance from ISO13702 [34] to such layouts is provided in the commentary.

COMMENTARY

This Commentary provides guidelines for the evaluation of fire and blast loads and structural response thereof. Nominal explosion overpressures are provided for certain classes of facilities. Discussion of alternative methods for the calculation of blast loads is included with reference to sources of detailed guidance. The commentary also includes examples of good practice for fire and blast design including guidelines for facilities layout and structural connection detailing.

COMMENTARY ON SECTION 2—RISK ASSESSMENT

C.2.1 GENERAL

A risk assessment is required if the platform does not meet the screening criteria as defined in Section 2.2. A risk assessment is not required if explicit consideration of nominal loads is found appropriate and used for the structural assessment to meet performance criteria.

C.2.2 SCREENING

For low-risk platforms, qualitative assessment of consequence of events and likelihood of events may be performed by close examination of the facilities of the platform.

For low-consequence events, the equipment count would probably be low, being limited to wellheads and manifold with no vessels and no associated pipe work, which would lead to low congestion and inventory. The consequence could also be low if the confinement is low with no more than two solid boundaries including solid decks. For low consequence facilities, the manning would be consistent with normally unattended installation with low maintenance frequency (less than one in six weeks).

The likelihood considerations tend to align closely with the consequence factors in that the low consequence installations will tend to be small and therefore less complex. Larger installations will have higher potential for leak and ignition sources and therefore a greater requirement for intervention and maintenance.

For low-likelihood events, installations and compartments will have a low equipment count. The frequency of manning of one in six weeks or less will contribute to low likelihood of events from the standpoint of maintenance risk.

Most normally manned offshore platforms with hydrocarbon facilities are expected to proceed from Task A-1 to Task A-2 in Figure 2.8.1.

C.2.4 EVENT BASED

Credible fire and blast events originate from the release of hydrocarbon. Causes of release may be dropped objects, ship impact, intervention, fatigue, vibration, extreme environmental conditions, imperfections, escalation from fire, exceedance of design conditions and human error [37].

Generic release scenarios based on historic evidence in the Gulf of Mexico [35] and the UK sector of the North Sea [36] can be found in the references cited.

COMMENTARY ON SECTION 3—FIRE AS A LOAD CONDITION

C.3.1 FIRE LOAD

For fire load consideration, two types of hydrocarbon fire are discussed; pool fires and jet fires. For jet fires in a compartment, see details given in references 5 and 21.

C.3.2 POOL FIRE

A pool fire develops when liquid fuel forms a pool on the deck and fuel evaporates from the surface of the pool by radiation from the burning flames above. The gaseous fuel burns causing more of the pool to evaporate. The process continues until the fuel is consumed or the ventilation conditions cause the fire to be extinguished.

Pool fires are characterized by negligible momentum of the fuel.

C.3.2.1 Calculation of Flame Geometry of Pool Fire

The specific mass-burning rate (mass/unit area-unit time) for a pool fire is given by [40]:

$$m = \left\{ \frac{0.001 H_c}{H_v + C_p (T_b - T_a)} \right\} \times \varepsilon$$

where

H_c	is the heat of combustion of the fuel at its combustion point (MJ/kg)
H_v	is the heat of vaporization of the fuel at its boiling point (kJ/kg)
T_b	is the liquid boiling temperature (°K)
ε	is the emmissivity of the flame (1.0 is typical).
C_p	is the specific heat of the fuel under constant pressure (kJ/kg/°C)
T_a	is the ambient temperature (°K= °C + 273)

The value of m is assumed to be a constant value for a given fuel type (0.14kg/m^2/s for LNG and 0.12 kg/m^2/s for LPG). Figure C.3.2.1-1 illustrates a pool fire situation modeled by the above equations with flame temperature T_f .

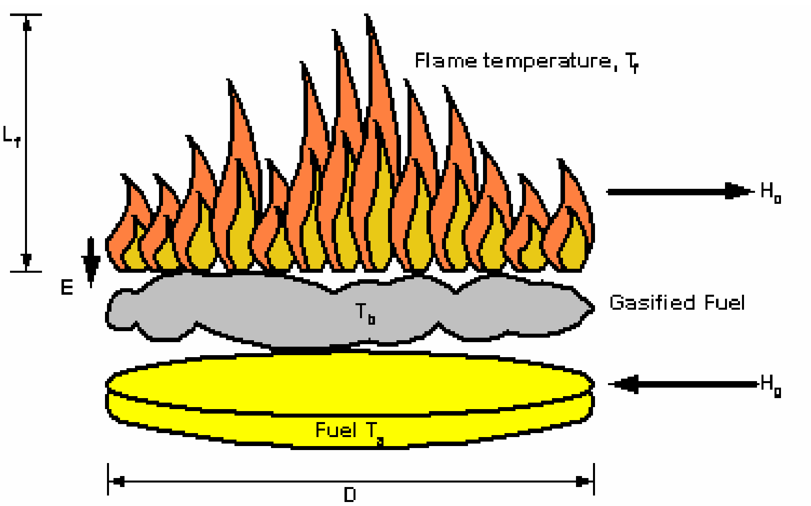


Figure C.3.2.1-1—Pool Fire

The energy release rate, R of a pool or jet fire, is affected by the ventilation conditions of the fire and the heat of combustion of the fuel. If the ventilation rate is not sufficient to ensure 'open conditions' then the energy release rate will be limited by the amount of ventilation the fire receives.

$R = MH_c$ if $M_a \geq S \times M$ 'fuel controlled/open conditions'

$R = M_a H_c / S$ if $M_a < S \times M$ 'ventilation controlled/confined fires'

where

S	is the stoichiometric air/fuel mass ratio
M_a	is the ventilation rate (kg/sec of air)
M	is the mass release rate (kg/sec fuel)

R is the energy release rate (kW)

Formulae for the ventilation rate exist for rectangular vertical and horizontal openings and depend on the vent dimensions. For a vertical opening of area A_w and height H the ventilation rate M_a is given by:

$$M_a = 0.5 A_w H^{1/2}$$

Air supplied by HVAC system under forced ventilation may be added to this ventilation rate.

In order to calculate the radiation levels received by a member it is necessary to know the flame geometry. The horizontal extent of the fire is required to determine whether the fire engulfs a member.

Given the energy release rate R, the diameter of the pool fire, D may be calculated from:

$$R = m \frac{\pi D^2}{4} H_c$$ where m = the specific mass burning rate

The flame length is given by [20]:

$$L_f = D\,(3.7\,Q^{0.4} - 1.02)$$

where D is the pool diameter in meters, and Q is a non-dimensional square-root of Froude number given in terms of heat energy release rate [20]:

$$Q = \left\{ \frac{R}{\rho_a \times C_p \times T_a \times D^2 \times \sqrt{gD}} \right\}$$

where

ρ_a is the ambient air density

g is the acceleration due to gravity.

The Thomas equation [48] is also used to compute flame length:

$$L = 42D \left(\frac{m}{\rho_a \sqrt{gD}} \right)^{0.61}$$

C.3.2.2 Radiation Levels from Pool Fire

Radiation levels from a pool fire are calculated using a surface emitter model. The radiation level, q_{ir}, is calculated from the equation [5]:

$$q_{ir} = \tau V S_e$$

where

S_e is the average surface emissive power radiated per square meter of the flame, taken to be between 130 to 300kW/m^2 (depending on the fuel type, to be verified in each case).

V is the view factor representing the proportion of the field of view occupied by flames

τ is the atmospheric transmissivity, representing the proportion of the radiation reaching the observation point. The atmospheric transmissivity is defined as the fraction of the radiant energy not absorbed by the CO_2 and water vapor in the atmosphere. Pieterson and Huaerta [49] developed the following equation to estimate atmospheric transmissivity:

$$\tau = 2.02 \left(\rho_w d_e \right)^{-0.09}$$

where

ρ_w = Partial pressure of water vapor (pascals)

$= 101322 P_w \left(\frac{H}{100} \right)$

d_e = Distance between source (edge of flame) and receiver (m)

H = Relative humidity (%)

P_w = Vapor pressure of water at 5°C – 50°C (41°F – 122°F) (atm)

$$P_w = \exp\left(14.2829 - \frac{5293.67}{T_a}\right)$$

The value of τ is sometimes taken as 1.0. However for longer path lengths, this value appear to be very conservative. For longer path lengths (over 20 m, 65 feet), where absorption could be 20 –40%, this will result in a substantial overestimate for received radiation [51]. The amount of radiation a single point receives from a given fire depends on the 'view factor'. The view factor represents the proportion of the field of view from the observation point, which is occupied by the flame surface. The view factor is a function of the size and shape of the fire, the distance from the fire and the height of the observation point above the base of the fire. This is illustrated in Figure C.3.2.2-1 [20] for open and confined pool fires.

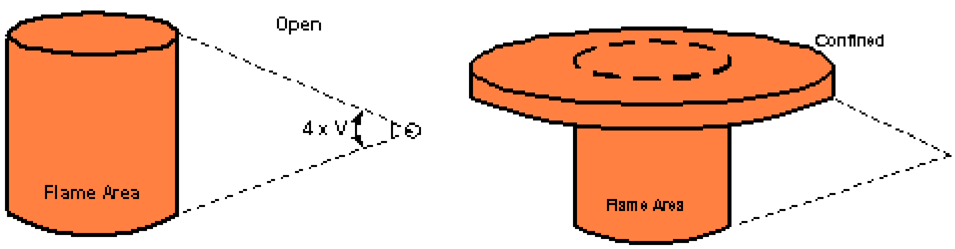
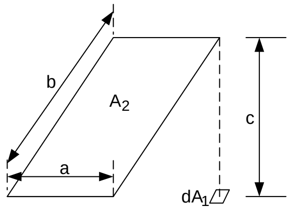


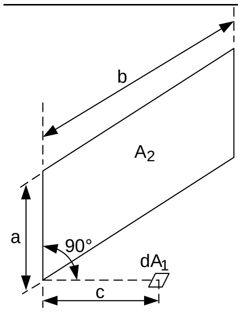
Figure C.3.2.2-1—View Factor for Open and Confined Fires

For an engulfed member V equals one. For a non-engulfed member it is usually conservative to assume a value of 0.5. Some simple expressions for the view factor corresponding to commonly assumed flame shapes and at different observation positions are given in Figure C.3.2.2-2. [20].



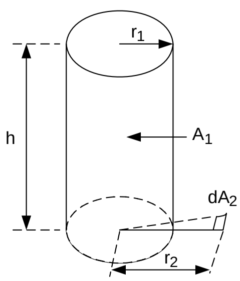
X = a/c Y = b/c

$$F_{d1-2} = \frac{1}{2\pi}\left\{\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right)+\frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right\}$$



X = a/b Y = c/b $A = 1/\sqrt{X^2 + Y^2}$

$$F_{d1-2} = \frac{1}{2\pi}\left\{\tan^{-1}(1/Y) - AY\tan^{-1}A\right\}$$



$R = r_1/r_2$ $L = h/r_2$ $X = \sqrt{(1+L^2+R^2)^2 - 4R^2}$

$$F_{d1-2} = \frac{1}{2\pi}\cos^{-1}R + \frac{1}{\pi}\left\{\tan^{-1}\left[\frac{R}{\sqrt{1-R^2}}\right] - \frac{1+L^2-R^2}{X}\tan^{-1}\left[\frac{X\tan(0.5\cos^{-1}R)}{1+L^2+R^2-2R}\right]\right\}$$

Figure C.3.2.2-2—Common View Factors

C.3.3 JET FIRE

A jet fire is usually a high-pressure release of gas or live crude containing gas in solution that forms a jet, which is ignited. The flame burns back against the flow towards the release point. Under certain release conditions, the flame may be unstable and may extinguish itself. An explosion may then result from the accumulated fuel/air cloud. A jet fire is illustrated in Figure C.3.3-1.

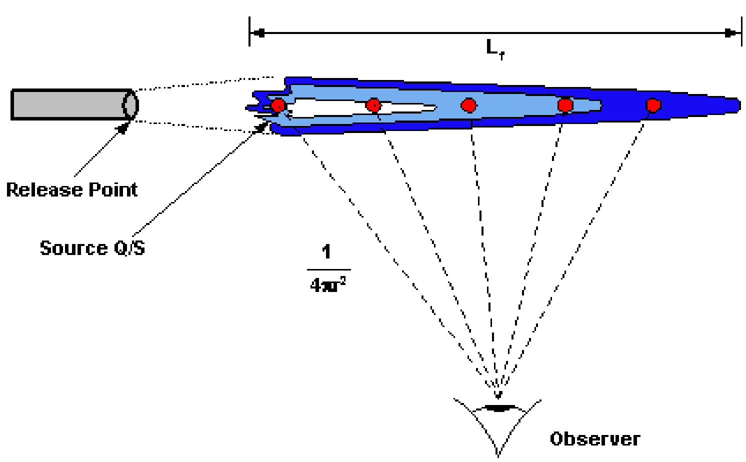


Figure C.3.3-1—Jet Fire

C.3.3.1 Calculation of Flame Geometry of Jet Fire

A number of expressions for jet flame lengths from vertical releases are given in Ref. [21]. Some are in terms of mass release rate; others are given in terms of energy release rate. In order to be able to use the same formulation for ventilation and fuel limited fires the multiple source models should be used, this depends on mass release rate. This model may also be extended to the calculation of radiation levels. The results are assumed to apply to non-vertical releases.

The flame may be thought of as burning back towards the point of release against the flow of fuel.

For a gas jet fire, the flame length, L_f, in meters is given by [21]:

$$L_f = 18.5 \times M^{0.41}$$

where M is the effective mass release rate in kg/sec.

For a liquid jet fire, the flame length is given by [21]:

$$L_f = 17 \times M^{1.35}$$

For an obstructed jet fire impinging on local obstacles or confined by plated decks the jet shape may be idealized as a sphere, hemisphere or cylinder with a flame volume V_f, given by :

$$V_f = C \times M^{1.35}$$

where

C = 100 for a Propane release

C = 90 for a Methane release

C = 170 for a crude oil release

C = 110 for a condensate release

For a compartment fire the effective mass release rate 'M' may be limited by the ventilation rate as described in the previous section.

C.3.3.2 Radiation Levels from Jet Fire

Most commonly, the multiple-point source model is used to calculate radiation levels from a conical jet flame. Five sources with source strength equal to one fifth of the total radiative power of the flame are placed at equal distances down the length of the flame. In this model, these sources are assumed isotropic emitters. The radiation level q_{ir}', from each source is given by:

$$q_{ir}' = \frac{R/5}{4\pi r^2}$$

where

R = energy release rate

r = radius of the flame

The total heat flux, q_{ir}, is the sum of the contributions from the five point sources.

Other type of models, such as, surface emitter or conical frustum and other point source models may also be used with due attention to their limitations.

C.3.3.3 Heat Load

C.3.3.3.1 Calculation of Steel Temperature

Structural steel members gain heat due to radiation; convection and conduction of heat resulting from either pool fires or jet fires in open or confined environments. The temperature-time history generated by the heat incident is used as fire load. Conduction may usually be ignored for members that are directly subject to thermal loading.

Steady-state temperature of steel members, attained during the fire scenario under consideration, will be needed for screening analysis and strength level analysis. For ductility level analysis, temperature-time history of steel members, during the fire scenario under consideration, will be needed. The procedure for calculating steel temperature resulting from a fire scenario requires thermal properties of steel.

Time-histories of steel temperature are calculated using a time-stepping iteration process. It is assumed that at any instant in time steady state conditions exist, i.e. thermal properties are not assumed to change significantly between two time intervals. The heat flux absorbed by the member is then assumed to act over the time increment and hence a gain in temperature of the member over the increment may be determined. The newly increased steel temperature is then assumed to act over the next time-period.

The methodology used to calculate the flame temperature is outlined below.

It is assumed that a fire is a 'black body' entity, i.e. it is a perfectly radiating and absorbing body, allowing full surface emmissivity (ε_f =1.0). The following equation is used to compute the flame temperature:

$$Q = \varepsilon_f \cdot \sigma \cdot \left(T_f^4\right)$$

where

Q	=	Flame radiation per unit area, kW/m^2
σ	=	Stefan Boltzmann constant, 5.67 x 10^{-8} Jm^{-2}s^{-1}K^{-4}
ε_f	=	Flame surface emmissivity (usually taken as 1)
T_f	=	Flame temperature, ° K (degrees Kelvin)

C.3.3.3.2 Heat Flux to Target

C.3.3.3.2.1 General

The method of determination of absorbed heat flux is given in the Interim Guidance Notes [24]. The general heat transfer equation may be written as:

$$\varepsilon_s q_{ir} + q_{ic} = q_{rad} + q_{conv} + q_{cond}$$

where

q_{ir} = Incident radiant heat flux

ε_s = Surface emmissivity (0.8 for unprotected steel)

q_{ic} = Incident convective heat flux (0 for an engulfed member)

q_{rad} = Heat flux radiated from surface

q_{conv} = Heat flux convected away from the surface (0 for an engulfed member)

q_{cond} = Heat flux conducted away from the surface (0 for an engulfed member)

All quantities are per unit length of the member.

A spreadsheet may be used to implement the fire load computation allowing incident radiation to be input as varying with time. This allows steel temperatures to be determined for a fire scenario with a limited inventory.

C.3.3.3.2.2 Engulfed Objects

Engulfed objects are objects assumed to be fully within the flame, whether it is a pool fire, or jet fire. For an object that is fully engulfed, there will be no net heat loss by convection. The heat transfer equation in this case will be:

$$\varepsilon\ q_{ir} = \sigma\varepsilon T_f^4 = \sigma\varepsilon T_s^4 + \frac{AC_s\rho_s}{H_p}\frac{dT_s}{dt}$$

where

σ = Stefan-Boltzman constant, (5.67 x 10-8 W/m2K-4)

T_f = actual temperature measured within the fire

T_s = steel temperature (°K)

A = cross-sectional area of the member

C_s = specific heat capacity

ρ_s = density of steel

H_p = heated perimeter (for an engulfed member, this is equal to the total member perimeter) of the member

All quantities are per unit length of the member.

C.3.3.3.2.3 Non-engulfed Objects

For non-engulfed objects, that is, members that are not completely immersed in the flame itself, heat may be convected away from the surface of the member, resulting in the following heat transfer equation:

$$\varepsilon q_{ir}H_p = \sigma\varepsilon\left(T_s^4 - T_a^4\right)P_{tot} + h\left(T_s - T_a\right)P_{tot} + AC_s\rho_s\frac{dT_s}{dt}$$

where

h = convective heat transfer coefficient, taken as 25 W/m^2 °K

P_{tot} = total member perimeter

The heat flux value for a particular type of fire varies with the individual fire characteristics.

For pool fires, heat flux may be conservatively set at 160 kW/m^2 for an engulfed member.

For jet fires, heat flux may be conservatively set at 300 kW/m^2 for engulfed members, but see ref. [23] for compartment fire values. For non-engulfed members near a jet fire, a multiple-point source model may be used to compute the heat flux.

C.3.4 MOMENTUM PRESSURE LOAD FROM FIRE

A jet fire is capable of producing significant momentum pressure load on a flat object such as firewall. The force, F, generated by a momentum jet on a flat object is defined as [10]:

$$F = \rho_g A v^2$$

where

ρ_g	=	gas density
A	=	cross-sectional area
v	=	velocity of jet

As the gas density changes rapidly after its release from the jet orifice, it is conservative to assume that the gas density remains the same as that within the source. The expression for the gas density is given by [13]:

$$\rho_g = \frac{PM}{R_0 T}$$

where

R_0	=	universal gas constant (8.314 J/mol. °K)
P	=	pressure of gas at source (N/m^2)
T	=	temperature of gas at source (°K)
M	=	molecular weight of gas (kg/mol)

While the force on the flat object is considered equal to the force at the orifice, the pressure will reduce with distance from the orifice since the cross-sectional area of the jet increases. The pressure applied to the flat surface can then be derived from the momentum force, F and area of impingement.

As the momentum pressure is directly proportional to the release pressure, the pressure will decay at the same rate. This decay may be modeled as:

$$P_t = P_o \times e^{-at}$$

where P_t is the momentum pressure at time, t. The decay constant, a, can be fitted to the time for the release pressure to reduce to ¼ of its initial value, $t_{1/4}$ during depressurizing of the system [24]:

$$a = \frac{\ln(4)}{t_{1/4}}$$

COMMENTARY ON SECTION 4—STRUCTURAL RESPONSE ASSESSMENT AGAINST FIRE

C.4 Structural Response Assessment Against Fire

Specific fire events or scenarios are required for which the response of the structure can then be determined. The scenarios are generally provided from a process hazard analysis involving process and safety disciplines, for which guidance is available in API RP 14 series documents.

For each fire event, the following steps need to be carried out for the structural assessment:

1. Calculation of the burning rate for the fire geometry enables the extent and duration of the fire to be determined. The heat output from the fire in terms of radiation and convected hot air and gases may then be determined.

   External flames at compartment openings may result for ventilation limited or confined fires.

2. The heat incident on structural members and panels may then be used to calculate the temperature/time history of the member and/or the steady state temperature.

For load bearing members, the temperature determines the appropriate values for the yield stress and Young's modulus of the material of the member to be used in the structural analysis.

For panels and firewalls, which are usually, not load bearing; the important parameters are the temperature of the cold face and the time to reach certain limiting temperatures, which determine the walls' rating.

The structural design of the platform may start with a screening (zone method) analysis. Should a structure fail to meet performance criteria for the screening analysis, then a design level analysis should be carried out. If the structure fails to meet the performance for the design level analysis then a ductility level analysis can be performed. The alternative is to mitigate the effects of the fire such that performance criteria are met for one of the lower levels of analysis i.e. screening or design level analyses.

C.4.A SCREENING ANALYSIS (ZONE METHOD)

In screening analysis, the maximum allowable temperature that a steel member can sustain without reducing its yield strength below 60% of the yield strength (F_y) at ambient temperature, is determined from Table C.4.1.1-1. As fire is treated as an accidental load, the allowable stress may be increased to yield stress. In this method of assessment, the stresses present in the member before the fire are not taken into account.

Using higher strain levels than 0.2% may give a proportionately higher decrease in Young's Modulus giving an unmatched reduction in yield stress. In that case, the zone method may not be applicable being unconservative locally for areas of higher strain.

For 0.2% strain limitation, structural members showing a utilization ratio of 1.5 with a reduced yield stress derived from Table C.4.1.1-2 should be considered to have passed the screening analysis as accidental load cases allow the stresses to reach full yield and not 0.66 times yield as required for non-accidental load cases.

Table C.4.1.1-1—Maximum Allowable Temperature of Steel

Strain (%)	Maximum Allowable Temperature of Steel	
	°C	°F
0.2	400	752
0.5	508	946
1.5	554	1029
2.0	559	1038

Table C.4.1.1-2—Yield Stress Reduction Factor with Maximum Member Temperature

Maximum Member Temperature		Yield Stress Reduction Factor	Member Utilization Ratio at ambient
°C	°F		
400	752	0.60	1.00
450	842	0.53	0.88
500	932	0.47	0.78
550	1022	0.37	0.62
600	1112	0.27	0.45

C.4.B STRENGTH LEVEL ANALYSIS

A strength level analysis consists of a conventional linear elastic analysis. The maximum temperature attained by structural members for the duration of a fire may be computed using the methods described in Section 3 or guidelines provided in [24].

Depending on the maximum temperature attained by individual structural members for the duration of the fire, the reduced stiffness and yield stress of the member should be used in the structural analysis. The analysis should consider the situation after the fire where this is relevant to meeting the performance criteria since further damage from restraint during cooling can cause more failures.

The linearization of the non-linear stress strain relationship of steel at elevated temperatures can be achieved by selection of a representative value of strain. A value of 0.2% is commonly used and has the benefit of resulting matched reduction in yield strength and Young's modulus, but has the disadvantage of limiting the allowable maximum steel temperature to 400°C. Using 0.2% strain criteria calls for reduction of yield stress to 0.6 of the yield stress at ambient temperature. Fire is treated as an accidental load thus the allowable stress may be increased to the yield stress. The reduced yield stress ($0.6F_y$) corresponding to 0.2% strain will then give an allowable stress the same as that for the structure before the fire.

Selection of a higher value of strain will result in a higher allowable temperature, but may well also result in an unmatched reduction in yield strength and Young's modulus.

The loads used in such an analysis should be in a form, which could be interpreted as a load case used in the design process.

In investigating the effects of a fire, the 'live' loads such as contained liquids and storage may be taken as 75% of their maximum values as in the case for the consideration of seismic effects. Alternatively, live loads may be taken as the values used in the fatigue analysis performed for the installation.

If the structure fails to meet the established performance criteria, then ductility level analysis may be performed or mitigation measures as described in Section 10 may be taken.

C.4.C DUCTILITY LEVEL ANALYSIS

A ductility level analysis, which is a progressive collapse analysis, allows redistribution of structural load from failed members and can indicate collapse of the structure after no further load distribution is possible. Facilities, which do not pass the strength level analysis, may be evaluated using ductility level analysis if prevention and mitigation measures are not available or desirable.

This level of analysis will also allow sequences of failure and time histories of events to be established. This may be important for emergency evacuation and escape assessments.

The temperature-time histories of the structural members subjected to the fire scenario are calculated. The linearization of non-linear stress strain relationship may not be necessary as most software used for ductility level analysis allow temperature-time history as well as temperature dependent stress-strain curves as input. The software may also have the capacity to compute reduction in yield stress and Young's modulus at elevated temperatures.

The live loads used in this analysis are the same as those used for strength level analysis.

If the structure does not satisfy the established performance criteria, then mitigation measures as described in Section 5 must be taken.

COMMENTARY ON SECTION 6—BLAST AS A LOAD CONDITION

C.6.1 BLAST AS A LOAD CONDITION

Gas explosions can be defined as the combustion of a premixed gas cloud containing fuel and an oxidizer that can result in a rapid rise in pressure. Gas explosions can occur in enclosed volumes such as industrial process equipment or pipes and in more open areas such as ventilated offshore modules or onshore process areas [13].

For an explosion to occur a gas cloud with a concentration between the upper flammability limit (UFL) and lower flammability limit (LFL) must be ignited. The overpressure caused by the explosion will depend, amongst other things, on:

a. The gas or gas mixture present
b. The cloud volume and concentration
c. Ignition source type and location
d. The confinement or venting surrounding the gas cloud
e. The congestion or obstacles within the cloud (size, shape, number, location)

For stoichiometric hydrocarbon gas clouds, filling a closed volume initially at atmospheric pressure, combustion without heat loss will result in overpressures of close to 8 bar [5]. This pressure rise is mainly due to the temperature rise caused by the combustion process and is generally not dependant on the congestion within the volume. This type of explosion is referred to as confined. A stoichiometric air/fuel mixture is such that it contains exactly the required amount of oxygen to completely consume the fuel.

A hydrocarbon explosion on an offshore installation may have a number of consequences other than the generation of overpressures including:

a. Dynamic pressure loads on vessels, piping and SCEs in the path of venting gases
b. Escalation resulting from further release of inventory, and subsequent fires
c. Secondary projectiles
d. External blasts
e. Strong shock response that may result in impairment of control systems and SCEs
f. Blast waves impinging on adjacent structures

C.6.2 DETERMINATION OF BLAST OVERPRESSURES

The blast simulation is event-based and typically requires a process hazard analysis involving process and safety disciplines, for which guidance is available in API RP 14 series documents and references [9,19]. Because of the complexity in predicting blast loads the pressure-time curves should be generated by an expert in this field. The steps in the development of the blast load from a credible blast event (as defined from the process hazard analysis) are typically:

1. The event may be the occurrence of a hole of a given size assumed to be present in a vessel, piping or riser, leading to a gas or spray release. Immediate ignition is assumed not to occur.
2. The time history of the release rate is calculated. The probability of the occurrence of the release may be estimated from published failure statistics or even from simulation.
3. A dispersion analysis will predict how the gas or vapor cloud develops and disperses under wind and ventilation conditions. Part of this cloud will be within the explosive concentration limits of the gas/air mixture.
4. An ignition source within the explosive part of the gas cloud is then assumed to ignite the local fuel/air mix causing expansion resulting from combustion in the region surrounding the ignition point.

5. Explosion loading software is then used to calculate how the flame front accelerates through the surrounding environment. Interaction with obstacles gives rise to increased turbulence, flame folding, and increased flame area, increasing overpressures and increasing gas velocities within and outside the gas cloud.
6. Overpressures may then be calculated for any barriers in the vicinity. Fuel/air particle velocities may also be calculated to determine dynamic pressures or drag loads on structural members, piping or vessels in the vicinity.

C.6.3 NOMINAL BLAST OVERPRESSURES

Nominal, space averaged, peak explosion overpressures 'nominal overpressures' have been defined, based on a limited data set, for a number of platform concept types. The rules for the derivation of 'nominal overpressures' were developed based on limited data extracted from a review of about 30 recent safety cases (about 50% post 1997) carried out in April 2002. This guidance has been reviewed and supplemented by API Task Group representatives from the major operators in the Gulf of Mexico. It is anticipated that the rules will continue to be updated and extended as further information becomes available.

The nominal overpressures may be used in assessing alternative concepts at early project phases. The methodology for the derivation of 'nominal overpressures' was first developed based on limited data extracted from a review of about 30 recent safety cases (about 50% post 1997) carried out in April 2002 [46]. The guidance allows a consideration of the variables that tend to be established at an early phase of a project with regard to their effect on blast loads. Nominal overpressures may also be used as a design basis at later project stages provided their applicability can be adequately justified for the facility in question.

At later project stages for higher risk facilities, novel facilities or facilities that do not adequately match those for which the nominal overpressures are provided it is recommended that a suitably validated phenomenological or a specialist CFD explosion simulation tool is used, refer to Section C6.2.

Establishing nominal overpressure loads requires the following steps:

1. Select concept type
2. Establish conditioning factors to apply
3. Determine nominal overpressures
4. Apply safety factors to account for data uncertainties

The nominal overpressures are for regions where turbulent combustion will occur. If it is necessary to calculate blast wave effects in the far field, for example at an adjacent platform, this could be done using empirical blast wave propagation methods described elsewhere. The external explosion which may occur as a result of the ignition of a vented unburnt air/fuel mixture is not explicitly included in the approach although in some of the base cases the external explosion may have contributed to blockage of the vents and increased the overpressures in the combustion region.

Table C.6.3.1-1 contains nominal overpressure values for some typical offshore installations. These are based on (limited) previous experience and have been used for the design of installations in the U.K. North Sea. It is expected that the data on which these nominal overpressures are based will be augmented in order to increase their reliability and extend the range of installation types. They are recommended for use in the early stages of a project in order to avoid late changes, which could be expensive in terms of time and cost.

C.6.3.1 Concept type

Nominal overpressures are provided for a number of offshore production facility concepts based on the data available [37]:

Fixed Jacket Structures

- Integrated production/drilling facilities
- Bridge linked production/drilling facilities
- Production only facilities

Floating Facilities

- Mono-hull FPSO (production only)
- Spar (integrated production/drilling, dry or wet trees)
- TLP (integrated production drilling, dry or wet trees)
- Semi-submersible (integrated production/drilling)
- Semi-submersible (production only)

The platform concept is the most influential factor impacting the characteristics of the explosion hazards.

In addition to the concept type, a number of other characteristics of the facility may influence the magnitude of potential blast loads. Characteristics for which specific modifiers, see Section C6.3.2, to the concept overpressures have been proposed include:

- Production Rate
- Gas Conditioning Requirements
- Gas Composition
- Number of Production Trains
- Deck Area (module footprint)
- Degree of Confinement on Deck
- Aspect Ratio of Deck

C.6.3.2 Load Modifiers

The concept specific nominal overpressures provided in Table C.6.3.1-1 should be adjusted to reflect specific characteristics of the facility that may increase or decrease the magnitude of the nominal overpressure. These modifiers should be applied to provide an estimate of the nominal overpressure to be used in the structural assessment. The modified nominal overpressure should not be considered as the maximum attainable overpressure; instead, it should be used in the structural assessment in lieu of more rigorous blast load determination.

The information contained in Table C.6.3.1-1 and Table C.6.3.2-1 is based on a limited data set [37] and must therefore be used with caution. At present, data for 'minimum facility concepts' are not available.

C.6.3.3 Associated Load Durations

In addition to establishing the nominal overpressure as outlined above, it is important that a time history profile of the blast is considered. Without undertaking detailed modeling it is not practicable to establish this profile for the specific situation. However, by assuming a symmetrical triangular profile and establishing a blast duration, the nominal peak blast loads generated above can be translated into a static load that is more readily usable by the project.

It is recommended that in the absence of project specific data the relationship between duration and peak overpressure described in Hoiset [38] and shown in Figure C.6.3.3-1 is used to derive a positive duration for the overpressure based on the assumption of a triangular pressure-time history with equal rise and fall times.

The blast wave impulse, I, is given by: -

$$I = 0.042\ P + 6{,}500$$

The positive phase duration, t^+, in seconds is then:

$$t^+ = 0.084 + 13{,}000/\ P$$

where

P is the nominal overpressure in Pascals (1 bar = 100,000 pascals)

I is the impulse in Pascal-seconds

t^+ is the positive phase of overpressure duration in the combustion region in seconds. These equations reflect the general observation that faster combustion results in higher peak overpressures but the gas is consumed in a shorter period.

These relationships should not be used for large open areas such as may occur on an FPSO. Load durations of as long as 700 milliseconds have been predicted for large gas accumulations

C.6.4 DISCUSSION ON BOUNDING/MINIMUM OVERPRESSURES

DNV Offshore Standard DNV-OS-A101 [9] provides some guidance on the concept of bounding or minimum overpressures. The bounding overpressures represent space averaged peak overpressure values. The Standard suggests these are the minimum overpressures that will be acceptable for design. The following extracts are taken from the guidance [9].

In a ventilated compartment, the explosion the relative ventilation and the level of congestion mainly determine the load given by the overpressure and duration.

For compartment volumes of up to $1000m^3$, with relative ventilation area of about 0.5, stoichiometric gas cloud ignition is expected to give approximately 1bar with a medium level of congestion. High congestion levels may increase overpressures by factors of 2 to 3. Larger volumes also tend to increase overpressures.

Design overpressure in a ventilated shale shaker room with less than $1000m^3$ volume and moderate congestion may be taken as 2bar, combined with a pulse duration of 0.2s (200 milliseconds) unless a more detailed assessment is carried out.

Table C.6.3.1-1—Unmodified Nominal Overpressures by Installation Type

Blast Prone Areas	Nominal Overpressure (bar) in Offshore Installation Type				
	Integrated Production/Drilling (Single Platform)	Bridge Linked Production/Drilling (Multiple Platforms)	Production Only (Single Jacket)	Production Only (Mono-hull FPSO)	Integrated Production/Drilling (TLP / Wet Trees)
Wellhead/ Drill Deck	2.5	2.0	-	-	2.5
Gas Separation Facilities	2.0	1.5	1.5	1.0	1.0
Gas Treatment/ Compression Facilities	1.5	1.0	1.0	1.0	1.0
Turret (Internal)	-	-	-	3.0	-
FPSO Main Deck	-	-	-	2.0	-
TLP Moon Pool	-	-	-	-	2.0
TLP Deck Box	-	-	-	-	2.5
Other	1.0	1.0	1.0	0.5	0.75

Note: 1 bar = 14.7 psi

Table C.6.3.2-1—Load Modifiers

Project Parameters		Nominal Blast Load Modifiers
Item	**Range/Rate/Qty**	
Production Rate	Less than 50,000 bbl/day	0.90
	50,000 to 100,000 bbl/day	1.05
	More than 100,000 bbl/day	1.10
Gas Compression Pressure	Less than 100 bar	1.00
	100 to 200 bar	1.05
	More than 200 bar	1.10
Gas Composition	Normal	1.00
	Onerous	1.10
	More onerous	1.35
Production Trains	1	0.90
	2	0.95
	3	1.10
Module Footprint Area	Less than 75,000 sqft	0.90*
	75,000 to 150,000 sqft	1.00
	More than 150,000 sqft	1.10
Confinement	3 sides or more open	0.85
	1 to 2 sides open	0.95
	All sides closed	1.25
Module Length to Width Aspect Ratio	Less than 1.0	0.90
	1.0 to 1.7	1.05
	More than 1.7	1.10
* For small and very congested platforms (~10000 sqft), the Load Modifier of 0.9 should not be applied to reduce the nominal explosion overpressures for Module Area.		
Note: Load Modifier should not be applied to wellheads/drilling decks, Moonpools, and FPSO main deck.		

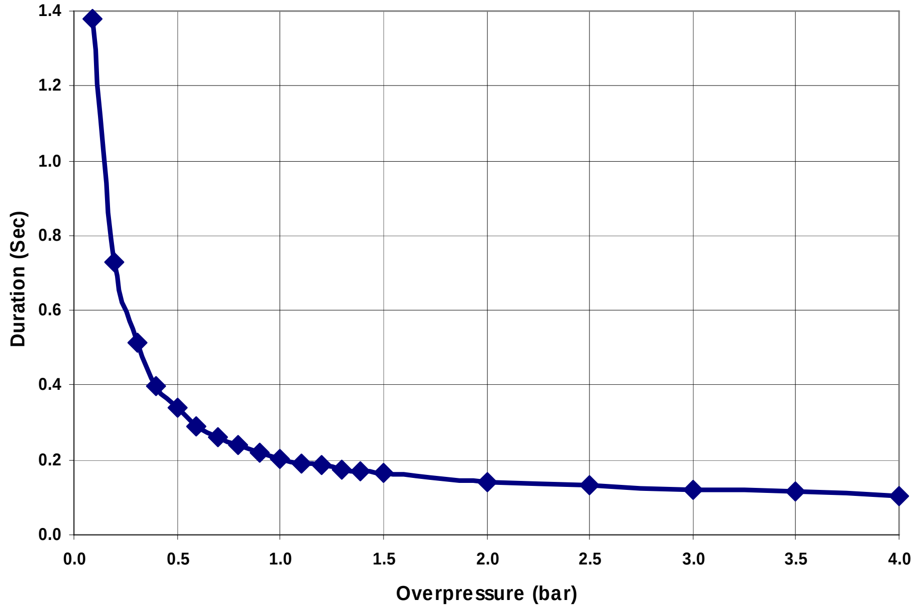


Figure C.6.3.3-1—Overpressure Duration Relationship - Hoiset [38]

Design overpressure on an open drill floor area may be 0.1bar combined with pulse duration of 0.2s unless a more detailed assessment is carried out.

Durations for explosions are expected to vary from 0.2s for fairly open compartments to 1s for quite closed compartments.

If panels or walls are intended to give explosion relief by failing a peak overpressure of 2-3 times their failure pressure can still be expected in the compartment. This is only the case if ventilation dominates. For large and congested compartments, local overpressures may be greater.

Long compartments with length/diameter ratio greater than 3, will tend to give higher overpressures due to the long flame acceleration lengths. The effective diameter can be estimated as $D = \sqrt{A}$ where A is the smallest cross section area.

For completely enclosed compartments generally, bulkheads that must survive an explosion will be designed for 4bar.

For process areas on open deck covering not more than 20m x 20m with an un-congested arrangement a design overpressure of 0.2bar with pulse duration of 0.2s may be used. Volume Blockage Ratio (VBR) of 0.05 may be considered as not congested. VBR is the ratio of the blocked volume to the total volume considered.

For larger or congested process areas, a design overpressure peak of 0.5bar with pulse duration of 0.2s may be used. A volume blockage ratio of 0.05 is considered not to be congested.

Table C6.4-1 provides an abbreviated summary of the above results. The proposed overpressures and durations are suggested unless more detailed assessments are carried out.

Table C.6.4-1—Minimum Blast Overpressure from DNV [9]

Item	Design Blast Overpressure (barg)	Pulse Duration (second)
Totally enclosed compartment (critical structure only)	4	1
Shale shaker room (volume < $1000m^3$)	2	0.2
Process area, large or congested	0.5	0.2
Process area, small (<20m x 20m) and not congested	0.2	0.2
Open drill floor*	0.1	0.2

Note: * For open drill floor > 10m x 10m having large number of drill pipes, local overpressures may be higher.

C.6.5 PRESSURE TRACE HISTORY

An example of an idealized pressure trace from a hydrocarbon blast is shown in Figure C.6.5-1.

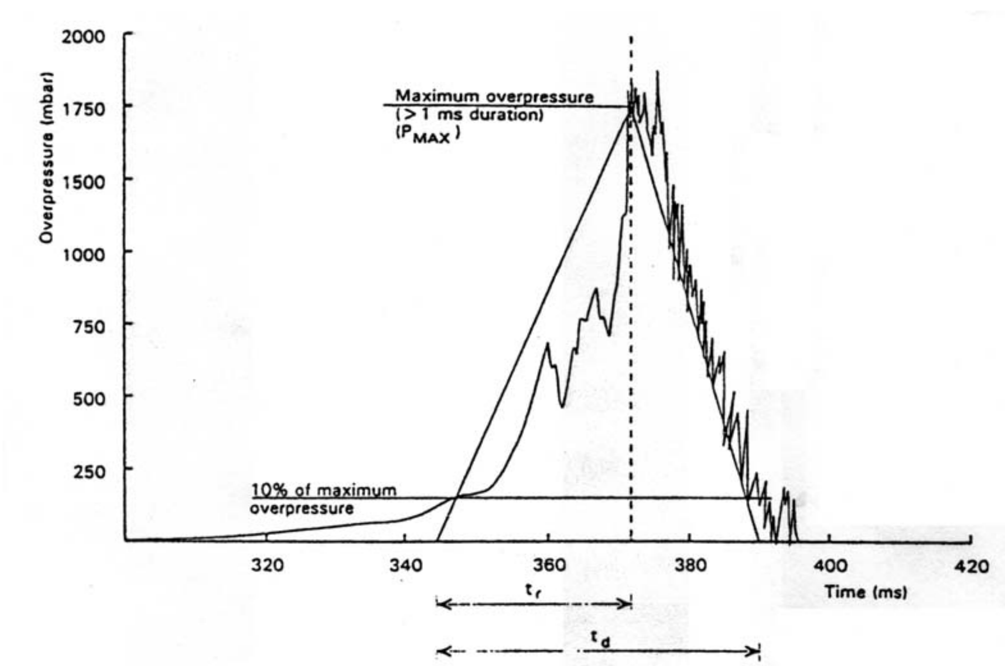


Figure C.6.5-1—Idealized Pressure Trace for a Hydrocarbon Blast

C.6.6 THE RESPONSE SPECTRUM APPROACH

The response spectrum approach takes into account the variations in response of structural elements resulting from their natural periods and differing dynamic properties for a given pressure-time history. The proposed method also enables the reserves of strength released when elements are allowed to deform plastically to be taken into account.

The purpose of the method is to enable equivalent static blanket loads to be derived for use in a conventional design check for blast loads of a given severity and duration. The method has been in use for decades in the earthquake response context.

Figure C.6.6-1 shows the application of blast response spectra in determining a static design pressure.

The severity of the blast loading is determined from local conditions by the use of nominal overpressures, previous experience, risk classification, simulations or experiment. A discussion of measures of explosion severity and their relative merits is given later in this section.

The structural element to be assessed, which may be panel, deck, module or whole topsides, is idealized as a one degree of system oscillator. This process will be familiar to designers who use the Biggs response method and is in routine use.

The structural element is represented by its natural period and resistance at effective yield. A further important parameter is the allowable ductility of the element, which is a measure of the amount of plasticity that the element can sustain before rupture and is related to the peak displacement. The allowance of local plastic deformation is an essential part of efficient blast resistant design.

The element natural period determines the position on the horizontal axis (Figure C.6.6-1) and the *design pressure* or required static resistance may be read of the relevant curve representing the allowable ductility.

It has been found that the response spectra for differing ductilities may be scaled using energy and impulse arguments to lie close to each other as shown in the figure. The envelope of these scaled curves is indicated as the solid line and this is a generic representation of the dynamic and plastic characteristics of a wide range of structural elements.

This process is similar to the use of the Biggs response curves in determining peak response, except that one actual and one simulated pressure time history have been used in the construction of the response spectra. In Biggs the triangular idealization of the load time history is commonly used but this creates difficulties where the triangular idealization is not valid or difficult to rationalize from a given pressure-time history.

In this context a 'nominal overpressure' would be represented by one point on one response spectrum curve, usually assuming an allowable ductility of one representing elastic response. The advantages of the response spectrum approach are greater generality and better representation of the target structure.

C.6.6.1 Blast Load Severity

The usual measure of severity of blast loading is the peak overpressure. Pressure traces, derived from experiment, often display multiple peaks of very short duration and are referred to as 'spikes'. These spikes are of such short duration that the structure does not respond to them and they have no effect on the damage to be anticipated.

The peak pressures within a scenario at different times and between different scenarios (with differing ignition points) can vary considerably. Recent work [37,47] has indicated that impulse (the integral of the pressure time history) or root mean square values of pressure are more robust representative measures of blast load severity than peak overpressure.

Simulations from computational fluid dynamics (CFD) models do not normally resolve these spikes, which may be viewed as being of very high frequency in origin. The correspondence between simulated and experimental results can be demonstrated in a general sense by considering the frequency spectra of the loading time histories. These spectra demonstrate much more regularity and similarity than the original traces and are a promising method for characterizing the severity of an explosion event. With correct scaling, by impulse, for example, they can be made to almost coincide for a variety of scenarios. A design loading will be representative and should reflect the level of risk presented by the hazard.

This work [47] is now under development and may be considered in later version after proper calibration.

C.6.7 DRAG LOADS

Gas explosions can generate both high overpressure and high-speed gas flows as a result of the gas combustion process.

Large components of the structure such as solid decks or walls experience loads due to the pressure differences on opposite sides of the structure. Typically within an explosion, there will be a strong variation of the spatial and temporal pressure distribution. There will typically be localized high regions of overpressure with lower values of average pressure acting on large components. The overpressure at a location within a gas explosion will typically rise to a peak value and then fall to a sub atmospheric value before returning to zero overpressure. The duration of the positive phase in an explosion can vary greatly with shorter durations associated with higher overpressure explosions. Typical durations range from 150ms to 600ms [8].

For smaller objects such as piping, the overpressures applied to the front and reverse sides will be of approximately the same magnitude at any moment in time, and in this case, the overpressure will not apply any net load to the object. For this type of object, the dynamic pressure associated with the gas flow in the explosion will dominate the applied loads.

Free spanning members such as primary columns, piping and braces will be more influenced by drag loads (dynamic pressures or blast wind).

The situation in Figure C.6.7-1 represents an explosion in a module compartment. In this example, all walls except the West wall are solid. The blast overpressure causes a pressure front to move from left to right from the point of ignition at about the speed of sound in the unburned mixture.

The unburned gas is pushed out of the module through the vented area with a velocity U. This velocity will be available directly from a CFD simulation or by the approximate method [6].

The air ahead of this front is pushed out through the vent in the West wall over a vessel and pipe work spanning the vent giving the possibility of vessel or piping failure, with further release of inventory and consequent escalation. The gas velocities in this case will occur predominantly near the vent. The magnitude of drag forces on the pipe work (with diameter D) at any time is given by the drag term in the Morison equation:

$$F_d = \tfrac{1}{2}\, C_d\, \rho u\, D\, U^2 \quad \text{(before the flame front has reached the obstacle.)}$$

$$F_d = \tfrac{1}{2}\, C_d\, \rho b\, D\, U^2 \quad \text{(after the flame front has reached the obstacle.)}$$

where

F_d is the drag force per unit length.

C_d is a drag coefficient. Little information is available for accelerating flows of combustion products but a drag coefficient of 1.0 is often used.

ρu is the density of the air ahead of the pressure front typically between 0.075 lbs/ft^3 (1.2 kg/m^3) and 0.15 lbs/ft^3 (2.4 kg/m^3).

ρb is the density of the burnt air gas mixture behind the flame front typically about 0.006243 lbs/ft^3 (0.1 kg/m^3).

U is the unburned gas mixture velocity

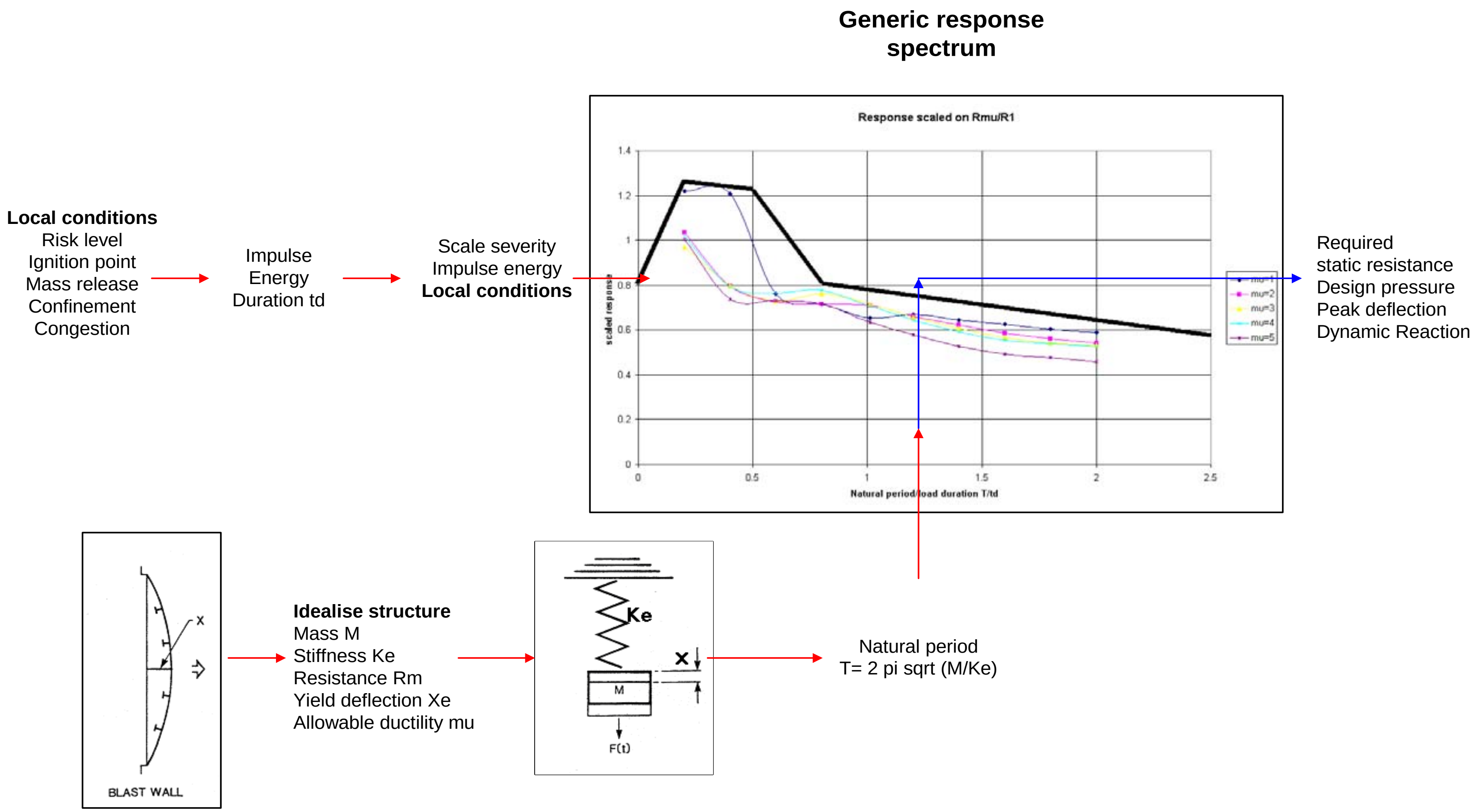


Figure C.6.6-1—Generic Response Spectra for a Hydrocarbon Blast

The force should be calculated for both cases as the burnt gas/air mixture may be traveling at a speed of ten times the speed of the un-burnt air even though the air is ten times denser. A typical time history for the drag load is shown in Figure C.6.7-2 [6]. Two peaks are shown corresponding to the peak gas velocities ahead of and behind the flame front. In a vented compartment flow, reversal of gases into the compartment could also occur at a later stage in the explosion. This would give a trace with a negative phase.

Drag loads are particularly important in open areas such as on the deck structures of an Floating Offshore Installation (FOI). The gas clouds associated with blasts on FOI may be very large and gas velocities up to 1640ft/sec (500m/s) could be experienced. The direction of gas flow may also be very variable for example in the case of the pipe rack of an FOI acted on by a blast ignited at low level. Secondary projectiles may be a problem for FOI in view of the higher gas velocities.

The formulae given above may be used to represent the total force on obstacles with cross flow dimensions of the order of 1ft (0.3m). For larger diameter obstacles or vessels, the pressure difference across the vessel may also need to be calculated directly.

Further details may be available in ref. [6,42].

As a rough guide the dynamic pressure, P_d is likely to be less than ½ P_{max}, where P_{max} is the maximum overpressure in the compartment. On the deck of an FOI, gas velocities may be higher and peak pressures lower so this guide may not apply in that case.

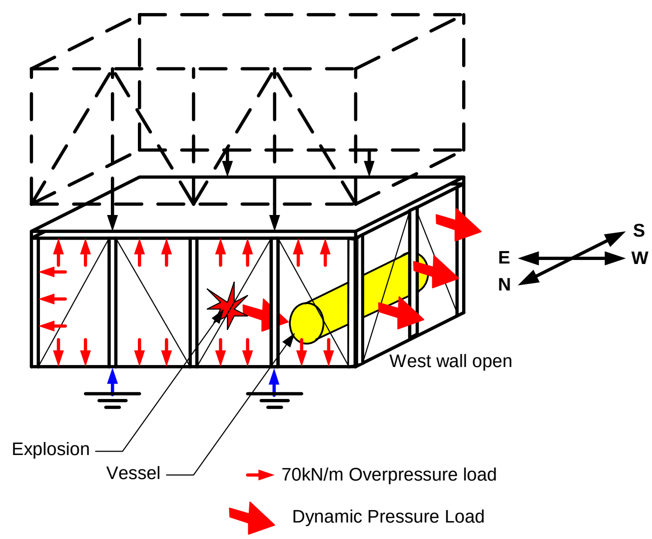


Figure C.6.7-1—Blast in a Compartment

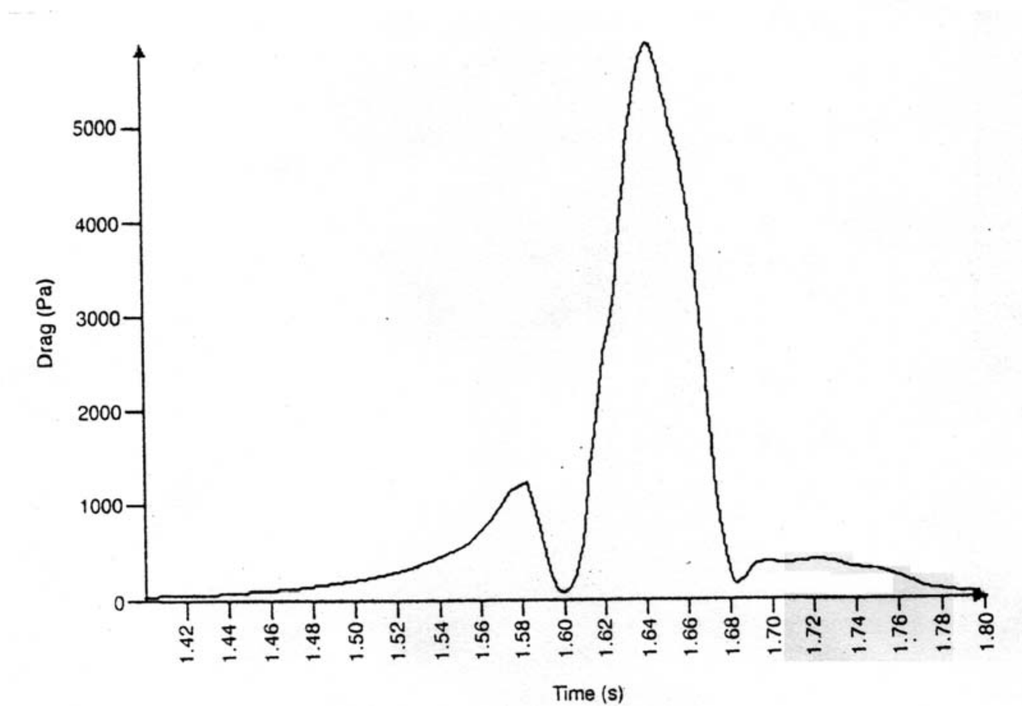


Figure C.6.7-2—Drag Loading on Piping – Typical Time-History

C.6.8 SHOCK AND GLOBAL REACTION LOADS

If the structure and appurtenances have been checked for Strength level or Ductility level earthquake loading following API RP 2A [2] then the 'strong shock' response to blast need not be checked.

Once the force is calculated it may be applied to a dynamic global platform structural model. The displacements and accelerations at points on the topsides may then be calculated. These accelerations are potentially damaging to essential safety systems such as:

a. Emergency escape and rescue systems
b. The temporary refuge and its supporting structure
c. Emergency lighting systems
d. Emergency power supply and battery systems
e. P.A., telecommunication systems and navigation aids
f. Fire water systems
g. Emergency shut down systems

One further consequence of shocks of this kind is that pipe runs between modules may be stressed due to relative displacements between modules. This would be particularly important for the fire water main.

Floating, tethered and moored installations are unlikely to suffer serious adverse response to this form of loading because the natural period in the horizontal direction is much longer than the load duration.

C.6.9 FAR-FIELD EFFECTS - BLAST WAVES

Following a gas explosion that generates significant overpressures, a blast wave will propagate into the surrounding atmosphere. The peak overpressure in this blast wave will decrease with distance while the blast wave duration will typically increase and as a result, the impulse will decrease more slowly than the overpressure. The blast wave will be affected by confining objects such as decks, blast walls and accommodation blocks that will result in reflection and diffraction of the blast wave. This may affect the decay of the blast wave and in some cases can increase local overpressures where a blast wave is reflected from a surface or object. Thus, the received pressure on a flat surface may be greater than that in the incident blast wave. At pressure levels typical of a blast wave generated by a hydrocarbon explosion, this received pressure may be up to twice the incident pressure, a process referred to as 'pressure doubling'. As blast wave may not be traveling normal to the surface, 'pressure doubling' may be a conservative assumption.

Less computationally intensive methods may be used to calculate far field blast waves in cases where it is not warranted to use CFD methods. Two of the most common procedures to do this are the TNT equivalency method and fuel air charge methods (including multi energy methods).

C.6.9. 1 TNT Equivalent Method

TNT equivalency is historically the older of the two procedures to calculate far field blast wave data.

The effects of detonation of high explosive charges are well documented [41] and can be represented as a series of scaling laws for the variation of parameters such as overpressure, duration, and impulse with distance from the explosion source. Scaling is typically based on the scaled radial distance parameter Z (Hopkinson-Cranz scaling parameter) defined as

$$Z = \frac{R}{W^{1/3}} \qquad (\text{m/kg}^{1/3})$$

Where R is the radial distance from the TNT charge source in meters and W is the TNT charge weight (kg).

For typical hydrocarbons such as methane, propane, butane, etc, the heat of combustion is approximately 10 times the heat of reaction of TNT. However, a hydrocarbon explosion is characterized by lower flame speeds than a TNT explosion and is generally less efficient in converting available chemical energy to heat and blast waves. Reference [42] outlines a relationship that accounts for these differences:

$$W_{TNT} \approx 0.16V \;\; (\text{kg})$$

Where V (m^3) is the volume the hydrocarbon cloud either, contained in a congested region or the total volume of hydrocarbon, whichever is the smaller. This expression was derived for natural gas but is broadly applicable to other hydrocarbons since the energy of combustion is approximately the same.

Peak overpressure (P_s), impulse (i_s), duration (T_s) and arrival time for the blast wave shock front (t_a), with scaling parameter can then be found for the equivalent TNT charge weight from ref. [41]. Summaries of other TNT based models may be found in ref. [5, 43].

While useful as an approximate method to calculate blast wave effects, the following limitations should be noted:

- The characteristics of a TNT explosion are significantly different from a vapor cloud explosion and hence the gas explosion process is not represented.
- TNT blast waves tend to decay at a more rapid rate with distance than a vapor cloud explosion. Consequently, TNT methods tend to over predict response in the near field (closer to the source) while under predicting response at distance far from the source.
- Vapor cloud explosions are variable in strength whereas TNT explosions are more predictable. This variability is not captured by TNT methods. This is particularly the case for a low strength vapor cloud explosion [43].
- The method only accounts for positive phase duration.

C.6.9.2 Fuel Air Blast Model

Fuel air charge models are more sophisticated methods of estimating blast wave characteristics, since they can take into account variation in strength of a vapor cloud explosion. Summaries of these models may be found in ref. [5, 43].

The most common fuel air model is the multi-energy method developed by Van Den Berg [44, 45] and is broadly based on a series of numerical simulations to determine the blast wave characteristics of a centrally ignited spherical cloud with constant flame speeds. Parametric results are developed for different flame speeds to develop curves that represent different vapor cloud explosion strengths. Curves are developed for peak side on over pressure and blast wave duration as a function of non-dimensional scaled radial distance ($\overline{R}$) from the ignition point.

The scaling parameter in this case is a characteristic length, which is a function of energy of combustion (E) of the vapor cloud and the ambient air pressure (p_0):

$$\overline{R} = \frac{R}{\left(E/p_0\right)^{1/3}}$$

The primary difficulties in applying the multi energy method to a blast event are in estimating energy of combustion and blast strength. Energy of combustion for a vapor cloud can be calculated from the specific energy of combustion of the gas (E_0 J/m^3) and the cloud volume (V m^3) as:

$$E = E_0 V$$

The specific energy can be approximated to 3.5 MJ/m^3 for a range of hydrocarbons in lieu of specific data.

The multi-energy method is more versatile than TNT method in that it can cater for multiple source ignitions with in the same cloud, provided the ignition sources are sufficiently remote. This allows a large cloud to be subdivided into zones, which can be evaluated on an individual basis.

As with the TNT method, the multi energy method can only be considered as approximate and hence its validity must be assessed for the specific case under consideration to determine that the method is applicable and that the underlying assumptions of the model are not violated.

Definition of blast strength to identify which of the parametric curves to use should take into account:

- Degree of obstruction by obstacles within the vapor cloud
- The type of the ignition source
- The degree of confinement of the blast scenario under evaluation

C.6.10 PROJECTILES

Small objects may be picked up by the explosion gas flow and become secondary projectiles. Primary projectiles may be parts of exploding vessels. Sample objects, which have been considered, include fire extinguishers, valves, scaffold poles and hard hats. These generally attain energy of the order of 5 kJ depending on gas velocities flight length and projected area to the gas flow direction. This energy is generally not large enough to perforate steel plate thicker than 6mm.

General tidiness in the area of the accommodation block and in the process areas will generally be enough to prevent the generation of projectiles.

Essential Safety Systems should be designed to resist impacts with energy of about 5kJ.

More information on the generation and impact of projectiles may be found in ref. [22, 27,29].

COMMENTARY ON SECTION 7—STRUCTURAL ASSESSMENT AGAINST BLAST

C.7.1 DYNAMIC EFFECTS

The duration of a typical hydrocarbon explosion, t_d, is of the order of 50 to 200 milliseconds (0.05 to 0.2 seconds). This will be close to the fundamental natural period, T, of typical structural members and panels and hence a dynamic assessment of structural response will be necessary. The fundamental natural period is the longest natural period at which the member will respond to an impulsive load and usually corresponds to the first bending mode with a maximum deflection at the middle of the member. The overpressure load on a single member is usually represented as a uniform load and this is the predominant mode of response in most explosion situations.

Conventionally the range for fully dynamic response is defined in the Interim Guidance Notes (IGN) [24] by:

$$0.4 < t_d /T < 2.0$$

A dynamic amplification factor ‘γ’ may be calculated for all such members assuming elastic response. For single structural components the dynamic amplification factor may be up to 2, for typical large structures such as modules and topsides the natural periods are likely to be longer (greater than 150ms) with dynamic amplification factors less than one. Taking into account the dynamics of the response of large structures will often result in a less conservative result.

The equivalent static load L_{static} is related to the peak pressure load L_{peak} by:

$$L_{static} = \gamma L_{peak}$$

The equivalent static load may be used for elastic response calculations in an elastic strength level analysis in the normal way and treated as a design load case.

If the structure is expected to deform plastically or if large deflections and local failures are likely then this approach may not be applicable. The plastic response of structural components may still be examined using the Biggs method [4] so long as the one-degree of freedom assumptions are valid.

Allowing local plastic deformation will mobilize some of the reserves of strength of the member and the material and will result in a less conservative, lighter structure.

C.7.2 SCREENING CHECK

A screening check is essentially a design basis check, which consists of verifying the basis of the design for the facility and determining if the methods used for the design are acceptable in the context of identified blast events.

Application of the peak overpressure as a static design load case with yield stress as allowable stress is likely to result in a conservative structure but may also be an underestimation of response in circumstances where the structure’s natural period is close to the load duration. Code check results from static design load case may be useful in identifying components of the structure for further attention.

Components may be analyzed in isolation as long as the interaction with the surrounding structure through fixity and the applied loads are negligible or are represented in the component model. Non-load bearing firewalls, blast walls and panels may be checked using Bigg’s method [4]. Sections of a plated deck may also be checked using the same method. The actual expected peak overpressure, rise time and duration must be used in these checks.

Many firewalls, blast walls and panels are manufactured items. The blast capacity for a particular barrier may be available from previous analysis or provided by the vendor. These capacities should be checked and in particular, the effect of any penetration, change in span or attachment details should be investigated.

C.7.3 STRENGTH LEVEL ANALYSIS

Strength level analysis is conventional linear elastic analysis. The platforms that do not pass the screening requirements may be evaluated using the strength level procedures outlined here.

The dead loads in the structure need to be combined with a realistic estimate of live or operating loads for the strength level analysis. The loads from an existing fatigue load case or seismic load case, where only 75% live loads are included, may be suitable. Environmental loads need not be included.

The dynamics of a blast event may be accounted for by derivation of an equivalent static load distribution using dynamic amplification factor.

A less conservative approach would be to derive the equivalent static load level by the performance of a dynamic elastic time stepping analysis to derive the general levels of response displacement and identify a static load level which results in the same general levels of displacement.

A linear elastic structural response analysis may be performed to represent the effect of a blast event on the primary framing of an installation. The code checks may be accepted with higher than normal utilization factors to allow for member plasticity, strain rate and strain hardening effects. Considering these factors, acceptable utilization factor may be 2.5 for a tension member and 2.0 for members under bending and/or compression so long as the member does not buckle, under the blast loading. However, if SLB is taken as

1/3rd of the DLB for reasons mentioned in Section 7.3, the utilization ratios in structural members should be restricted to 1.0 to leave the reserve capacity to be exploited in Ductility Level analysis.

The shear behavior of structures at their supports and in the joints of the primary frame will also affect the utilization factors derived in the code checks. The safety factors implicit in the code checks will be different from those associated with bending. Shear strains at supports should generally be limited to the elastic strain.

For a dynamic situation, the shear forces will be quite different from the values obtained by static analysis because of the inertia forces acting on the structure. Dynamic amplification factors may be used to determine such shear force.

Further checks may be necessary to ensure that deflections will not compromise the usability of escape routes or cause further release of inventory. The allowable deflection into equipment spaces will depend on the clearances to equipment.

The response of cladding panels and plates that form part of the primary structure may be analyzed in detail using finite element analysis assuming the supporting beams are fixed at the main nodes of the structure, as the stresses in the panel are dominated by local response of the panel out of plane and that the stresses induced by the deflection of the main framing are comparatively small.

Buckling checks must be performed to ensure that the full plastic capacity of a member can develop. These checks should be made particularly for deck beams loaded from an explosion below as flanges usually in tension may be in compression during the explosion. Buckling of flange into web and flange curling effects in beams and corrugated walls must be checked.

Deck beams loaded for an explosion below should also be checked for re-bound effects.

C.7.4 DUCTILITY LEVEL ANALYSIS

The ductility level analysis method accounts for large displacements, load re-distribution, material property changes, non-linear effects and the dynamics of the structure. This method of analysis takes into account the reserve strengths of the structure.

For ductility level analysis method, standard code checks may not be appropriate. In lieu of code checks, the following explicit checks on member response should be adopted:

- Strength limit checks similar to code checks
    - Failure is defined to occur when the design load exceeds the design strength. This criterion may be applied in the plastic region.
- Deformation limit checks
    - Permanent deformation may be acceptable so long as safety critical equipment is not impinged upon and collapse is not caused even in presence of a fire. Mechanisms may be formed momentarily during a blast event.
- Fracture checks to identify weld and member failures.
- Buckling checks, to identify where plastic response may be limited by local buckling.

Members may be classified as plastic, compact or non-compact. Plastic and compact members will generally reach their full plastic capacity before buckling.

The buckling checks should include, local buckling, flexural buckling of struts and lateral torsional buckling of beams working beyond elastic limit. Flange buckling into web (web crushing) and flange curling should also be checked.

If the structural response software is capable of representing finite displacement effects, plates may be included in the model to represent barriers and loaded surfaces. The inclusion of plates with equivalent thickness to represent mid-point deflection will also help to represent the tension and shear effects from these members.

The restraining effect of cladding can conservatively be omitted from the model so long as the loads applied to them are applied to the bounding members according to the area associated with each one.

The effect of longitudinal stresses can become significant when the maximum deflection of the member exceeds the depth of the member. Blast panels and module cladding, which is typically less than 3/8 inch thick, achieve most of their capacity due to tension effects.

A static resistance-displacement function for a plate may be constructed using stress-strain relationships for rectangular plates taking into account membrane and bending effects [28,30].

Membrane tension forces in plating and reactive compressive forces in members for both sagging moment regions and hogging moment regions should be evaluated. Methods of including tension and membrane effects by modifying the resistance displacement function with non-zero slope to represent membrane action can be utilized from reference [7,16].

Particular attention is drawn for investigation into composite action of deck plating with secondary beams or stringers. When assessing the deck plating contribution to the section modulus of the stringer, the effective area is reduced due to the presence of coexisting membrane stress and shear stress. Where the deck plate is in tension, shear-lag governs the effective width. For deck panel aspect ratio greater than 5, shear lag may be ignored. Where the deck plate is in compression, the effective width may be appropriately computed.

The structural design of the stringer section should include an evaluation of the shear transfer in the weld between the stringer and the deck plating. As the contribution of these welds is important to the blast resistance of the deck structure as a whole, a full assessment of shear force and direct load transfer must be performed.

For joints, the principal ultimate failure mechanism is rupture or brittle facture unless the joint is stronger than the weaker of the members it joins. The joints are to be designed such that the excessive loading or imposed rotation causes ductile deformation of the adjacent member.

Weld overmatching should be considered where high strains are anticipated. Weldment load capacity may be verified from appropriate weld and base material stress-strain curves by applying (a) a upper-bound curve (or mean + 2 standard deviations) for base materials, (b) a lower bound curve (or mean – 2 standard deviations) for weld metals, and (c) the lesser of (a) or (b) for heat effected zone and fusion line zone.

Floor to ceiling ties will be subjected to dynamic axial loading which will be compressive on rebound. Columns, ties and braces should be provided with reserve capacity so that ductile bending of the beams they support can occur without failure of the support.

COMMENTARY SECTION 9—FIRE AND BLAST INTERACTION

C.9.1 GENERAL

Fire and blast are often synergistic. Fires may occur after a blast has occurred and a blast may be one of the escalation consequences of a fire. The consequences of combined fire and blast scenarios with either component occurring first should be considered in the structural design or assessment. The fire and blast analyses should be performed together and the effects of one on the other carefully analyzed.

COMMENTARY ON SECTION 11—MATERIALS

C.11.1 THERMAL PROPERTIES OF STEEL

The thermal properties of steel vary with temperature. Experimental data are available for linear expansion, specific heat, density, and thermal conductivity [20,23]. Nominal thermal properties for structural steel that are valid for the range of room temperature to 600°C used to calculate fire load due to radiation, convection and conduction are given in Table C.11.1-1 [25].

Table C.11.1-1—Thermal Properties of Steel

Steel Type	Specific Heat (J/kg °C)	Thermal Conductivity (W/m °C)	Emmissivity	Coefficient of Linear Expansion (/ °C)
ASTM A36 A633 GR.C or D	520	46 - 65	0.75 - 0.90	14×10^{-6}
Stainless Steel	533	14 - 20	0.75	18×10^{-6}

The thermal expansion generates compressive loading on highly constrained members that may result in buckling, even at modest temperature. The effects of differential thermal expansion on members due to an uneven temperature profile across the member's section can generate additional bending moment on the section.

C.11.2 STRENGTH AND STIFFNESS OF STEEL

At elevated temperature, strength and stiffness of steel reduce.

Reduction of yield stress and Young's modulus may be calculated for carbon steel from the data furnished in Table C11.2-1 [23]. The values furnished are for 0.2%, 0.5%, 1.5%, and 2.0% strain.

Poisson's ratio for steel remains constant at 0.3 for steel, up to the melting point.

Loads induced by thermal expansion can be significant for highly restrained members and should be considered.

The interpretation of these data to obtain representative values of temperature effects on yield strength and Young's modulus should be performed at a strain level consistent with the design approach used:

For a design approach that does not permit some permanent set in the steel work after the fire load condition ceases, a strain of 0.2% should be used.

For a design approach that allows some permanent set in the steel work after the fire load condition ceases, higher values of strain, 0.5% to 2.0%, may be appropriate.

At a strain level of 0.2%, the yield strength for steel at elevated temperatures (up to 600°C) is given by the following equation resulting from test data [19]:

$$\sigma_{yt} = \sigma_y \cdot \left(1 + \frac{T_S}{767 \cdot \ln\left(\frac{T_S}{1750}\right)} \right) \qquad \text{for} \quad 20°\text{C} \le T_s < 600°\text{C}$$

σ = Yield stress at 20° C

σ_{yt} = Yield stress at elevated temperature

T_s = Steel temperature in °C

Table C.11.2-1—Young's Modulus and Yield Stress Reduction Factors for Carbon Steel at Elevated Temperature (ASTM A-36 and A-633 GR.C and D)

Steel Temperature		Young's Modulus Reduction Factor	Yield Stress Reduction Factor at Strain of			
(°C)	(°F)		0.2%	0.5%	1.5%	2.0%
20	68	1.000	1.000	1.000	1.000	1.000
100	212	0.991	0.940	0.970	1.000	1.000
200	392	0.961	0.847	0.946	1.000	1.000
300	572	0.916	0.653	0.854	1.000	1.000
400	752	0.826	0.600	0.798	0.956	0.971
500	932	0.617	0.467	0.622	0.756	0.776
600	1112	0.173	0.265	0.378	0.460	0.474
700	1292	0.130	-	0.186	0.223	0.232
800	1472	0.090	-	0.072	0.108	0.115
900	1652	0.0675	-	0.030	0.059	0.062
1000	1832	0.0450	-	0.0206	0.0394	0.0446
1100	2012	0.0225	-	0.0137	0.0263	0.0297
1200	2192	0.0000	-	0.0069	0.0131	0.0149

Beyond 600°C temperature, the yield strength is calculated by the following equation [19].

$$\sigma_{yt} = \sigma_y \cdot \left(108 \cdot \frac{\left(1 - \frac{T_s}{1000}\right)}{T_s - 440} \right) \qquad \text{for} \quad 600°\text{C} \le T_s < 1000°\text{C}$$

If permanent set in the structure is to be avoided, strain should be limited to 0.2%.

The equation for the modulus of elasticity at elevated temperature of up to 600°C, from the results of the tests has been incorporated in ECCS [11]:

$$E_t = E(1 - 17.2 \times 10^{-12} T^4 + 11.8 \times 10^{-9} T^3 - 34.5 \times 10^{-7} T^2 + 15.9 \times 10^{-5} T)$$

where

E	=	Modulus of elasticity at room temperature
T	=	Temperature in °C

At steel temperature of 600°C, the modulus of elasticity reduces to less than 18% of its value at ambient temperature.

At temperatures above 600°C (1112°F), the creep behavior of steel may be significant and should be considered.

C.11.3 MATERIAL BEHAVIOR

Due to the nature of fire and blast loading and the fact that the structure is likely to form plastic hinges during the response, it is necessary to consider strain rate effects in determining the yield stress to be used in the analysis, and where applicable strain hardening effect in the analysis.

C.11.4 STRAIN RATE EFFECTS

The dynamic nature of the blast loading and the fact that the structure is likely to form plastic hinges during the response means that it is necessary to consider strain rate effects in determining the yield stress to be used in the analysis.

The nominal yield stress quoted in the codes is a specified minimum for the grade of steel. This may be as much as 25% less than the actual yield stress for a particular sample. If mill certificates are available for particular components, then the specified values given may be used for assessment provided it is used in conjunction with information on tolerances applied to allowable plate thickness [15].

The Cowper Simmonds relation for strain rate enhancement of yield stress is used for computation of dynamic yield stress.

$$\frac{\sigma_{dy}}{\sigma_y} = 1 + \left[\frac{\dot{\varepsilon}}{D}\right]^{1/q}$$

where

σ_{dy} = Dynamic yield stress

σ_y = Static yield stress, and

$\dot{\varepsilon}$ = Strain rate

D and q are dimensionless curve fitting coefficients as given in Table C.11.4-1 for different materials.

Table C.11.4-1—Values of D and q for Different Materials

Material	D (s^{-1})	q
Mild Steel	40.4	5
Aluminum Alloy	6500	4
Stainless Steel	100	10

The dynamic yield stress used for capacity and buckling calculations is given by:

$$\sigma_{dy(lower-bound)} = \sigma_s - range + \sigma_s \cdot \left[\frac{\left(\frac{d\varepsilon}{dt}\right)}{D}\right]^{1/q} - 0.12 \cdot \sigma_s$$

$$\sigma_{dy(upper-bound)} = \sigma_s + range + \sigma_s \cdot \left[\frac{\left(\frac{d\varepsilon}{dt}\right)}{D}\right]^{1/q} - 0.12 \cdot \sigma_s$$

where

range = range of static yield stress

$\sigma_{dy(upper-bound)}$ = The upper bound dynamic yield stress

$\sigma_{dy(lower-bound)}$ = The lower bound dynamic yield stress

σ_y = The static yield stress

ε = The strain increasing at the rate of $\frac{d\varepsilon}{dt}$

The last term in the above equation allows for strain rate enhancement during testing using again the Cowper Simmonds relation assuming a strain rate of 10^{-3} per second.

Typical strain rates for steel structure are given in Table C11.4.1-2.

Table C.11.4.1-2—Strain Rate for Different Stress Conditions

Condition	Strain Rate
Structural members in the elastic range	0.02sec^{-1}
Structural members in the elastic range but plastic hinges may develop	$0.2\ \text{sec}^{-1}$
Structural members whose ductility ratio exceed two (2)	$0.6\ \text{sec}^{-1}$

Alternatively, empirical scaling factors adopted by ASCE [39] may be used to determine static and dynamic ultimate stress values. In addition to a static strength increase factor, a global dynamic increase factor may be applied to account for strain rate effects as well as a dynamic loading factor that accounts for the type of response expected. Table C.11.4.1-3 gives the details of the strength increase factors:

Table C.11.4.1-3—Dynamic Strength Increase Factor [39]

Material Type	Dynamic Strength Increase Factor	Dynamic Increase Factor		
		Bending/Shear	Tension/ Compression	Ultimate Stress
Structural steel (σ_y < 36 ksi)	1.10	1.29	1.19	1.10
Cold Formed Steel	1.21	1.10	1.10	1.00

C.11.5 STRAIN HARDENING

Strain hardening may be taken into account for tension members and plastic sections by taking design strength to be the ultimate strength divided by 1.25 [24]. It is conservative for cases where the ratio of yield strength and tensile strength >0.8 but is non-conservative for cases where the ratio is <0.8. The strain hardening effect should not be considered when designing supports against reaction forces.

It is, however, necessary to demonstrate that the strains are high enough to mobilize the benefits of the strain hardening.

Tension members may sustain high plastic strain without losing strength from local or overall buckling, unless in the case of reversal of blast loading where tension members may be subjected to compression loading and buckling check may be required.

The compact sections are capable of developing a fully plastic stress distribution and possess rotation capacity of approximately 3.0 before the onset of local buckling [14,31]. For more details, see commentary on the AISC LRFD specifications [1].

C.11.6 Ductility Ratio

The ductility ratio (μ) is defined by:

$$\mu = \frac{\delta}{y_{el}}$$

where

δ = total deflection

y_{el} = deflection at elastic limit

The deflection at elastic limit is the deflection at which bending behavior can be assumed to change from elastic to plastic. The ductility ratio for a given beam, load and strain limit assuming elastic-perfectly plastic material behavior can be obtained from ref. [4,16].

Taking lower bound shape factors, conservative ductility ratio limits, which would avoid brittle fractures, are indicated in Table C.11.6-1 [24].

Table C.11.6-1—Ductility Ratios for Steel Beams ($\sigma_y \approx 50$ ksi)

Beam Type	Load Type	Cross-section			Plate
		Plastic	Compact	Semi-compact	(2 edge support in bending)
Cantilevered	Point Load	5.7	3.8	1.9	15.7
	Distributed Load	7.5	4.9	2.3	22.5
Pinned Ends	Point Load	5.7	3.8	1.9	15.7
	Distributed Load	12.5	7.9	3.3	21.4
Fixed Ends	Point Load	5.7	3.8	1.9	15.7
	Distributed Load (End)	4.2	2.9	1.6	11.3
	Distributed Load (Mid-span)	14.6	9.1	3.7	24.9

C.13 GOOD PRACTICE DETAILS

To effect adequate capacity utilization of structural members during a blast event, it is advisable to adopt some good detailing practice, such as, provisions for rotation to take place at desired locations and ensure ductile behavior, provision for restraining compression flange against local buckling, etc.

Some typical examples of good practice detailing are shown in the following Figures C.13-1 through C.13 -3.

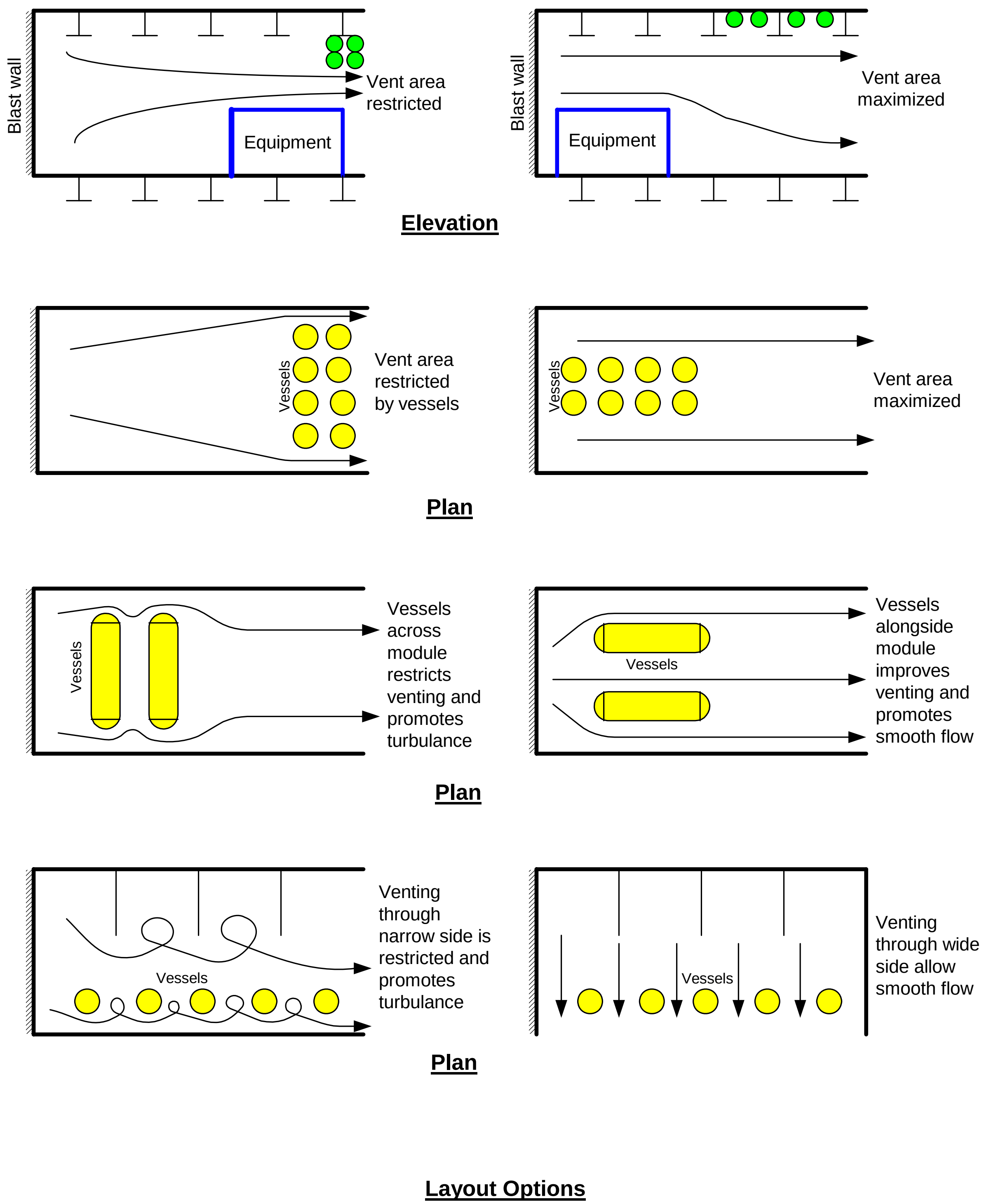


Figure C.13-1—Layout Options

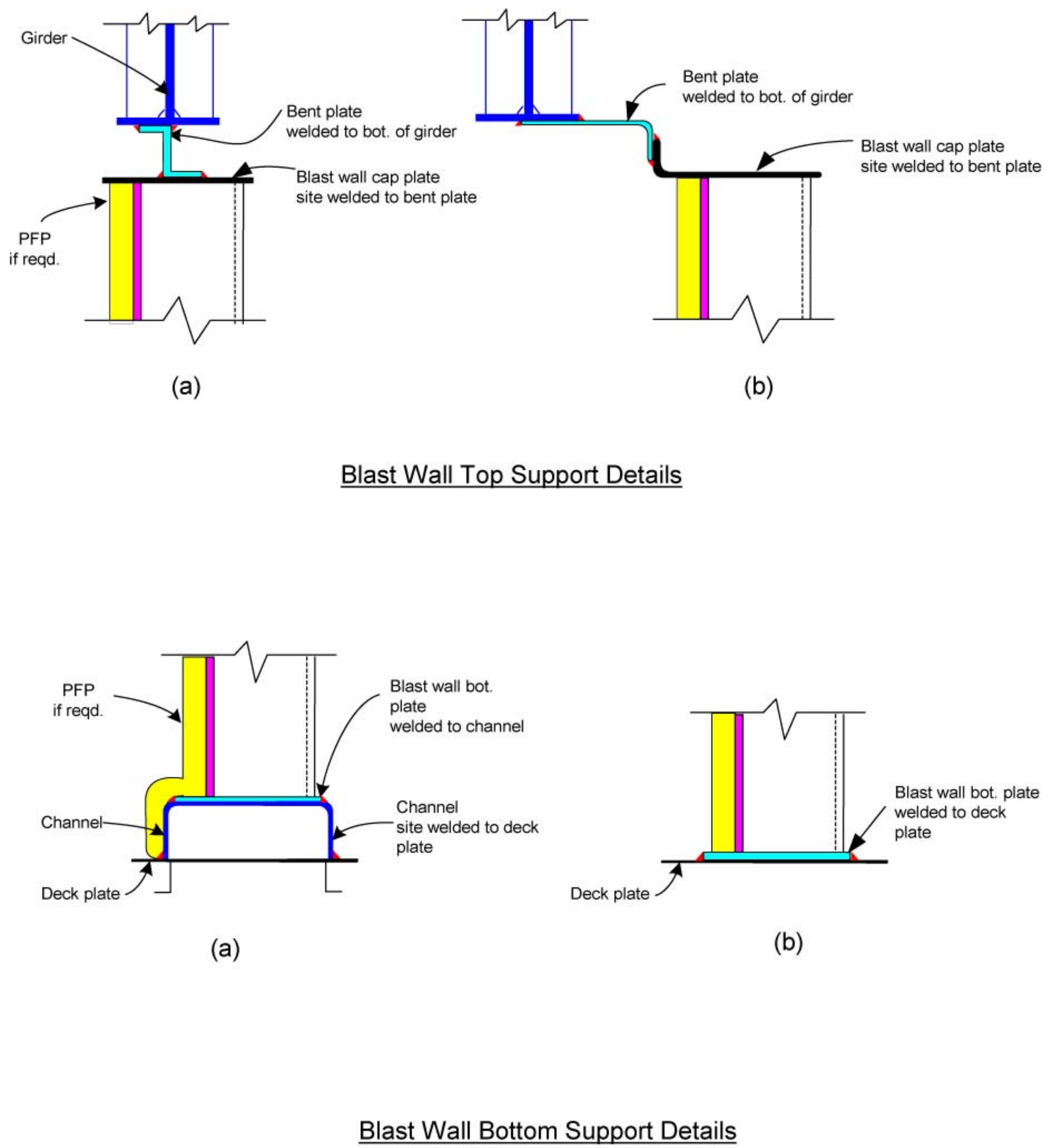
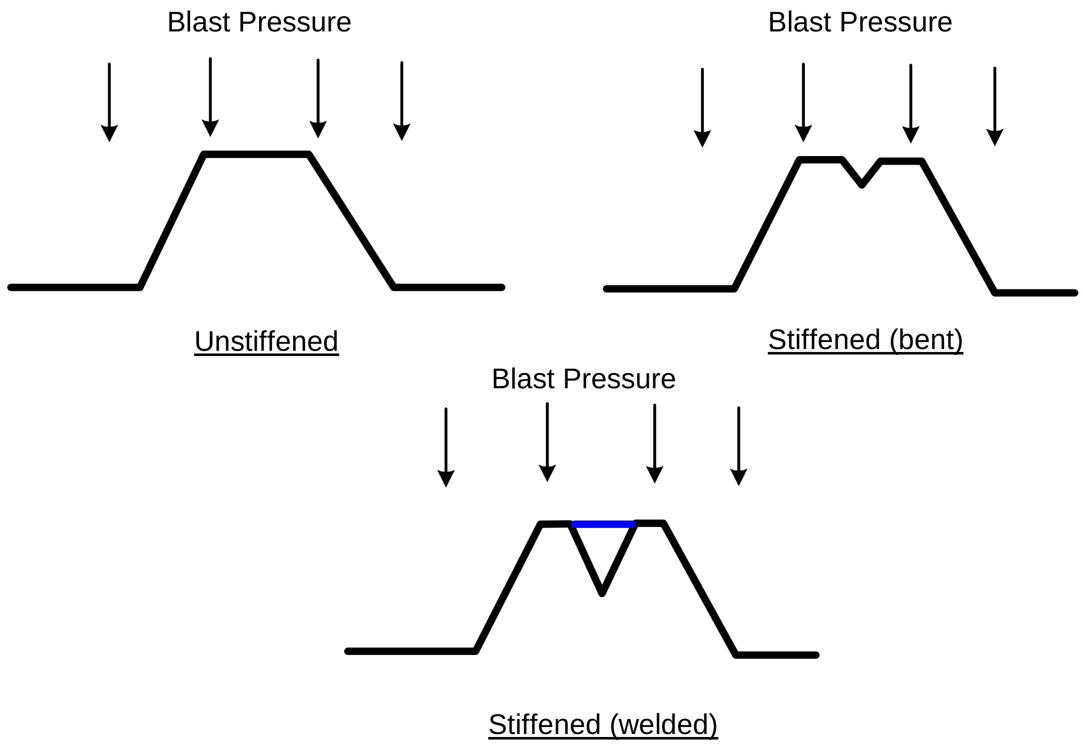
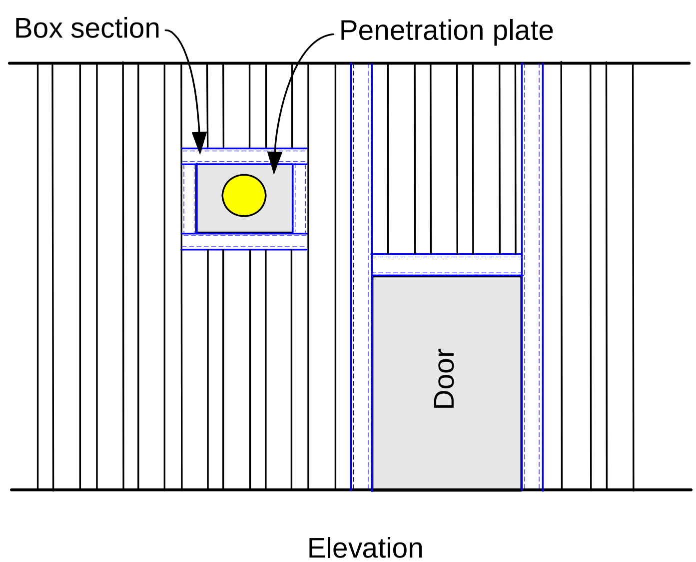


Figure C.13-2—Blast Wall Support Details



Blast Wall Panel Sections



Blast Wall Penetration Details

Figure C.13-3—Blast Wall Panels and Penetration Details

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