IAEA SAFETY STANDARDS SERIES

External Events Excluding Earthquakes in the Design of Nuclear Power Plants

SAFETY GUIDE

No. NS-G-1.5

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International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

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EXTERNAL EVENTS EXCLUDING EARTHQUAKES IN THE DESIGN OF NUCLEAR POWER PLANTS

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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EXTERNAL EVENTS EXCLUDING EARTHQUAKES IN THE DESIGN OF NUCLEAR POWER PLANTS

SAFETY GUIDE

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FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide was prepared under the IAEA programme for safety standards for nuclear power plants. It supplements the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1].

1.2. The present Safety Guide is the second revision of a Safety Guide issued in 1982 on the design of nuclear power plants for external human induced events. The main changes are as follows:

(1) Recommendations on design features relating to all external events[1], excluding earthquakes, have been incorporated into this publication, which makes reference to the Safety Guides on external human induced events, flood hazards and extreme meteorological events [2–4].
(2) Recommendations on design for protection from the effects of external events, which previously appeared in Ref. [2] and earlier IAEA safety standards[2], have been included in this publication, with the exception of recommendations on site protection measures which are retained in the relevant Safety Guides on site evaluation.
(3) The sections dealing with hazardous materials have been reorganized for consistency with Ref. [2]. Two groups of hazardous material are identified: asphyxiant and toxic gases, and corrosive and radioactive gases and liquids.

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[1] An external event is an event that originates outside the site and whose effects on the nuclear power plant should be considered. Such events could be of natural or human induced origin and are identified and selected for design purposes during the site evaluation process. In some cases events originating on the site but outside the safety related buildings can be treated as external events if the characteristics of the generated loads are similar to those caused by off-site events.

[2] Design Basis Flood for Nuclear Power Plants on River Sites, Safety Series No. 50-SG-S10A (1983); Design Basis Flood for Nuclear Power Plants on Coastal Sites, Safety Series No. 50-SG-S10B (1983); Extreme Meteorological Events in Nuclear Power Plant Siting, Excluding Tropical Cyclones, Safety Series No. 50-SG-S11A (1981); Design Basis Tropical Cyclone for Nuclear Power Plants, Safety Series No. 50-SG-S11B (1984); Ultimate Heat Sink and Directly Associated Heat Transport Systems for Nuclear Power Plants, Safety Series No. 50-SG-D6 (1981).

(4) Operating experience since 1986, as collected in the IAEA Incident Reporting System [5] and as expert experience, has been studied and discussed as guidance for improving the approach to design. A paragraph has been added in several sections with the main outcomes from this experience.
(5) Section 2, concerning the general approach and the design philosophy for protection against external events, has been considerably expanded, with new information added on structures, systems and components (SSCs) to be protected against external events and on load combinations and acceptance criteria.
(6) Individual sections have been prepared on aircraft crashes (with a strong emphasis on fuel effects), external fires, explosions, drifting gas clouds, releases of corrosive fluids, collisions with water intakes and all remaining external natural events. The discussion on each of these topics has been expanded and updated. Some material that appeared in the previous Safety Guides on these topics has been deleted.
(7) The text has been reorganized.

1.3. This Safety Guide provides recommendations for both design basis external human induced events and design basis external natural events[3], while the related Safety Guides [2–4] provide recommendations on site evaluation.

1.4. Other Safety Guides relating to the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1] present a discussion on external events and in this sense are complementary to the present Safety Guide — fire effects are in general addressed also in Ref. [6], certain missiles[4] (as secondary effects of explosions mainly internal to buildings) are treated in Ref. [7], while the effects of earthquakes, vibration and shaking of the ground are discussed in Ref. [8].

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[3] A design basis external natural event is an external natural event selected for deriving design bases.

[4] A missile is a mass that has kinetic energy and has left its design location. The term missile is used to describe a moving object in general, but military missiles, whether explosive or not (e.g. bombs and rockets), are specifically excluded from consideration. In general, military projectiles have velocities higher than Mach 1, and are therefore usually beyond the range of applicability of the techniques described in this Safety Guide. However, for non-explosive military projectiles with characteristics lying within the quoted ranges of applicability, the techniques described may be used.

1.5. There are other Safety Guides that deal with the same external event scenarios but in the context of the design of specific plant systems: Ref. [9] deals with the entire reactor cooling system, Ref. [10] with the containment, Ref. [11] with the emergency power system and Ref. [12] with instrumentation and control systems.

OBJECTIVE

1.6. The purpose of this Safety Guide is to provide recommendations and guidance on design for the protection of nuclear power plants from the effects of external events (excluding earthquakes). External events are events that originate either off the site or within the boundaries of the site but from sources that are not directly involved in the operational states of the nuclear power plant units, such as fuel depots or areas for the storage of hazardous materials handled during the construction, operation and decommissioning of units located at the same site. Significant events, either as design basis external human induced events[5] or design basis external natural events, should be identified and selected as design basis external events (DBEEs)[6] in the preliminary phases of the site evaluation process, in accordance with Refs [2–4].

1.7. This Safety Guide is intended to provide recommendations on engineering related matters in order to comply with the safety objectives and requirements established in Sections 2 and 3 of the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1].

1.8. This Safety Guide aims to provide the reader with a generally accepted way of defining an appropriate design basis for a nuclear power plant from the site hazard evaluation carried out in the site evaluation phase and according to the specific layout of the plant. Recommendations for methods and procedures

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[5] A design basis external human induced event is an external human induced event selected for deriving design bases.

[6] A design basis external event is an external event or a combination of external events selected for the design of all or any part of a nuclear power plant, characterized by or having associated with it certain parameter values. Design basis external events should be independent of the plant layout. An engineering analysis may be necessary to develop the loading scheme to be applied to the specific numerical or experimental models selected for the design.

to perform the plant design so as to minimize the probability that the selected DBEEs at the site could jeopardize the safety of the plant are also provided.

SCOPE

1.9. This Safety Guide is applicable to the design and safety assessment of items important to the safety of land based stationary nuclear power plants with water cooled reactors. It covers the safety of new nuclear power plants in relation to the following DBEEs:

Human induced events

- Aircraft crashes;
- Explosions (deflagrations and detonations) with or without fire, with or without secondary missiles, originating from off-site and on-site sources (but external to safety related buildings), such as hazardous or pressurized materials in storage, transformers, pressure vessels or high energy rotating equipment;
- Release of hazardous gases (asphyxiant, toxic) from off-site and on-site storage;
- Release of radioactive material from off-site sources;
- Release of corrosive gases and liquids from off-site and on-site storage;
- Fire generated from off-site sources (mainly for its potential for generating smoke and toxic gases);
- Collision of ships or floating debris with accessible safety related structures, such as water intakes and ultimate heat sink (UHS) components;
- Collision of vehicles at the site with SSCs;
- Electromagnetic interference from off the site (e.g. from communication centres and portable phone antennas) and on the site (e.g. from the activation of high voltage electric switch gear and from unshielded cables;
- Any combination of the above as a result of a common initiating event (such as an explosion with fire and release of hazardous gases and smoke).

Natural events

- Extreme meteorological conditions (of temperature, snow, hail, frost, subsurface freezing and drought);
- Floods (due to tides, tsunamis, seiches, storm surges, precipitation, waterspouts, dam forming and dam failures, snow melt, landslides into water bodies, channel changes and work in the channel);

- Cyclones (hurricanes, tornadoes and tropical typhoons) and straight winds;
- Abrasive dust and sand storms;
- Lightning;
- Volcanism;
- Biological phenomena;
- Collision of floating debris (ice, logs, etc.) with accessible safety related structures such as water intakes and UHS components.

1.10. This list is not exhaustive and other external events, not included in the list, may be identified and selected as DBEEs at the site. All such events should be evaluated in accordance with specific requirements, consistent with the safety requirements established in respect of them by the State concerned.

1.11. The completeness of the definition of hazards due to DBEEs may be affected by possible changes that have occurred in both the industrial environment and the transport environment since the siting process was followed, and also in natural hazards (e.g. because of climate changes), as foreseen in the Safety Requirements for Design [1]. Such changes are mainly considered in periodic safety reviews [13].

1.12. The coverage provided in this Safety Guide for the different scenarios is variable: most emphasis is given to explosions, floods and aircraft crashes. However, this is consistent with the consequences for plant safety expected in the different scenarios and also with the engineering efforts generally expended to protect the plant or to mitigate the consequences of such events.

1.13. Particularly in the case of natural events, some scenarios are treated as exclusion criteria for the site itself (e.g. local volcanism and local active fault) and so they are not discussed here [14]. Other scenarios are dealt with preferably through site protection features (e.g. the ‘dry site’ concept, site drainage, protecting dams and levees) rather than by plant design measures and therefore they are discussed in the relevant publication on site evaluation.

1.14. Throughout this publication the term ‘external events’ always excludes earthquakes and ground shaking scenarios, which are discussed in Ref. [8].

1.15. External human induced events are defined as of accidental origin. Considerations relating to the physical protection of the plant from wilful actions by third parties are outside the scope of this Safety Guide. However, the methods described herein may also have certain application to problems of physical protection for such scenarios.

1.16. This Safety Guide might be applied also to reactor types other than water cooled reactors at stationary nuclear power plants. However, engineering judgement should be used to assess such applicability, in compliance with the specific safety objectives defined for any plant type.

1.17. This Safety Guide provides recommendations and guidance for design procedures suggesting levels of accuracy consistent with current practice in the design of nuclear power plants, dealing primarily with the application of deterministic methods in design and assessment. Recommendations for the application of probabilistic methods in design and assessment phases are not included here (see Ref. [15]). Moreover, the proposed design method represents a limited number of the many engineering approaches that can be used: other procedures could be applied according to individual circumstances, specific plant layout and safety requirements.

1.18. This Safety Guide is mainly concerned with the design phase, but most of the recommendations could be applied in the safety assessment phase of new installations (described in Ref. [16]), in the periodic safety review phase (described in Ref. [13]) and in the re-evaluation of existing plants by means of extensive use of engineering judgement and in compliance with the relevant regulatory requirements for the specific phase.

STRUCTURE

1.19. The general approach to safety and the design philosophy are presented in Section 2, together with the concepts needed to develop the list of safety related items to be protected. The derivation of the design parameters from the site hazard analysis and the design basis is discussed in Section 3, along with the suitable load combinations and acceptance criteria under these together. Some specific events are treated individually in Sections 4–15. Examples of the design basis for aircraft crashes, solid explosions and gas cloud explosions, and toxicity limits in different States are presented in the annexes. Owing to a lack of general consensus on such issues among States, only examples from practice can be provided. These examples, together with due consideration of the general safety criteria, may help in the selection of the most suitable approach for any specific State.

2. APPLICATION OF SAFETY CRITERIA TO THE DESIGN FOR PROTECTION AGAINST EXTERNAL EVENTS

APPLICABLE DESIGN REQUIREMENTS

2.1. The Safety Requirements publication on Safety of Nuclear Power Plants: Design [1] establishes requirements in paras 4.2 and 4.4:

> “To ensure that the overall safety concept of defence in depth is maintained, the design shall be such as to prevent as far as practicable:
>
> (1) challenges to the integrity of physical barriers;
> (2) failure of a barrier when challenged;
> (3) failure of a barrier as a consequence of failure of another barrier.
>
> “All levels of defence shall be available at all times, although some relaxations may be specified for the various operational modes other than power operation.”

In relation to the concept of defence in depth, Ref. [1] (para. 2.11) also states:

> “The number of physical barriers that will be necessary will depend on the potential internal and external hazards, and the potential consequences of failures.”

STRUCTURES, SYSTEMS AND COMPONENTS TO BE PROTECTED AGAINST EXTERNAL EVENTS

2.2. In order to meet the safety requirements for protection against the external events selected in the site evaluation phase, a classification of the plant items is useful to provide a rational basis for design. In addition to the safety classification, an external event (EE) classification of items may be developed so as to identify the system requirements in a DBEE (for design and maintenance), to estimate the consequences of their failure and to develop focused post-event operator actions.[7] The EE classification can also be used within the modification process to ensure that modifications are suitably classified and do not erode the design basis.

2.3. The external event classification, if applied, does not imply different load levels for the external event scenarios and therefore the design of items classified for external events should refer only to the extreme values of DBEEs (as identified in Refs [2–4]), or to a combination of DBEEs where at least one of them is taken at, or close to, its extreme value.[8] However, lower load intensities could be used in the design for two main reasons:

- for *operational reasons*, in order to identify an operational level for the plant, with associated requirements for shutdown, inspection and emergency procedures in case the load intensities exceed the threshold;
- for *load combinations* with other design basis events, as a consequence of a probabilistic evaluation of the frequency of occurrence of some load combinations (e.g. including frequent wind, normal temperature and normal precipitation).

2.4. When different levels of the same external events are considered in the same load combination, the acceptance criteria of the items classified for external events should refer to the DBEE which in the combination is assumed to be at its extreme value.

2.5. In some cases probabilistic considerations on the probability of the load combination and its associated risk can justify less stringent acceptance criteria

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[7] The EE classification is the process that associates an external event category to any plant item, in addition to other classifications (e.g. for purposes of safety, seismic evaluation, quality assurance (QA) and maintenance), according to its required performance during and after a DBEE. The relevant acceptance criterion associated with the item is part of the classification. The EE classification is a general concept to be applied to all EEs affecting the plant, including earthquakes. A discussion on earthquakes is presented in the Safety Guide on seismic design [8], together with examples and procedures, but fully consistent with the general concepts defined here.

[8] Some States adopt two levels of classification/load resistance depending upon a deterministic frequent/infrequent categorization: infrequent faults ($<10^{-3}$ per year) require one line of protection, whereas frequent faults ($>10^{-3}$ per year) require two lines of protection.

during short duration DBEEs, provided that the item is not in the safety group for the events in the combination and that post-event inspections are developed to assess the compliance with the reference acceptance criteria (as specified in its classification) after the event (Ref. [1], paras 4.3, 5.7).

2.6. The external event classification should be developed in addition to and to be consistent with the general safety classification of the plant, which identifies those SSCs important to safety (Ref. [1], paras 5.1–5.3). The safety classification covers the following items:

- Items whose failure could directly or indirectly constitute a postulated initiating event (e.g. items protecting the plant from external events are included here);
- Items required for shutting down the reactor, monitoring critical parameters, maintaining the reactor in a shutdown condition and removing residual heat over a required period;
- Items required for preventing radioactive releases or for maintaining releases below limits established by the regulatory body for accident conditions (e.g. all the defence in depth levels and barriers).

2.7. All items assigned to a safety class and possibly other items should be considered in the EE classification, such as:

- the items ‘not important to safety’ which in a DBEE can affect the functionality of a safety classified item (‘interacting items’);
- the items not included in (2) and (3) above that are required for preventing or mitigating plant accident conditions for such a long period that there is a reasonable likelihood that a DBEE may occur during that period.

The EE classification can exclude items not affected by any DBEE (e.g. items located at an elevation higher than the flood level and not affected by any other DBEE).

2.8. The EE classification should be based on a clear understanding of the safety functions required of the items during and after a DBEE or a design basis accident (including the severe accidents if included in the load combinations) not caused by a DBEE. Parts of a system, according to their different functions, may belong to different categories.

2.9. SSCs identified as defined above may be divided into two or more external event categories in terms of their impact on plant safety in the event of failure caused by a DBEE. A recommended classification for external events, to be reflected in different design requirements, is as follows:

- *External event category 1 (EE-C1):* Items whose functioning should be maintained in the event of the DBEE and items required for preventing or mitigating plant accident conditions for such a long period that there is a reasonable likelihood that a DBEE may occur during that period (i.e. items ‘important to safety’). These items should be designed in accordance with acceptance criteria corresponding to the safety functions required during and after a DBEE;
- *External event category 2 (EE-C2):* Items whose loss of functionality may be permitted but should not impair the functionality of EE–C1 items in the event of a DBEE. These items should have acceptance criteria related to their potential interaction with EE-C1 items;
- *External event category 3 (EE-C3):* Items that are parts of systems that may generate events with radiological consequences different from those generated by the reactor (e.g. spent fuel building and radioactive waste building). These items should have load combination coefficients and acceptance criteria related to their specific potential for radiological accidents, which should be less than those for the reactor;
- *External event, non-classified (EE-NC):* All other items.

2.10. Within each EE classification category a range of acceptance criteria (according to the required function) and a range of safety margins together with specific construction, operation, inspection and maintenance procedures should be applied to the items depending on their importance or vulnerability in the event of a DBEE.

2.11. Nuclear power plant items of EE-C1 should be designed, installed and maintained in accordance with engineering practice for nuclear applications, for which appropriate safety margins should be established according to the associated consequences. For any item in Category 1, an appropriate acceptance criterion should be established (e.g. functionality, leaktightness and maximum distortion) according to the required safety function.

2.12. Since integrity is required for EE-C2 items and only limited (or, in some cases, no) functionality is required to prevent their interaction with Category 1 items, more simplified and less conservative criteria for design, installation and maintenance may be used, in some cases with a lower intrinsic safety margin than for EE-C1 items, in relation to their probability of being the initiator of an accident. Often, experience based walkdowns are implemented in response to this concern (see Section 3).

2.13. EE-C3 items should be designed, installed and maintained in accordance with engineering practice for nuclear applications. If their acceptance criteria can be explicitly connected with the specific associated radiological consequences (assumed different from the reactor induced consequences), such criteria could be different from (and in general less conservative than) those defined for EE-C1.

2.14. Nuclear power plant EE-NC items should be designed as a minimum in accordance with engineering practice for non-nuclear applications. For some items of this category of paramount importance for the operation of the plant, it may be reasonable to choose more stringent acceptance criteria, on the basis of operational targets. Such an approach would minimize the need for plant shutdown, inspection and relicensing, thus allowing the plant to continue to operate after a DBEE.

2.15. Typical systems that should be classified as EE-C1 are:

- The reactor system containment structure (including foundations) or the external shielding structure, if any, to the extent necessary to preclude significant loss of leaktightness;
- The structures supporting, housing or protecting items important to safety, to the extent necessary to ensure their functionality;
- Structures protecting the plant from external events;
- The power and instrumentation and control (I&C) cables relevant to safety related items;
- The control room or the supplementary control points, including all equipment necessary to maintain the control room or supplementary control points within safe habitability limits for personnel and safe environmental limits for equipment protected against DBEEs;
- Systems or portions of systems that are required for monitoring, actuating and operating those parts of systems protected against DBEEs;
- The emergency power supplies and their auxiliary systems necessary for the active safety functions;
- The post-accident monitoring system.

2.16. Typical systems that should be classified as EE-C2 are:

- Those parts of SSCs whose continued functionality is not required but whose failure could reduce the functional capability of any plant features specified above (EE-C1) to an unacceptable safety level or could result in incapacitating injury to occupants of the control room who are necessary to perform a safety function.

2.17. Typical systems that should be classified as EE-C3 are:

- SSCs for spent fuel confinement;
- Spent fuel cooling systems;
- Systems for the containment of highly radioactive waste in gaseous, vapour, liquid and/or solid form.

GUIDELINES FOR SAFETY ANALYSIS FOR DBEEs

2.18. An external event includes any credible consequential effects of that event [2–4]. External events are expected to challenge plant safety by different means, for example: the deterioration of structural capacities, the impairment of equipment operation, the impairment of operator action, the unavailability of the heat sink, and the unavailability of off-site power sources and emergency resources.

2.19. Having selected the external events to be considered for a particular site, the designer should evaluate their effects on the plant, including all credible secondary effects, following the single failure criterion and its limitations as explained in Ref. [1], para. 5.39. To this end, a safety analysis should be carried out, using continuous feedback to optimize the design of the protective measures, as explained in Ref. [16]. Care should be taken in the evaluation of effects on the plant to ensure that realistic and credible scenarios are developed — a single enveloping scenario may be unduly conservative.

2.20. The possibility of common cause failures should also be taken into account.[9] The single failure criterion is only capable of dealing with random

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[9] In some States the probability of occurrence of certain human induced events, such as external explosions or aircraft crashes, is considered very low, and the passive components are usually assumed to be designed, manufactured, inspected and maintained to an extremely high quality. Therefore, the single failure non-compliance clause (para. 5.39) of Ref. [1] can be applied to the passive components. In some States system outage due to repair, test or maintenance with its associated change in plant configuration is considered one possible mode of a single failure in this context. Other States include the single failure criterion for all DBEEs.

failures and therefore the redundancy, which is the ultimate outcome of such an analysis, may be defeated by common cause failures [17], typically associated with external events that are expected to have adverse effects over relatively large plant areas.

2.21. A DBEE should not be considered in combination with events that may occur independently, such as other external human induced events, natural phenomena, equipment failures and operator errors, unless a combination of these events is shown to have a sufficiently high probability of occurrence. In this assessment, the possibility of a causal relationship should be evaluated, according to Ref. [16].

2.22. A loss of off-site power should be assumed coincident with any extreme DBEE if a direct or indirect causal relationship cannot be excluded. Particularly, for DBEEs that are expected to affect the entire site and, therefore, to give rise to a potential for a common cause failure mode, a loss of off-site power should be combined with the DBEE. For other events, a loss of off-site power should be assumed if the location of the transmission lines or the switchyard is such that the direct effects on them of the DBEE could cause a loss of off-site power. For external events such as ship collisions and internal events such as fire or anticipated operational occurrences, a coincident loss of off-site power should be assumed if the event could be expected to result in an unplanned turbine trip or reactor trip that would increase the potential for grid instability.

2.23. When justified, in the design for protecting against DBEEs that produce primary and secondary effects, the time delay between such effects should be taken into consideration in specifying how the primary and secondary effects are to be combined.

2.24. Phenomena that are expected to show a slow development may receive a lower level of consideration in the safety analysis, provided that it can be demonstrated that corrective actions could be taken before there were serious consequences for plant safety.[10]

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[10] This is the case, for example, for the design of UHS structures, and particularly of transfer channels, against soil settlement, landslides, subsidence or uplift due to changes in subsurface groundwater, and changes in oil or gas deposits due to natural events or human induced events such as pumping operations.

2.25. Consideration should be given in the safety analysis to the possible duration of extreme events, particularly for extreme weather conditions. Thus if the extreme conditions postulated for the site could endure for a considerable period, the feasibility of providing any backup measure from off the site should be evaluated, in view of the damage that is likely to occur and the probable conditions for the emergency services. Therefore, realistic assessments should be made of the ability to respond off the site under extreme conditions in the site region, when other demands for emergency services may be paramount. Either an adequate capacity should be provided for such circumstances or such backup measures should be excluded from the safety analysis.

2.26. In general, for corrective actions involving the support of off-site facilities, credit for unplanned corrective actions should be based on the analysis of the specific DBEE and particular site conditions, and should include adequate margin for uncertainties. As a minimum, for any event or site, no credit for such action should be taken for at least 48 hours following the onset of the event.

2.27. In particular for the UHS, the need for make-up of heat transport fluids should also be examined. Where a limited quantity of heat transport fluids is stored on site, the capability for make-up should be ensured by either (a) providing an adequate quantity of such fluids to allow time to repair the damaged part of the make-up system, or (b) protecting the make-up system from an external event. In case the make-up facilities cannot be fully protected, they should at least be dispersed or protected in such a way that a minimum capacity remains immediately available after any external event.

2.28. In the design, no credit for operator action should be assumed for any actions that should be taken immediately following the onset of a DBEE: difficulties in operator access at the site, long distances and difficulties in communication at the site may obstruct or prevent a clear diagnosis and local mitigation. No credit for operator actions should be given for the correction of equipment failures or the repair of damage as a consequence of a DBEE, unless there is a clear demonstration that such an action can be reliably accomplished within a time-frame consistent with the complexity and difficulty of the required action. A considerable margin should be applied to account for uncertainties, time needed to diagnose the extent of failure and to develop or modify corrective procedures, and the possible unavailability of appropriate personnel or replacement parts.

2.29. External events may challenge defence in depth at many levels. The basic plant protection should be addressed in the first level of defence either by means of an adequate design of all the physical barriers or by component qualification. However, all the levels should be designed against external events to guarantee that in the event of an internal design basis accident all levels of defence are in place (Ref. [1], para. 4.4). Probabilistic evaluations should be carried out for the definition of suitable design combinations between external events and internal accidents, addressing both their potential correlation and their joint probability.

2.30. Some external events included in the design basis may be associated with very low probability and catastrophic scenarios: examples include impacts of large aircraft, devastating explosions in the vicinity of the plant and extreme floods. The evaluation of their effects on the plant can be affected by high uncertainties, for the following reasons:

- Extreme external events with a very low probability of occurrence could have effects not properly foreseen in terms of their action on the plant and/or their magnitude;
- The estimation of the effects of extreme external events has gross uncertainties associated with it, as discussed in Refs [2–4] for the hazards, but is not explicitly considered in a deterministic design;
- There is an intrinsic lack of operating experience relating to the effects that such extreme events could have on plant safety, owing to their low probability of occurrence.

For these reasons, the design of a full scope protecting barrier may be unreliable and in some cases even unfeasible[11] and a challenge to one level of defence in depth may be envisaged.

2.31. In these cases some special engineering approaches may be adopted, including all or a selection of the following measures:

- The selection of EE-C1 systems required for the protection of the plant against such events may be less stringent than for other DBEEs, including only a subset of safety classified items, usually only the items in the safety group of the extreme events;

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[11] This is the case, for example, for a containment building subjected to the crash of a large aircraft: its leaktightness is usually not required.

- Only load combinations with the most probable plant statuses and operational modes are considered (i.e. no accident states and no refuelling or maintenance conditions with the containment open);
- Lower safety margins or reduced acceptance criteria compared with other DBEEs may be specified for items pertaining to the third or fourth level of defence in depth (mitigation of design basis accidents and of severe accidents);
- Best estimate rather than conservative material properties, design and analysis methods may be used.

2.32. If such a challenge to a level of defence in depth is envisaged, dedicated operational procedures should be put in place with reference to limits and conditions for normal operation, supported by adequate warning systems (where possible) and monitoring (see the following subsections). Moreover, a dedicated probabilistic evaluation should be made of the consequences of these special assumptions.

DESIGN SAFETY FEATURES FOR DBEEs

2.33. To perform the safety functions required for DBEEs the designer should use either systems specific to external events or the safety systems already present in the plant for internal events. In both cases, the design of the plant for safety should show due regard for the single failure criterion; this may be achieved by means of the redundancy of safety systems.

2.34. There are two basic forms of plant protection against external events:

(1) either the causal influences of an external event are reduced by means of a ‘passive barrier’ (e.g. ‘dry site’ for flood, site protection dam for flood, external shield for aircraft crash, barriers for explosions and building base isolation for earthquake),
(2) or the ability of the safety systems to resist the effects of EEs is assessed by means of adequate item qualification (including redundancy, diversity or segregation).

2.35. The solution should represent the best balance among safety aspects, operational aspects and other important factors. For example, an inherent capability to withstand localized events (e.g. aircraft crash) can be provided by the physical separation of redundant systems, such that the simultaneous failure of the redundant systems due to the effects of building vibration, debris or fire from aircraft fuel is precluded. Otherwise, it is necessary to provide additional protection in the form of barriers or to increase the spatial separation by modification of the plant layout.

2.36. Recommendations for the application of redundancy, diversity and segregation are made in Refs [1, 17]. In particular, special provisions against common cause failure should be made for large and extensive systems, namely the systems used to transport heat to the UHS, pump houses, cooling towers or long piping systems with large ring main systems.[12] A combination of the following protection strategies should be implemented.

- An adequate redundancy of safety related items. The level of redundancy should be an outcome of the application of the single failure approach to the design. Exceptions to the single failure approach may be accepted on a case by case basis where the DBEE has a very low probability and the systems are passive (Ref. [1], para. 5.39).
- Extensive spatial separation between redundant components. This measure should prevent both common cause failures from localized external events (e.g. missile impact) and interactions in the event of failure of one system that could be a source of internal accidents. A detailed analysis of the areas of influence or expected damage from the DBEE should be carried out for the purpose of application of the physical separation.
- Diversity in the redundant components. In the case of external event scenarios with a potential for common cause failures, the benefits of diversity should be evaluated with care. Diversity should be combined with separation when possible.

2.37. To provide additional defence in depth to the basic forms of protection defined above, for some external events proactive, active or administrative measures based on forewarning can also provide safety benefits. Examples of such measures include the reduction of fire loading materials adjacent to or on the nuclear site, the installation of additional barriers (damboards) or the closure of watertight gates in anticipation of flooding, and the inspection of drainage channels. While these measures are not normally as reliable as passive engineered systems, they nevertheless can provide additional safety benefits. The reliability ascribed to such measures should be commensurate with the reliability of the monitoring and forecasting equipment and operator reliabilities.

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[12] A ring main system is a piping system that interconnects systems used to transport heat to the UHS.

2.38. The effectiveness of administrative measures is strongly dependent on their enforcement level, particularly when different administrations are involved. Their reliability should therefore be evaluated with care.

2.39. The following aspects should also be considered in a design for safety:

— Following the occurrence of a DBEE the design should ensure accessibility to the main control room, to supplementary control points and to the points, rooms and facilities necessary for meeting the requirements;

— The design should ensure that during the occurrence of a DBEE the plant status does not deteriorate to the extent that it cannot be controlled by the safety measures;

— The systems not protected against DBEEs (i.e. EE-NC items) should be assumed to be ‘operable’ or ‘non-operable’, depending on which status provides the more conservative scenario in the design of protection measures against the DBEE.

2.40. Provisions in the design to protect the plant against DBEEs should not impair its response in the other design basis events. In designing for additional protection, it should be borne in mind that barriers can introduce difficulties for inspection and maintenance, while a greater spread in plant layout may require more staff to handle the increased task of surveillance, as well as longer routing of piping, cable trays and ventilation ducts.

2.41. In the plant design for protection against EEs, adequate robustness should be used to provide the plant with some additional capacity for beyond design basis values for conditions in the selected external event scenarios. In general, this capacity should be provided by a combination of the following: high quality design, low sensitivity to variation in design parameters, and high and demonstrable conservatism in material selection, construction standards and QA. An evaluation of the design conservatism should be carried out either with probabilistic tools or by simplified deterministic bounding analysis.

2.42. Moreover, a special evaluation should be carried out so as to avoid potential small deviations in plant parameters from giving rise to severely abnormal plant behaviour (‘cliff edge effects’) in relation to the specific nature of the external event scenario (e.g. in the case of a site protection dam, if as soon as the dam is overtopped with a small additional steady state water level, the site could be suddenly flooded to the maximum level of the flood). In this case, addi-tional engineering provisions should be implemented on safety systems at least for a safe shutdown mode, such as warning, monitoring and operating procedures.

INTERFACE WITH OPERATIONAL SAFETY FEATURES

2.43. Particular operating limits and conditions (OLCs) (Ref. [18], paras 5.8 and 6.9) should be defined for any external event that proves to be important for plant design, in terms of relevance of the hazard, contribution to sizing of safety related items and contribution to the results of probabilistic safety assessment (PSA). The OLCs should be associated with dedicated surveillance procedures (pre- and/or post-event), a plant safe state (possibly a reactor shutdown) that is to be reached after such 'abnormal' events and a post-event revalidation procedure for any item important to safety that may have been challenged.

2.44. A set of operational limits should be defined for items classified for external events, derived from Ref. [19]:

- Safety limits (safe operating limits — SOLs): these are specified in the safety classification (and also in the EE classification) and represent the design basis conditions for the items. Their exceedance represents a challenge for plant safety and therefore a plant shutdown is required with precise post-event revalidation;
- Limits and conditions for normal operation (NOLs): these represent the limits for safe operation with due consideration of the uncertainties in the design process described above. They do not affect the design being intrinsically related to the uncertainty of the hazard for a very low probability of exceedance. Their exceedance is preliminary to the activation of the safety systems in the safety group able to bring the plant into a safer state, such as power reduction or reactor shutdown. Resuming operation is conditional on appropriate investigations of causes and effects.

2.45. NOLs should be identified in the hazard evaluation phase. Adequate procedures should be implemented for monitoring and for the prompt evaluation of their exceedance, to be specified in terms of all the parameters affecting the hazard definition. Actions arising from the exceedance of NOLs could include enhanced monitoring, administrative measures and review of forecasts.

2.46. If design provisions to protect the plant against the external events rely on passive barriers to reduce the effects of external events on the plant, NOLs should be referred to the barrier safety function and plant operation can be extended up to SOLs, on the assumption of a high degree of conservatism in the design of the barrier, provided that no cliff edge effects are foreseen for beyond design basis values. However, due account should be taken of the uncertainties, of the reliabilities of monitoring and forecasting systems and of the margin between the time needed for shutdown and the time before the external event parameters exceed the barrier's capacity.

2.47. In any case, in relation to the development of an external event, plant shutdown should start if any of the following conditions is met [18]:

- If the operating personnel cannot ascertain that the power plant is being operated within OLCs;
- If there is any evidence of damage to classified items;
- If there is reasonable confidence that the OLCs will be exceeded in a shorter time than is needed for a shutdown, according to reliable forecasting procedures for the development of the event (e.g. for flood or cyclones).

2.48. For most external events with sudden or unexpected effects, the parameters associated with the design basis cannot be monitored: examples would include aircraft impact parameters, blast pressures or impulse. In such cases a precautionary principle should apply and shutdown should be initiated after the event upon the basis of operator judgement.

2.49. To prevent unnecessary trips or demands on safety systems, for those external events whose parameters are continuous variables, such as water level or wind speed, consideration should be given to making routine measurements. The equipment and systems used to measure and report these parameters should have a reliability and accuracy commensurate with the safety claims made upon them.

3. DESIGN BASIS FOR EXTERNAL EVENTS

DERIVATION OF THE DESIGN BASIS FROM THE SITE HAZARD ANALYSIS

3.1. The first step in the design of a nuclear power plant against external events is to identify those events that are considered credible for a particular site. Reference [2] provides a method for selecting those credible human induced events that should be considered for the site, while Refs [3, 4] present the hazard evaluation for some natural events. For other reasons, such as national safety policy, a certain type of external initiating event may be defined for design on a deterministic basis.

3.2. A general approach in the design is to establish the design input parameters by a combination of deterministic and probabilistic methods and to proceed with the design in a deterministic manner.

3.3. In some cases, even though the combined deterministic and probabilistic approach might identify a specific external human induced event as a potential design basis event, it may still be excluded from specific analysis if it is shown that the corresponding effects are bounded by the effects of other design basis events. However, it should be kept in the design basis to guarantee that potential engineering and administrative measures to be taken for the bounding event are valid for the bounded ones also.

3.4. When the hazard is defined in a probabilistic context, because of the deterministic approach applied in the design, the site hazard should be analysed and a ‘single value’ on the hazard curve should be selected to be used in the design basis. In this case, the selection of the design basis includes an implicit probabilistic assumption concerning the risk of a radiological accident that a nuclear installation can present, according to the Safety Requirements [1]. Therefore the final target of such an action is to keep the risk acceptably small, which implies an evaluation of the probability that an event will affect safety related items (‘design probability values’) and then the probability of unacceptable consequences of their failure.

3.5. However, a complete probabilistic analysis is usually carried out only in the framework of a PSA, i.e. in a confirmatory phase of the design. In the early design phase, therefore, assumptions for such conditional probabilities should be made, driven mainly by deterministic calculations (e.g. stress analysis and impact damage evaluation) and expert judgement, so as to select a design basis value on the hazard curve in a reasonable way.[13] Because of its nature, this process is strictly plant dependent and should be assessed in the design assessment phase [16]. This value should also be compatible with the criteria applied in the probabilistic screening at the site evaluation phase.

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[13] In some States an acceptably small probability of an event generating an unacceptable radioactive release is defined as about 10^{-7} per reactor per year for a new nuclear power plant.

3.6. It may be prudent to specify minimum deterministic design loading conditions for those external events with potentially significant consequences for plant safety. States may wish to specify minimum loading conditions for missile impact, explosions and external fire. To do so provides a degree of confidence that a robustness of design will be ensured over the design lifetime of the plant to take account of unanticipated future scenarios.[14]

3.7. A higher probability value for some events may also be extracted from the hazard curve in relation to operational and load combination needs (see Section 2.3). The entire set of values should be consistent with the site hazard evaluation and should be inserted into a monitoring programme for hazard review as part of the process of periodic safety review.

3.8. The entire process should be approved by the regulatory body, and approved also for consistency with other risks from natural and industrial sources.

3.9. The following issues should be considered in the definition of the probability levels for the DBEEs:

- Installed power or hazard characteristic of the radiological source (in some States the spent fuel pool has a different DBEE than the reactor building);
- Concentration of event effects: probability of common cause failures as a consequence of the events (e.g. large fire, flood or extreme ambient temperature would be more prone to develop common cause failures than an aircraft crash);
- The need for active versus passive safety systems to prevent or mitigate unacceptable effects;
- The possible installation of warning systems able to detect in time the potential unfavourable development of an event (e.g. meteorological events versus aircraft crashes);
- The potential for quick dispersion following an event (e.g. explosions, flood and wind might have higher dispersion potential than extreme ambient temperature);
- The kind of potential contamination: long term effects, difficulties in decontamination, dispersed versus concentrated contamination and direct effects on the population;

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[14] In some States the following minimum deterministic loads are considered: external fire resistance of safety related buildings at 300°C, longer than 2.5 h; air blast pressure wave at 10 kPa; missile of 510 kg, 0.34 m diameter, 10.7 m long, at speed 25 m/s, rigid.

- Easy implementation of emergency planning in relation to the event: access to the site, availability of evacuation routes and time delay between accident and releases;
- Characteristics of the engineering features that might exhibit some form of cliff edge effect in the event of an accident (e.g. overtopping of a dyke in the event of a flood), without the possibility of preventing a degeneration of the situation with radiological consequences.

3.10. External event PSA, monitoring, inspection, surveillance and periodic safety reviews are the tools that should be used to confirm the selected target probability levels.

OVERALL DESIGN APPROACH

3.11. The initial operational modes to be considered at the time of occurrence of any DBEE, such as power, hot shutdown, cold shutdown, refuelling, maintenance and repair, should be determined in general on a probabilistic basis.

3.12. A typical logic diagram for analysis of the effects of DBEEs on classified items is shown in Fig. 1. The first steps identify the design basis events according to the site evaluation process and the postulated plant conditions (see Boxes 1 and 2 of Fig. 1). Then, probable scenarios of the consequences for the DBEE should be developed and on this basis the list of affected items should be produced and the items should be classified (see Box 3). Afterwards, the corresponding design parameters and loading schemes should be identified (see Box 4).

3.13. The selection of plant locations affected by a DBEE (e.g. site areas, buildings and exposed equipment) should be made carefully, since the possible effects on any particular function caused by the impairment of a system may not be obvious. For example, the repair time for a power line damaged by an event may determine the minimum amount of stored fuel required for the diesel generators, if the supply of diesel oil from sources nearby cannot be guaranteed. Failure of a ventilation system due to an aircraft crash may lead to a temperature rise inside a building, which in turn may cause the malfunctioning of electronic and pneumatic equipment.

3.14. The next step is to determine which items important to safety may be affected by an external event, either directly or by interaction, so as to ensure that the general design requirements can be met (Box 5). The designer should

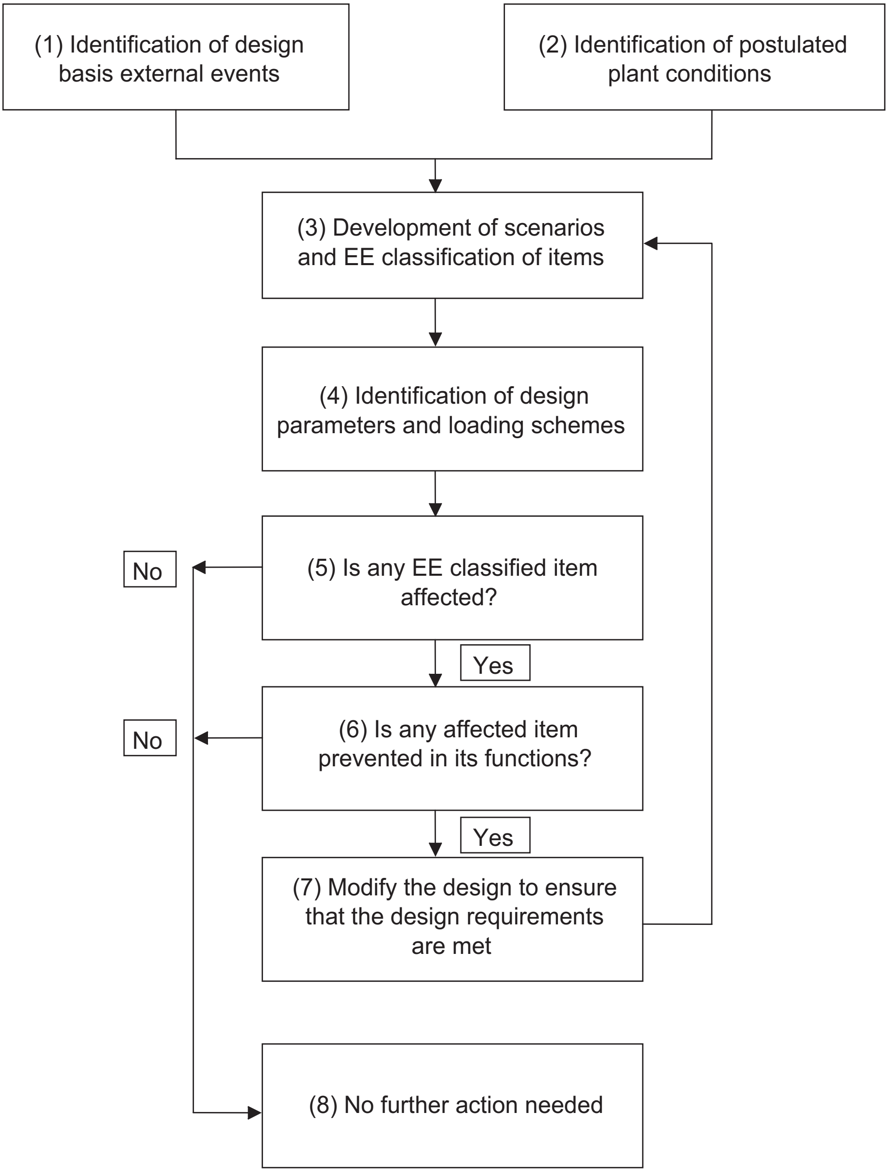

FIG. 1. Logic diagram for the design process in relation to external events.

decide whether the affected area is limited or whether it may extend over the entire plant site. Usually, events such as aircraft crashes and missile strikes have limited impact areas (even when more than one missile is considered), while explosions, ground motions and gas clouds can have plant-wide effects. At the end of this step the EE classification should be completed.

3.15. If the impact area is limited and the affected location can be determined, the items important to safety that might be affected can be identified. These items should be protected when the requirements cannot be met for this postulated initiating event (PIE) (i.e. if the answer to the question in Box 6 is Yes).

3.16. Once an external event is identified as a design basis event, the design to protect against it is generally based on a deterministic analysis. Different ways of ensuring the safety objectives (Box 7) are:

(a) To strengthen the items so that they can withstand the impact, if their inherent capabilities would otherwise be insufficient;
(b) To protect them either by passive means (such as barriers) or by active means (such as qualified actuators that operate closure valves);
(c) To provide redundant items in a different location with sufficient separation between them;
(d) To limit the consequences of damage.

3.17. If the affected area is limited but is not confined to a specific location, the designer should analyse which functions could be impaired, on the assumption that the impact area may be anywhere on the site (Box 6). As a case in point, it is not possible to predict the location of the impact area for an aircraft crash or a missile, but it may be possible to identify areas where aircraft crashes are not probable. For example, when a building is near other buildings these may serve to shield against the effects of an aircraft crash.

3.18. If the affected area is plant-wide, as would be expected in the case of high winds or toxic clouds, items important to safety located anywhere in the plant could be affected coincidentally (and the answer to Box 5 would be Yes). This possible coincidence should be taken into consideration in analysing whether necessary functions might be affected (Box 6). Therefore, for protection against events that may affect plant-wide areas, separation by distance alone may not be adequate, and special provisions should be considered to strengthen the items or to protect them from the effects (Box 7); for example, to isolate the air intake of the main control room in the event of toxic clouds.

3.19. After these provisions are made, the new design should be subjected to an overall assessment, including the effects of the changes on plant behaviour in relation to other events (the return arrow in the logic diagram). The next sections clarify the approaches to be followed in most of the steps identified previously.

3.20. Systematic inspections by expert engineers organized in a formal plant walkdown should be performed during commissioning to provide final verification of the design for external events, particularly floods, including also internal interactions through internal fire, flood, mechanical impact and electromagnetic interference; to verify that there are no unanticipated situations; and to provide sample verification of specific design features. The walkdown team should consist of experts in external events, design of nuclear structures and component design, together with systems analysts and plant operators.

LOADING DERIVATION

3.21. The derivation of the design basis parameters and the relevant loading scheme for the selected DBEEs should be carried out consistently with the level of detail required for the design limit[15] assessment (e.g. leaktightness, perforation[16] and scabbing[17]) and to the accuracy level associated with the design procedures to be applied (e.g. linear, non-linear, three dimensional (3-D) and dynamic).

3.22. Particular care should be taken with the derivation of static loads equivalent to time dependent effects, of load functions modelling the impacts between rigid bodies, of spatial averaging and of specific load cases for specific components from the same event.

3.23. Many of the loads corresponding to external events described in subsequent sections, and particularly in Ref. [2], are loads of short duration and rapid rise time which are characterized by a finite energy or a defined momentum transfer. The loads are often localized, causing substantial local response of the individual target but with little effect on massive structures as a whole. Load–time functions can be derived by experimentation or analytical

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[15] The design limit is an interpretation of acceptance criteria in terms of design parameters (e.g. elasticity, maximum crack opening, no buckling and maximum ductility).

[16] Perforation is the state when an impacting missile has passed completely through the target.

[17] Scabbing is the ejection of irregular pieces of that face of the target opposite the impact face as a result of a missile impact.

simulation, usually on rigid targets. Some suggested procedures for load function definition in use in some States are presented in Annexes I and II.

3.24. In general, full 3-D finite element analysis of the fluid domain (impulse, in the case of wind or explosions) or full impact analysis (impact, in the case of aircraft crash or tornado missiles) are not used in the design process for the derivation of a suitable load function. Very detailed research programmes have been carried out in the engineering community and in some cases simplified engineering approaches are now available for a reliable design process, on the basis of the interpretation of test data or data from numerical analysis.

3.25. A very careful assessment of the basic assumptions and applicability limits of such simplified techniques should be carried out by the designer to check their applicability to the case of interest and their compatibility with the general accuracy level required in the design. A sensitivity analysis should always be conducted on input data and among different acceptable approaches.

3.26. Refined studies supported by numerical analyses and/or physical testing should be carried out for specific layout configurations: typical examples are the grouping effects among cooling towers, dynamic amplification of tall and slender stacks or, in the case of aircraft crash, the dynamic interaction effects on large and flexible slabs.

LOAD COMBINATIONS AND ACCEPTANCE CRITERIA

3.27. Because of their infrequent nature and very short duration, statistically independent loadings from any single DBEE are usually combined only with normal operational loads using unity load factors for all loadings. Multiple DBEE loadings such as aircraft crash and explosions usually do not have to be combined together. However, all effects from a single DBEE should be properly time phased and combined, with due attention paid to the physical meaning of the combinations. Thus, for aircraft crash, the various effects of the impact (e.g. missiles, induced vibrations and fuel fires) should be combined. Furthermore, when a causal relationship exists between events (such as explosions induced by earthquakes or a flood induced by a dam break), the effects should be properly time phased and combined. In the case of meteorological events and floods, combinations are extensively discussed in Ref. [3].

3.28. Acceptance criteria (e.g. leaktightness, stability and operability) should be assessed according to the external event classification of the items. Such criteria should be interpreted in design terms, leading to appropriate design limits (e.g. allowed leak rate, maximum crack opening, elasticity and maximum displacement). However, for this process, it should be noted that while it is the practice to design for DBEE loads on an elastic basis with normal operating limits, the severe local nature of these loads might make the evaluation of the safety margin very unreliable, and therefore a proper modelling of the physical reality, to the extent possible, should always be preferred.

3.29. Design which utilizes localized plastic deformation to absorb the energy input of the load is acceptable, provided that the overall stability of the structure is not impaired. Inelastic behaviour (localized plastic) is generally permissible for individual ductile structural elements (beams, slabs and their connections) where local inelastic deformation would not jeopardize the stability of the structure as a whole, and for protective substructures (restraints and barriers) whose sole function is to provide protection against DBEE loads.

3.30. Limited global or system inelastic behaviour (global plastic) is also permitted for frames, shear walls and other types of structural systems. However, the overall structure should be checked against reaction loads from the individual elements or substructures, and its response should generally remain within the linear domain.

GENERAL GUIDANCE ON THE PROCEDURES FOR STRUCTURAL DESIGN AND EQUIPMENT QUALIFICATION

3.31. Design procedures should be selected according to the accuracy necessary to meet the design limits. In current practice, design for DBEE often requires a series of numerical models (finite elements, finite differences and fixed control volumes), local and global, and design formulas, oriented to capture the specific structural behaviour to be assessed.

3.32. The design models should be consistent and therefore special attention should be paid to the assessment of the data flow from one to another. In the case of numerical models used in sequence, attention should be paid to the accuracy level of any task of the sequence, in order to guarantee that the final results are representative of the real structural response.

3.33. The level of detail to be represented in the numerical models should allow an adequate representation of the reference structural behaviour: the need for very refined modelling (e.g. structural joints, steel rebars in reinforced concrete, structural interfaces and liners) should be reviewed, mindful of the need to balance the accuracy and the reliability of the analysis.

3.34. The finite element grid should be validated for any specific load case to be represented. Short duration loads (typical in explosions) often require dedicated models, different, for example, from the traditional dynamic models used for seismic analysis. Particularly, in order to avoid spurious filtering effects, a dense finite element grid should be used to represent the vibration field in the structure at high frequencies (above 20 Hz). Moreover, limitations to the finite element grid size should be adopted in explicit time integration schemes to avoid numerical instabilities.

3.35. In the definition of boundary conditions for the numerical models, the following should be considered:

— An evaluation of the influence of foundation or support properties on the response of the global models;
— An evaluation of the boundary conditions for local models, equivalent to the response of the remaining structural parts.

3.36. The design methodology, static or dynamic, linear or non-linear, should be consistent with the main loading characteristics and appropriate to the design limit to be assessed. Special care should be taken to ensure that the model dynamic behaviour is representative of the input frequency content.

3.37. Owing to the high variability of the results implicit in the complicated modelling approaches, any design procedures used in the DBEE simulation, numerical or analytical, should be validated through sensitivity analyses of the input data and assessed by means of alternative approaches with different complexity levels.

3.38. Design methods based on test results are particularly appropriate for loads in design basis external human induced events, on account of the wide spread of response predictions observed in non-linear numerical analyses not using benchmarked computer solutions. However, extreme care should be taken when empirical or semi-empirical approaches are employed outside the range of parameters of the corresponding database.

3.39. Vibratory motions and mechanical actions (e.g. those caused by debris, secondary missiles and gaps) calculated on the protecting structures should be analysed independently of and prior to any design limit assessment and prior to the qualification of anchored safety related equipment. Engineering judgement should be exercised in order to associate an appropriate uncertainty margin with the results (typically the floor response spectra) related to the modelling assumptions and to the intrinsic scattering of the input data.

3.40. EE classified equipment required for performing the safety functions during and after the occurrence of a DBEE should be functionally qualified for the induced conditions, including vibrational loading. Particularly, qualification for impact or impulse loading may be quite different from qualification for earthquake induced vibrations, and therefore specific procedures should be selected, according to the performance required (stability, integrity and functionality).

3.41. The qualification conditions should be compared with the demand, usually represented by vibration, impact or impulse forcing functions at the anchoring on the structural support, but very stringent requirements could be derived by functionality under conditions of dust, smoke, humidity, cold temperatures or corrosive atmospheres, combined with stress. Adequate safety margins should be provided according to the item classification.

3.42. For some DBEEs, such as corrosive actions or biological phenomena, the degradation occurs over a considerable time period. In such cases, the design may not need to provide a high performance and durability of protective measures provided that the items or parts of items subject to degradation can be inspected. The inspection regimes should have scope, periodicity and method commensurate with the degradation rates. The installed protective measures should also be capable of reapplication or else the design should permit treatment to inhibit, stop or reverse the degradation.

MATERIAL PROPERTIES

3.43. Material properties should be assumed to be consistent with the rate of loading and in agreement with material procurement, construction and QA procedures required by the EE classification. For some design basis external human induced events, which require design against impulse and impact loads, appropriate values for material properties should be obtained from standard references. These may also include considerations relating to statistical and strain rate variations which are significant for impulsive loads.[18] Both types of

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[18] An impulsive load is a short duration transient loading that is characterized by a defined transfer of momentum.

variation represent increases in yield strength over specified minimum values and they should be taken into account to predict realistic reaction loads or pass-through loads from a structural element affected by design basis external human induced events [20].

3.44. In the design of the affected element itself, it is common practice to take credit for the increase in the strain rate yield strength, but not the statistical increase.[19]

INTERACTION EFFECTS

3.45. DBEEs may cause direct damage to the plant: such effects are called ‘primary effects’. In addition they may cause indirect damage (‘secondary effects’) by means of interaction mechanisms that can propagate the damage. This indirect damage should be included in the analysis of the DBEEs as it may cause damage which could exceed that caused by the primary effects. Secondary effects are explicitly addressed in the classification (EE-C2).

3.46. In the systematic analysis of the interaction effects on safety related items and operator actions to be addressed in the design, the following should be evaluated and possibly included in the design basis:

(a) Secondary missiles (such as pieces of metal or concrete scabbed off walls, steel structures or parts of an aircraft itself, typically the engines);
(b) Falling objects loosened as a consequence of vibrations (mechanical interaction);
(c) Failure of high energy pipes and components (see Ref. [7] for an extended discussion);
(d) Flooding, from liquid retaining structures;
(e) Chemical reactions: combustion, release of asphyxiant and toxic substances and corrosive liquids;
(f) Secondary fires from failures of electrical equipment;
(g) Electromagnetic interference (see Ref. [12] for an extended discussion).

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[19] The statistical increase is defined as the difference between the actual value of a material property and the lower bound or minimum guaranteed value assumed in standard references.

3.47. All cascading secondary effects of the failure caused by an EE should be evaluated in the design process. Interaction effects are of such a nature that the potential damage can vary widely. Many factors come into play that are beyond the control of a designer and should be assessed by an appropriate walkdown (see para. 3.20). Because of these difficulties preferred practice should be to emphasize the means of stopping the cascading effect, preferring global protection against the event rather than individual protection from all potential secondary effects.

3.48. Special emphasis should be given to potential interaction effects between UHS components (such as failure of cooling towers and flooding from the UHS basin) and other safety related structures.

3.49. A screening process should be carried out to evaluate the situations that give rise to the need for safety systems to operate as a consequence of interactions from a main DBEE scenario.

3.50. The possibility of a DBEE resulting in common cause failures through interaction effects should be considered.

DOCUMENTATION AND QUALITY ASSURANCE

3.51. The evaluation of a nuclear power plant for protection against external events should be documented in a manner suitable for a detailed technical review of conceptual assumptions and of detailed calculation procedures. As a minimum, the documentation should identify the events considered, their primary and secondary effects (if any) and the basis for determining the adequacy of protection for each case. The technical documentation should allow for a complete record of the data flow among the different design tasks for the purpose of accuracy assessment.

3.52. A technical evaluation should be carried out in accordance with the requirements of the quality assurance programme implemented for the design of the nuclear power plant, as established in Ref. [21].

ACCIDENT MONITORING AND POST-ACCIDENT PROCEDURES

3.53. When a DBEE is deemed to be a sizing scenario for most safety related SSCs, a structural monitoring system (e.g. for displacement, deformation or stress) should be designed, installed and operated to prevent the development of accidents (this is safety related and EE-C1), as support for design confirmation (this is non-safety-related, but EE-C1) and to guide post-event operator actions (this is safety related and EE-C1), as described in Section 2. Such systems should include sensors at the site, in the structure and in some critical equipment.

3.54. When practicable according to event characteristics (e.g. development time and possibility of forecasting), environmental monitoring should be designed, installed and operated to provide adequate warning signals for emergency operator actions for the DBEEs with a relatively slow development time and to support the periodic safety review at the site [13] as confirmation of the site specific hazard. Guidelines for emergency operator action should be developed. Such a system should include sensors at the site and at the potential sources of design basis events. When such a system supports emergency action by the operator, it should be classified as safety related and EE-C1.

3.55. The occurrence of external events significant to plant safety should be documented and reported. An extensive plant inspection after the occurrence of an external event either close to the DBEE or significant to plant safety should be performed in order to assess the behaviour and consequences for SSCs against their safety classification and accessibility and their representativeness of all EE classification items.

3.56. Provisions should be made in the design of the UHS and its directly associated heat transport systems to permit in-service monitoring and inspection so as to provide adequate assurance of its continued functional capability throughout the lifetime of the plant.

3.57. Water levels at intakes, tanks or reservoirs and water or air temperatures should be monitored. Instrumentation should be provided for the heat transport systems directly associated with the UHS to verify performance or to detect failures and malfunctions during system operation. The system flow rate, temperatures and activity, the status of components and other relevant parameters should be monitored.

3.58. The design should also include provisions for periodic testing of the heat transport systems directly associated with the UHS. The design should allow, to the extent practicable, testing of all the systems during power generation or at least during shutdown conditions, to the extent necessary to demonstrate their capability.

4. AIRCRAFT CRASH

GENERAL DISCUSSION

4.1. Reference [2] gives recommendations and guidance for a site specific review of the potential risk of an aircraft crash on the site and the nuclear power plant itself. The result of this analysis, which is based on a screening procedure to identify the potential hazard associated with an aircraft crash, is expressed in terms of either specific parameters for the aircraft (mass, velocity and stiffness) or load–time functions (with associated impact areas).

4.2. In the probabilistic approach for hazard evaluation, this information is complemented by a selected probability limit (value), but it is not to be used in a deterministic design (structural and functional). In the deterministic approach for hazard evaluation, the reference load case may be identified without explicit reference to an aircraft type or to a probability of occurrence.

4.3. SSCs requiring a design for aircraft crash are defined by a safety analysis conducted as specified in Section 2. Section 2 defines the overall safety functions to be performed by the plant. Alternative paths may be selected to achieve satisfactory performance of these functions. Iterations between the designers of the SSCs may occur before the final EE classification of the SSCs is determined.

4.4. All SSCs classified as EE-C1, EE-C2 and EE-C3 should be designed or evaluated for the aircraft crash event. In some cases and for some phenomena, such as overall aircraft impact, selected structures may be shielded by other structures designed to resist the aircraft crash. For these cases, the shielded structure may not need to be assessed with respect to direct impact.

4.5. There is no experience of damage induced by aircraft falling on nuclear islands, although some crashes have been recorded in their vicinity, sometimes with long skidding (300 m) of the engines far from the impact areas, with damage to residential and industrial facilities. Some malevolent and wartime attacks with non-explosive missiles have been recorded: these can be studied for their effects on structures as the effects are expected to be similar to those of aircraft, but this Safety Guide excludes them from consideration in the design.

4.6. Wind induced missiles usually generate effects of the same nature as those of aircraft crashes, but smaller. Reference [2] discusses such enveloping on the hazard side, while provisions in this section could be easily adapted to such load cases.

4.7. Explosion induced missiles could pose serious hazards to the plant. While their source mechanism is discussed in Ref. [2], their design implications could be analysed according to the content of this section, after appropriate adaptation, the aircraft crash being the enveloping scenario in most cases.

4.8. The postulated aircraft crash should be analysed to determine its effects and the steps required to limit the consequences to an acceptable level. In an evaluation for an aircraft crash, the following should generally be considered:

- Global structural damage of the affected structures, including excessive structural deformations or displacements which prevent the structure from performing its function, structure collapse or overturning ('overall missile effects'[20]);
- Functional failure of SSCs due to induced vibrations in structural members and safety related equipment ('global effects'), particularly when safety related items are located close to the external perimeter of the structures;
- Localized structural damage due to the effects of missile impact, including penetration[21], perforation, scabbing and spalling[22], leading to failure of a structural element or of safety related equipment as a result of the effects of primary and secondary missiles ('local effects')[23];
- The effects of fuel initiated fires and possibly explosion on SSCs.

LOADING

4.9. In those cases for which the characteristics of the primary missile (aircraft) and the secondary missiles (engines and landing gear) have to be

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[20] Overall missile effects are those effects that depend to a large extent on the dynamic and other characteristics of the target (an SSC) subjected to impact and that are therefore not limited to the immediate area of impact (e.g. vibration, structural deflection).

[21] Penetration is the state when an impacting missile has formed a notch on the impact face but has not perforated the target.

[22] Spalling is the ejection of target material from an impact face as a result of a missile impact.

[23] A primary missile effect is an effect on a target by either direct strike or ricochet strike from a missile which originates from an initial equipment failure. A secondary missile effect is a subsequent effect due to the consequences of primary missile effects.

defined, the characteristics of the missiles to be defined explicitly include, but are not limited to:

- Class, velocity and impact angles of the aircraft to be considered;
- Mass and stiffness (both are a function of the aircraft length), loading capacity and global ductility or local strain limits of the structural systems or elements of the target structures and of the aircraft;
- The size and location of the impact area;
- Consequences in conjunction with those of a single impact, e.g. debris, secondary missiles or fuel spills.

4.10. In most cases two missiles (the aircraft and the hard missiles such as engines or landing gear) are identified for the maximization of global and local effects respectively, as described in Ref. [2]. For the consideration of the scenario of an aircraft impact close to the site with the hard missiles (typically the engines) skidding against the nuclear islands, the selection of a representative missile, relevant impact area and realistic impact path should be assessed.

4.11. Where a reference load function (force–time history method) is used in the design, the general input information should include:

- the assumed load–time function,
- the size and location of the impact area.

4.12. For impact analysis of stiff or massive structures, load–time functions are generally preferred to define the impulse loading applied to the structure, since the influence of the structural behaviour on the characteristic of the forcing function is expected to be minor.

4.13. For impact on flexible structures, the equivalent load function might be heavily influenced by the dynamic interaction between missile and target, and therefore special attention should be paid to the definition of a representative load function to be applied on the structure.

Use of load–time functions

4.14. Whenever an equivalent load function has to be derived for a missile, it should be derived from a defined aircraft via either an experimental or an analytical approach. Load functions may also be derived from existing data through correlation of the physical characteristics of the missile and its input parameters such as velocity at impact. Very extended experimental programmes have been carried out with true scale aircraft and targets of different stiffness: they should be analysed to provide enough confidence in the reliability of the derived design methods.

4.15. Particular attention should be paid to the nominal target stiffness and general input conditions, which can show large variations in the various locations of the buildings impacted and could differ also from those for the experiment.

4.16. In an analytical evaluation of an equivalent load function, a full non-linear analysis with a flexible target and a deformable missile should be carried out, with a strong emphasis on a sensitivity study of the results to the wide variety of assumptions which usually affect such approaches (e.g. non-linear material properties and simulation of erosion effects). After the simulation, a smoothing process should be applied to the result to filter out as far as possible the unavoidable spurious noise from the numerical integration: attention should be paid not to exclude physical high frequency effects from the load function.

4.17. In both cases (analytical or experimental study), although there is no precise agreement in this respect, the function should be considered an average representation of a transient random load. Any specific realization of such an event (a real aircraft crash) would nevertheless result in a load–time function characterized by short duration spikes, with large amplitudes, distributed throughout the duration of the crash. Although, by definition, the additional total momentum of these short lived spikes should be nil, they may influence the structural resistance to penetration, perforation and scabbing, as well as the induced vibrations, and therefore a separate evaluation should be carried out of their potential effects.

4.18. The derived load functions, having passed through essentially a filtering process, might have introduced a spurious frequency content, particularly in the high frequency range (above 20–30 Hz), with fictitious sharp corners and straight edges. Therefore, in general, engineering judgement should be firmly exercised to determine whether the load function to be applied is really representative of all the effects induced by the aircraft crash on the structures of concern and to select a design process consistent with the load function characteristics.

4.19. Examples of load–time functions, reference missiles and related parameters established in some States for the purpose of specifying the design basis are given in Annex I.

Direct simulation of missile impact

4.20. When a detailed evaluation of local damage is necessary or when the dynamic interaction between missiles and target is expected to be significant, an impact problem should be explicitly solved. The full description of the missile should therefore be available, since the application of an equivalent load function is not representative of the physical phenomena.

4.21. The impact area should be evaluated by assuming a perpendicular impact of the aircraft nose against the surface of interest, as the worst possible case, and estimating the increase in contact area as the fuselage is crushed.[24]

4.22. Attention should be paid to the fact that the aircraft may break up into pieces, each of which may become a separate missile with its own trajectory. An analysis of the missiles that could be produced and their significance should be made on the basis of engineering judgement, with due regard for the possibility of simultaneous impacts on separate redundant systems. In special circumstances the effects of secondary missiles should be considered.

Fuel effects

4.23. The consequences that may result from the release of fuel carried by the crashing aircraft should be estimated on the basis of engineering judgement, according to the following list of potential consequences:

(a) Burning of aircraft fuel outdoors causing damage to exterior plant components important to safety;
(b) Explosion of part or all of the fuel externally to buildings;
(c) Entry of combustion products into ventilation or air supply systems, thereby affecting personnel or causing plant malfunctions such as electrical faults or failures in emergency diesel generators;
(d) Entry of fuel into buildings important to safety through normal openings, through holes which may have resulted from the crash or as a vapour or aerosol through air intake ducts, leading to subsequent fires or explosions.

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[24] In some States, for sites more than 5 km from an airfield, it is recommended to consider an angle between the normal to the walls and the trajectory in the range 0–45°. In other States there is a limitation on the angle between the aircraft axis and the horizon, which is limited to the range 10–45°.

Load combinations

4.24. When the structural analysis is performed, it is not necessary to combine all design loads with the aircraft crash loading. Generally, it suffices to combine with the aircraft crash loading only those loads expected to be present for a significant duration — that is, dead and live loads (not including extreme snow or extreme wind) and normal operating loads.

REFERENCE ANALYTICAL APPROACHES

4.25. The design or evaluation for global structural damage may be performed by one of three methods: energy balance, force–time history analysis or missile–target interaction analysis.

4.26. The energy balance method correlates the initial kinetic energy of the missile with the strain energy of the missile during impact and collapse and the kinetic and strain energy of the target during the impact. This method treats overall behaviour of the system and is helpful for preliminary design considerations. Assumptions on the effective mass of the target and the amount of energy absorbed by the missile during the impact should be developed. Variations of the method use the principles of conservation of momentum and conservation of energy to determine the effective initial conditions of the target so as to determine the overall structural capacity. The method is limited in application to overall behaviour and does not produce detailed results such as time histories of motion for equipment evaluation. It is most applicable to simple configurations of the target.

4.27. The force–time history method applies force–time histories to dynamic models of the target structure to determine structural behaviour (structural deformations and displacements, velocities and accelerations). These histories are generally derived from the characteristics of the missiles, on the assumption of impact on a rigid target. One method of deriving the force–time histories is summarized in Ref. [15] together with numerous force–time histories that have been validated against experimental data and analytical data. Application of these histories to a flexible structure is generally conservative in terms of the evaluation of structural capacity, since accounting for target flexibility reduces the effective load. In addition to the force–time histories, the impacted area should be determined on the basis of the specific characteristics of the missile.

4.28. The missile–target interaction analysis method analyses the impact explicitly with a combined model of the target and missile. Non-linear material behaviour and the geometry of the target and missile are modelled. The impact is defined by the initial velocity of the missile and upon impact the behaviour of the combined system is modelled in the time domain. A simplified form of this method, which approaches the force–time history method, is sometimes implemented, by which, for impact, assumptions as to the behaviour of the missile are made (e.g., energy absorbed by the missile itself during impact), and the dynamic analysis of the target is continued, given the initial conditions of the impact area (initial velocity of the interacting node points). The result of this analysis is the determination of the structural behaviour of the target (structural deformations and displacements, velocities and accelerations).

4.29. In all cases, sensitivity studies should be performed to determine the range of consequences and the most sensitive parameters. In addition, computer codes for non-linear analysis should be validated and verified for analysis of the specific problems identified herein.

DESIGN AND QUALIFICATION

4.30. The postulated aircraft crash should be analysed to determine its effects and the steps necessary to limit their consequences to an acceptable level. The evaluation for an aircraft crash should in general consider:

- Global bending and shear effects on the affected structures (‘overall missile effects’);
- Induced vibrations on structural members and safety related equipment (‘global effects’), particularly when safety related items are located close to the external perimeter of the structures;
- Localized effects, including penetration, perforation, scabbing and spalling, of primary and secondary missiles (‘local effects’);
- The effects of fuel fires and possibly explosions on structural members as well as exposed safety related equipment (ventilation systems, containment openings and air baffles).

Global structural effects

4.31. The global evaluation should include analyses of the potential for significant structural damage due to excessive deformations or displacements, which prohibit the structure from performing its function or cause the collapse or overturning of the structure. The global evaluation should model the propagation of shock waves that could affect items important to safety.

4.32. The impact load is generally assumed to act perpendicularly to the surface of the external structure, which can be directly impacted. A global analysis should be performed to find the displacements in different points of the buildings and to calculate the internal forces in the members not directly impacted. The representation of the impact area and its vicinity is usually done as a substructure of the global model.

4.33. To calculate deflection loads and shear forces, exposed concrete walls are designed by means of either a linear dynamic analysis, or an equivalent static analysis with usual standards for concrete structures using maximum loading resulting from the peak impact force multiplied by a dynamic amplification factor and a plasticity factor. This plasticity coefficient should be determined by calculation and validated by tests. Generally, stresses (normal stress, shearing stress, bending moment and torque) are calculated from the element forces, with the use of local elastic and linear models. The time progression of the impact loading should be taken into account to ensure that the assumed plastic behaviour can occur in the time required.

Vibration effects

4.34. Vibratory loads induced by the impact should be evaluated by means of a specific dynamic analysis of structures and equipment, with account taken of the material properties of reinforced concrete subjected to dynamic loads (stiffness and damping). The floor response spectra should be calculated for all the main structural elements of the buildings which house safety related equipment. Appropriate transfer functions should be evaluated for the estimation of the vibratory action transferred to any safety related equipment. The numerical model should be specifically validated for the dynamic transient analysis, so as to guarantee a proper representation of the vibratory field at least in the frequency range in which the power spectrum of the load function has major contributions.

4.35. For the numerical analysis a load function is usually applied to an elastic model: the impact area and its close vicinity, where most of the non-linear effects are to be expected, should not be included in the evaluation of the results.

4.36. The soil should be represented by a damped spring mass system. For normal foundations and site conditions it is sufficient to consider the average dynamic soil conditions of the site, since the variation in soil properties is expected usually to have negligible effects on such a global analysis.

4.37. The masses of the structural members as well as the dead load of the plant equipment should be taken into account in the numerical model. Fluid stored in tanks or pools can be represented as rigidly connected masses. Actual live loads should be considered rather than the generally assumed design live loading conditions.

4.38. For the calculation of the building responses (motions and internal forces), velocity proportional (linear viscous) damping should be used, with care taken to avoid unreasonable values in the high frequency range.

4.39. The use of a cut-off high frequency in the resulting floor response spectra above a range of 20–30 Hz is accepted in some States. This is generally done where specific structural layouts are well defined and it takes into account high structural damping at such high frequencies and the presence of structural discontinuities. Such use is only allowed when the calculated displacement is lower than a defined acceptability threshold and the motion is propagated over a distance in the structure.

Local structural effects

4.40. Depending on the type of aircraft, the specific location of the impact area and the properties of the wall, the effect of an aircraft impact may be highly non-linear, with a high energy absorption. In all cases, the local effects of the impact generally due to hard missiles (such as engines or landing gear) should be evaluated either by means of using non-linear calculations with limited local deformations at the point of impact or by means of empirical or semi-empirical numerical formulas generated for the specific configuration.

4.41. In the case of a numerical non-linear analysis, the model could be limited to that part of the entire structure that is affected by the non-linear behaviour. The part of the model to be analysed for non-linear behaviour should be extended beyond the impact area, generally to points where appropriate boundary conditions can be applied. The steel reinforcement should be included in the numerical modelling of reinforced concrete targets.

4.42. The simulation should represent the impact between the selected deformable missile and the target. Only if a preliminary evaluation of the relative stiffness has identified a negligible influence of the dynamic interaction of the two bodies, or if it has been determined to be conservative to do so, can the problem be simplified and can a load–time function be applied for the impact area. Extensive engineering judgement should be applied in these cases to assess the representativeness of the solution.

4.43. An alternative approach relies on the application of empirical and semi-empirical analytical formulae, mainly derived for rigid missiles. However, most of the available formulas, having been derived for rigid missiles, tend to overpredict the wall thickness necessary to prevent perforation and scabbing for concrete structures. The ranges of shape, mass, stiffness and velocity for which they were developed do not usually coincide with those of interest in a typical problem of aircraft impact on a nuclear power plant. Therefore, an engineering judgement of the applicability of this type of formula should be extensively applied.

4.44. For the design of local reinforcement for concrete structures, the punching cone geometry is usually defined by the radius of the impact area, by the shell thickness and by the angle of the punching cone.[25]

4.45. The material properties for structural steel, steel reinforcement and concrete to be considered in such evaluations should represent the realistic ductility of the materials (defined by test) and should also include strain rate effects if the impact velocity is compatible with the selected scenario. Safety factors could be increased for direct impact on safety related structures and lowered for impact on sacrificial shielding structures.

4.46. Directly impacted concrete members should be reinforced on both sides, with sufficient stirrups. Plane bearing structures should be provided with mesh reinforcement.

4.47. The reinforcement should be designed according to the minimum and maximum values of the internal forces as calculated from the resulting time history and adequately combined with the other prescribed load conditions.

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[25] A minimum angle of 35° to the perpendicular to the surface is considered in many States.

Fuel effects

4.48. The effects of explosions from fuel, after their quantification, should be taken into account in accordance with to the recommendations provided in Section 5 or in Ref. [6].

4.49. The relevant fire load should be directly related to the amount of fuel carried by the reference aircraft (corresponding to the assumed scenario of take-off, cruising or landing) and to the potential involvement of other flammable material present at the site.

Equipment qualification

4.50. According to the safety classification for the equipment, the vibration induced by the impact of the aircraft should be assessed with reference to the failure mode of the equipment. The external event classification of the equipment should include the required function of the equipment during and after the impact. Fail-safe and reset provisions may be taken into account if appropriate.

4.51. In the event that the equipment is not explicitly qualified for short transient loads but only for steady state vibration in the low frequency range typical of the seismic qualification, a specific qualification programme should be carried out, since no information on the response to impulse loads can be retrieved from the seismic qualification.

4.52. In the event that a qualification programme for shock impulse has been carried out, the cumulated damage of the vibration induced by the aircraft impact should be considered in an evaluation of the equipment's ruggedness.

4.53. The evaluation should cover all the critical failure modes identified in the safety analysis for any equipment: functionality, integrity and stability.

MEANS OF PROTECTION

4.54. Since impulsive loads associated with a design basis aircraft crash may exceed those associated with most natural phenomena or other human induced events, the potential for damage to any item important to safety should be assessed. In general it cannot be conservatively assumed that protection provided for other reasons will suffice to protect against an aircraft crash.

However, comparison with similar effects associated with other events may show that certain potential consequences of an aircraft crash can be withstood by the protection provided for other events.

4.55. When protection against an aircraft crash and its associated physical effects is provided by the design, the different global and local physical effects of the crash should be borne in mind. Global effects (vibration) should be accommodated by means of local or global design measures such as shielding of components, by barriers, by vibration isolation measures, or by providing redundant and sufficiently separated components.

4.56. Global effects should be considered for all components important to safety contained in the affected building. In the reactor building, for example, the vibration induced by an impact would be transferred through the structures or the foundation to the locations of the different components. Engineering evaluations can support a cut-off of analytical values (see para. 4.39).

4.57. Protection measures that could be implemented include: a modification of the vibration path in the structure (through structural discontinuities and/or shielding); a review of the layout of equipment (with safety related equipment placed as far away as possible from potential impact areas); a vibration qualification programme for the equipment; or a local isolation of the equipment support. In this last option (local isolation), special care should be taken to avoid unfavourable modification of the seismic response, which usually dominates the structural response at the lower frequencies.

4.58. Where local structural failure (including scabbing) could impair a safety function by causing damage to equipment important to safety, the following measures should be taken (also in combination):

- The structural resistance of the shielding structure, or its layout, should be improved by increasing the thickness and/or the reinforcement (or the earth covering in the case of underground distribution systems), by adding missile shields or by other appropriate measures;
- Redundant equipment should be located at an adequate distance (physical separation);
- A specific equipment qualification programme should be carried out for the potentially affected items.

4.59. If protective barriers or structures are shown to be insufficient, separation distances should be sufficient to ensure that the system will survive the impact.

These distances will depend on the dimensions of the aircraft involved in the assumed crash and the characteristics of the assumed flight path. As a minimum, the distances should be sufficient to prevent the aircraft impact from reducing the system's capability to perform the safety functions below acceptable levels, for example by redundancy. Intermediate barriers between initial impact surfaces and the systems and components required to perform functions should be evaluated. The combination of the principles of separation, segregation and diversity can help to ensure the performance of SSCs. The spread of fire, in an area much larger than the impact area, caused by burning spilled fuel and burning debris should also be considered in relation to this concern.

5. EXTERNAL FIRE

GENERAL DISCUSSION

5.1. Only a few accidents due to a fire external to a nuclear power plant site have been recorded. Most of these affected the availability of off-site power or threatened operator action owing to the release of smoke and toxic gases.

5.2. Fire that originates outside the site (such as from fuel storage, vehicles, bushes, peat and wood) may have safety significance. Precautionary measures should be taken to reduce the amount of combustibles in the vicinity of the plant and near access routes, or else adequate protection barriers should be installed. For example, vegetation that could propagate a fire in close proximity to the plant should be removed. A specific analysis for coastal sites should consider the potential for burning oil spilled into the sea (by a stricken vessel or an extraction platform). If necessary, appropriate measures for establishing an exclusion zone should be taken. A detailed discussion is provided in Ref. [2].

5.3. At sites for which an aircraft crash scenario is postulated, the crash event is generally associated with the release of significant amounts of fuel, which most probably will be ignited, and this may lead to subsequent explosions. The design measures for such an event generally envelop the provisions necessary to handle other external fire scenarios as mentioned above.

5.4. The plant design should prevent smoke or heat from fires of external origin both from impairing the accomplishment of necessary safety functions and from impairing the stability of safety related structures at the site.

5.5. When an external fire propagates at the site or when a fire is originated at the site but outside the safety related buildings (such as from a transformer, fuel storage or a vehicle at the site), general fire protection measures should be taken, as specified in Ref. [6].

5.6. The ventilation system may be affected by smoke or heat. It should be designed to prevent smoke and heat from affecting redundant divisions of safety systems and causing the loss of a necessary safety function (including operator action).

5.7. Diesel generators usually need air for combustion. The plant design should ensure an adequate supply of air to all diesel generators that are required to perform necessary safety functions.

5.8. Where the site of a nuclear power plant requires consideration of the effects of an aircraft crash at or near the site, a fire hazard analysis of such an event should be made. It should be taken into account in this analysis that fires may occur at several locations because of the spreading of the aircraft's fuel. Smoke may also be produced at several locations. Special equipment such as foam generators and entrenching tools as well as specially trained on-site and off-site fire fighting personnel may be used to prevent such fires from penetrating structures containing items important to safety. (See Ref. [6], Section 2.)

LOADING

5.9. The characteristics of the postulated fire to be modelled may be described as radiant energy, flame area and flame shape, view factor from the target, speed of propagation and duration. Secondary effects such as spreading of smoke and gases should also be specified.

5.10. The effects of an external fire originating from sources such as fuel storage, vehicles, bushes, peat or wood should be combined with normal operating loads. Fires as a consequence of scenarios such as an aircraft crash should be considered in the same load combination and with the same design assumptions (e.g. as external events beyond the design basis, for which the redundancy and single failure criteria may not be followed) as for the initiating event itself.

DESIGN METHODS

5.11. A procedure for safety verification in the event of a postulated fire is to determine the maximum heat flux arriving at the buildings important to safety and to determine whether the barrier resistance provided by the exterior skin of the building (concrete, steel, doors and penetrations) is sufficient.

5.12. The vulnerability of the structures to the thermal environments arising from large external fires should be assessed against the inherent capacity of the envelope of the structures to withstand such environmental condition. The verification should be based on the capacity of the material to absorb thermal loads without exceeding the appropriate structural design criteria. The capacity of the concrete to resist fires is mainly based on the thickness, the composition of aggregates, the reinforcing steel cover and the limiting temperature at the interior surface.[26] The limiting structural criteria may be the temperature at the location of the first reinforcing steel bar and the ablation of the surface exposed to the fire.

5.13. Reinforced concrete structures designed to carry impact loads resulting from an aircraft crash are generally strong enough to resist failures of structural elements that relate to external fire scenarios. In general the capacity of steel structures exposed to large fires is limited. Steel structures directly exposed to external fires should not therefore have safety related functions. If the fire resistance of steel structures relies on separation from external cladding or any applied intumescent cooling, for example, it should be verified that such an improvement in fire protection is not endangered by secondary effects potentially associated with the fire scenario (e.g. explosion pressure waves and missiles).

5.14. Other criteria concerning the interior face and the room air temperature should be assessed in order to protect items important to safety housed in the affected rooms. These criteria are usually not exceeded if sufficient thickness is provided to satisfy other considerations. Design penetrations of all types should also be checked.

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[26] Special care should be taken with regard to the resistance of high strength concrete in fire scenarios.

5.15. In some cases where thick concrete walls or slabs are provided and a fire may occur, a structural analysis should be carried out with the temperature gradient due to fire plus any additional operating loads under fire conditions (e.g. extinguishing water). In accordance with extreme load conditions the load factor of unity may be used under ultimate load design for postulated fire loading conditions.

5.16. Any load bearing concrete structure for the protection of systems important to safety against postulated external fires should have a minimum thickness of 0.15 m for a standard fire of three hours' duration.

5.17. Construction codes generally provide maximum allowable temperatures of materials. As a guideline, the allowable temperature for reinforcing bars and structural steel subjected to short term (less than six hours) fires is 500°C [22]. This value may be used unless a different value is provided by codes or otherwise justified.

MEANS OF PROTECTION

5.18. Protection of the plant against fires may be achieved by minimizing the probability of a fire and by strengthening the barriers against external fires when necessary. Other design characteristics, such as redundancy of safety systems, physical separation by distance, by separate fire compartments or by specific barriers, and the use of fire detection and extinguishing systems should also be provided.

5.19. If the inherent capacity of the structure does not suffice, an additional barrier or distance separation should be provided. An increase in the concrete thickness of the exposed structure may also be considered if this enhances the structural capacity to resist other postulated loads. Additionally, heat resistant cladding or tumescent coatings could be used to provide further protection for structural elements. However, it should be verified that such improvements are not endangered by secondary effects potentially associated with the fire scenario (e.g. explosion pressure waves and generated missiles).

5.20. The ventilation system can be protected by isolation of the systems from outside air by means of dampers with reliance on alternative systems to accomplish the functions of the ventilation system. This can also be achieved by separating the inlet and exhaust hoods of one ventilation system serving one safety system from the inlet and exhaust hoods serving other redundant safety systems. Thus a fire of external origin will not prevent the performance of a necessary safety function.

5.21. The plant design should ensure an adequate supply of air to all diesel generators required to perform necessary safety functions. This objective should be met by segregating the air intakes and separating them by distance.

5.22. Safety related instrumentation and control systems, which have been demonstrated to be particularly vulnerable to smoke and dust, should be qualified for such a scenario.

6. EXPLOSIONS

GENERAL DISCUSSION

6.1. Recent operating experience shows a significant number of on-site explosions generated either by hazardous or flammable material (oil and waste) in storage or by transformers after a short circuit or vaporization of the cooling fluid.

6.2. Explosions during the processing, handling, transport or storage of potentially explosive substances outside the safety related buildings should be considered in accordance with Ref. [2], in which hazard parameters are defined. An analysis of each postulated explosion should be performed to determine the steps to be taken for limiting the effects to an acceptable level.

6.3. Explosions internal to the plant buildings as a consequence of the internal release of gas are usually excluded from the design basis by means of an appropriate qualification of gas retaining structures and therefore they are not discussed here. However, coverage of such scenarios is provided in Ref. [7].

6.4. The word explosion is used in this Safety Guide in a general way for all chemical reactions that may cause a substantial pressure rise in the surrounding space from solid, liquid, vapour or gas, and possibly by impulse and drag loads, fire or heat. Additional details are provided in Annex II.

6.5. According to the combustion mode, an explosion can take the form of a *deflagration,* which generates moderate pressures, heat or fire, or a *detonation* (in which the reaction front advances at greater than sonic velocity) [23], which generates very high near field pressures and associated drag loading: usually thermal effects are present only in the case of special fuel–air mixtures. Whether or not the ignition of a particular chemical vapour or gas behaves as a deflagration or detonation in air depends primarily on the concentration of the chemical vapour or gas present. At concentrations two to three times the deflagration limit, detonation can occur.[27]

6.6. *Explosions of gas or vapour clouds* can affect the entire plant area. Therefore the postulated gas or vapour cloud should be the most severe credible gas or vapour cloud relevant to the site. An analysis of the ability of plant structures to resist the effects of a gas cloud explosion can normally be limited to an examination of their capacity to withstand the overpressure (direct and drag) loading. Other effects should be considered: fire, smoke and heated gases, ground and other vibratory motions, and missiles resulting from the explosion.

6.7. *Solid explosion* properties might be conservatively associated with a trinitrotoluene (TNT) equivalence and with an assumed ground surface location of a detonating substance. The primary effect of a detonation is an overpressure loading, but the drag loading from the wind generated behind the blast wave front should also be considered in the design.

6.8. In general the effects of explosions which are generally of concern when analysing structural response are:

- — incident and reflected pressure (mainly from detonation),
- — time dependence of overpressure and drag pressure,

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[27] The classification of explosions might be very different: a classification more closely related to the physical phenomena associated with different explosion mechanisms is more suitable for a detailed analysis in the presence of high explosion hazards, such as analyses required for chemical plants. In this framework explosive effects should include vapour cloud explosions, confined explosions, condensed phase explosions, uncontrolled chemical reactions, boiling liquid expanding vapour explosions (BLEVEs) and physical explosions; while fire effects should be related to pool fire, jet fire, flash fire and fireballs. These latter effects may or may not be associated with explosive effects, depending on the source and environmental conditions. Here a simplified approach based on the structural effects (which depend on the combustion mode), rather than on physical source analysis, should be taken since the hazard study should detect in advance and mitigate the potential effects of sources close to the site (or even at the site), avoiding the high level of hazard typical of chemical plants, which would require more detailed studies. Consistency with Ref. [2] is maintained.

- — blast generated missiles,
- — blast induced ground motion (mainly from detonation),
- — heat or fire.

The relative importance of these effects depends mainly on the quantity and type of the explosive substances, the distance of the structure under consideration from the source of the explosion, and details of the geometry and spatial arrangements of the structures and the explosive.

6.9. When industrial facilities served by fluid pipelines that are located near a nuclear power plant have been identified as a hazard for consideration in the design, the effects of the rupture of such pipelines should be considered, as explained in Ref. [2]. The analyst should consider the potential for drifting of a gas cloud towards the plant before an explosion.

6.10. While instances have been recorded in which missiles were found thousands of metres from the point of an explosion, it is unlikely that any considerable number of large, hard missiles would be propelled for significant distances as a result of an explosion. If the plant has been designed to accommodate the effects of externally generated missiles resulting from other events such as a hurricane, typhoon, tornado or aircraft crash, the effects of missiles generated by an explosion may already have been taken into account. However, if particularly threatening missiles produced by explosions can be identified, they should be considered in the plant design. If missiles from an aircraft crash or natural phenomena are not included in the design basis, potential blast generated missiles should be considered.

LOADING

Introduction

6.11. *Detonations* in solid material are characterized by a sharp rise in pressure which expands from the centre of the detonation as a pressure wave impulse at or above the speed of sound in the transmission media. It is followed by a much lower amplitude negative pressure impulse, which is usually ignored in the design, and is accompanied by a dynamic wind caused by air behind the pressure wave moving in the direction of the wave.

6.12. Unlike the detonation of solid materials, liquid, vapour and gaseous explosive materials exhibit a considerable variation of their blast pressure output. An explosion of such materials is in many cases incomplete, and only a portion of the total mass of the explosive (the effective charge weight) should be considered in relation to the denotation process. The remainder of the mass is usually consumed by conflagration (burning) resulting in a large amount of the chemical energy of the material being dissipated as thermal energy which, in turn, may cause fires. The discontinuation in the detonation process is caused by the physical and chemical properties of the material, combining of the various physical states, ineffective combining of the fuel and oxidizer and other related factors.

6.13. The forces on a structure associated with a blast wave resulting from an external detonation are dependent upon the peak values and the pressure–time variation of the incident and dynamic wind pressure action, including characteristics of the reflected blast wave caused by interaction with the structure.[28]

6.14. In a gas cloud explosion, the overpressure developed by a detonation is a function of the energy release rate, as well as of the total energy release. Practices vary in different States as regards estimating the overpressure load associated with gas cloud explosions. In view of the results of some accidental explosions, which are thought to have been too destructive to have been caused by a deflagration, it could be useful to consider the assumption of a partial detonation. In either case, the overpressure–time history for a particular structure is heavily dependent on the layout of the surrounding structures. The overpressure should be taken as acting on the exposed surface, with due allowance made for the shape of the structure.

6.15. *Deflagrations* are usually associated with relatively dilute gas or vapour clouds for which most of the chemical energy is dissipated in the form of heat

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[28] Practices in some States suggest that consideration of the design pressure on each part of the structures concerned should take into account reflection and focusing effects, assuming a horizontal direction for the reference wave, without any preferential angle. The maximum overpressure on vertical walls exposed to reflection from higher buildings is taken to be equal to twice the maximum incident overpressure wave value. The maximum overpressure on roofs exposed to reflections from higher buildings is taken to be equal to 1.5 times the maximum incident overpressure wave value. The duration of the overpressure on vertical walls should be assumed to the equal to at least half that of the incident overpressure wave. If multiple reflections are possible, focusing coefficients should be calculated as a function of the building geometry.

rather than blast. The heat loads on a target structure should also be considered. These are a function of the burning characteristics of deflagrating material.

6.16. A deflagration normally results in a slow increase in pressure at the wave front and has a long duration relative to a detonation, with the peak pressure decreasing relatively slowly with distance, whereas a detonation may result in a much higher overpressure with a steep pressure rise and a short duration. A building designed against deflagration may also withstand a detonation with higher overpressure if the overpressure is of sufficiently short duration in relation to the response period of the structure. The rate of decrease of overpressure with distance of travel differs between deflagration and detonation. Near the source, the high detonation peak overpressure decreases quickly with distance. These characteristics, in addition to being functions of the propagation distance, are also influenced by the weather conditions and the topography.

6.17. A major difference between deflagrations and detonations is the heat or fire load on the target structure. In general the heat or fire load from a detonation is not considered a part of the design basis for a target structure but is so considered for a deflagration. This effect should be dealt with on the same basis as fires due to other human induced events. However, particularly in the case of fuel–air mixtures, fire effects associated with a detonation may be significant, and the same provisions should be applied as for deflagrating media.

6.18. Overpressure loads, incident and reflected *and focused*, drag loads if appropriate and heat effects should be combined with normal operation loads.

Detonation

6.19. Various techniques determining loading from explosions (TNT equivalent, multienergy methods, Baker–Strehlow method and computational fluid dynamics) are available, mainly developed for hazard studies for chemical plants [24]. In the case of solid detonation, the TNT equivalent technique is the most widely used approach. In the case of a gas or vapour cloud, the elevation of the explosion and the reaction characteristics may suggest other approaches.

6.20. In the context of design for a nuclear power plant, design and operating experience have shown that explosion hazard has effects close to and often enveloped by those of other hazard sources (such as impacts and wind) and therefore the use of simplified approaches, such as the TNT equivalent, is usually justified if applied to conservative, first order screening type evaluations.[29]

6.21. For the purposes of structural design or evaluation, the variation or decline of both the incident and dynamic pressures with time should be established, since the response of a structure subjected to a blast loading depends upon the time history of the loading as well as the dynamic response characteristics of the structure. The idealized form of the incident blast wave is characterized by an abrupt rise in pressure to a peak value, a period of decay to ambient pressure and a period in which the pressure is below ambient (the 'negative pressure' phase). A simpler representation of only the positive blast pressure phase including reflected wave effects is usually sufficient for the purposes of engineering evaluation.

6.22. An analysis of the ability of plant structures to resist the effects of explosions can usually be limited to an examination of their capacity to resist the free field or reflected and focused overpressure. In estimating the peak overpressure on a structure, the pressure–distance relationships developed for TNT can be utilized for the detonation of solid substances. For solid substances whose energy density differs from that of TNT, factors to be used in calculating equivalent weights of TNT should be recovered from the literature. For substances known to have explosive potential but whose explosive properties have not been investigated and tabulated, it is reasonable, as a first estimate, to assume that their explosive properties are equivalent to those of TNT.

6.23. There are two principal ways of determining the design basis parameters so as to protect the nuclear power plant against unacceptable damage by pressure waves from detonations:

(1) If there is a potential source in the vicinity of the plant that can produce a pressure wave postulated initiating event (PIE) as determined in Ref. [2],

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[29] Special care should be taken particularly in the case of gas cloud explosions as the TNT method overpredicts near field effects and underpredicts far field effects. In some States the application of TNT equivalency is limited to overpressure values of 0.5 bar and other approaches are used for higher values, such as 'multienergy methods' in which the separate effects from pressure and drag wind coming from different explosion cells are accounted for. However, the use of different TNT equivalencies in the near and far fields can overcome such a modelling deficiency. In general, TNT methods are considered suitable for greater distances from the source, for which the source mechanism is less important and such a simplified approach is more realistic and widely valid.

propagation of the wave to the plant can be calculated and the resulting pressure wave and associated drag force will be the basis for the design.

(2) If there is already a design requirement to provide protection against other events (such as tornadoes), a value should be calculated for the corresponding overpressure. This value allows the calculation of safe distances between the plant and any potential source. That is, distances from the source are given at which the pressure wave is calculated not to exceed the overpressure corresponding to the design basis for the other event. This can also be done if there is a design basis for the entire plant against overpressure or if the design basis of the least protected structure, system or component important to safety is known.

Deflagration

6.24. Deflagration loadings are not as well defined as detonation loads. In practice in some States the deflagration loading factors are taken as a fraction of the explosive material at risk consistent with the energy release from deflagration as compared with detonation. In such loading calculations a value between 5% and 10% on weight is used.

6.25. If fire as a secondary effect of the explosion is considered, the recommendations in Section 5 and Ref. [7] should be followed.

6.26. Methods for calculating safe distances and some distance–overpressure relationships, developed from well accepted engineering experience, are provided in Annex II.

DESIGN METHODS AND PROTECTION MEASURES

6.27. Structures will often have been designed to accommodate extreme loadings such as those resulting from aircraft impacts, tornado generated pressure and missile loads or earthquakes. Such structures, with reinforced concrete walls with a minimum thickness of about 0.5 m and with consistent attention paid to structural connections, should be capable of withstanding substantial overpressures without compromising the essential functions of the systems important to safety that they house. It is often unnecessary, therefore, to apply additional design measures to mitigate the effects of design basis external explosions, unless their effects are found to be more severe than those corresponding to the other extreme loadings already considered. Systems such as the emergency power supply that may be housed in relatively light structures, and items exposed in the open, such as parts of the ultimate heat sink, are likely to be more vulnerable to the effects of explosions. These should be evaluated to determine whether there is any need for special design provisions to accommodate safely the effects of any postulated external explosions.

6.28. Protection against the effects of an external explosion can be ensured by designing structures to withstand detonation or deflagration explosion effects, or by requiring a suitable stand-off distance between the explosion source and the target structure to take account of the effect of fire on deflagration heat loading. For each safety function required, the effects of the explosion on either the relevant safety system or component or the housing structures, according to their EE classification, should be analysed. This should include an evaluation of the effects on the air supply and the ventilation system. In most cases, since the system is inside a structure, the analysis should consist of ensuring that the structure is not damaged to the extent that the safety function cannot be accomplished and that any dampers in the air and ventilation systems perform their required safety functions.

6.29. Shielding structures may be considered in the protection against blast wave loading and heat. Such structures are most useful for explosions generated by vessel ruptures or detonations, as their main advantage is to provide missile protection to the buildings (in this case they have to intercept the missile's trajectory) and explosion overpressure protection (in this case the barrier should be close to the protected building to avoid pressure refraction behind the wall). In Annex II an example from common engineering practice of pressure evaluation on a shielding structure is provided.

6.30. When calculating distances necessary to provide protection by means of separation, the attenuation of peak overpressure and heat as a function of distance from the explosion source should be used. The data available for TNT can reasonably be used for other solid substances by using the proper TNT equivalence (examples are provided in Annex II). The adequacy of the protection afforded should be evaluated carefully when the location of the explosion particularly associated with vehicles can vary, as is the case in accidents on transport routes in the site vicinity. A sufficient number of plausible locations for the explosion should be postulated in accordance with Ref. [2] to ensure that the worst credible situation has been analysed.

6.31. The effective loads on structures due to blast and associated dynamic wind loads are a function not only of the dynamic characteristics of the load but also the dynamic response characteristics of the structure, which should be explicitly considered in the analysis. If, for example, the blast wave and dynamic wind load are of very short duration in relation to the natural vibrational period of the structure, the blast wave and wind will pass the structure before it has time to respond to the load.

6.32. Another factor that should be considered is ignition of gas or vapour accumulated in confined external areas of the plant such as courtyards or alleys. Explosions under these conditions may result in high local overpressures. To reduce the likelihood of such explosions, the design should, as far as practicable, provide a compact layout devoid of long alleys and inner courtyards, or provide adequate openings to prevent the development of an explosive concentration of gases.

6.33. In the evaluation of blast damage to structures, a distinction should be made between local and global response of structures. Local response would be associated with response of wall elements relative to their supporting members (girt, purlin, beam and column). For local structural elements the blast and dynamic wind loads are typically associated with only their load on the local structure.

6.34. Design measures include adding supporting members to increase resistance and reduce unsupported spans, using strong backing walls for increased resistance, through bolting of walls to roofs, floors and intersecting walls to improve overall structural integrity, and replacing or reinforcing doors and windows with blast resistant elements.

6.35. Global response is typically associated with the primary load carrying system or members of the structure to include frames, beams, columns, diagonal bracing, shear walls and floor diaphragms which support the overall structural elements. Furthermore, the overall response of the structure to a blast load is a function of the interaction of the blast loadings with the combination or assembly of primary load carrying members. Global structural elements are often engineered for specific loads in accordance with applicable structural codes and standards, and checked to determine their capacity to carry explosive load effects.

6.36. Vibratory loads induced into the building structures by pressure waves should be evaluated and the relevant floor response spectra should be calculated for the dynamic design of components and equipment.

6.37. Large ductile excursions into the ‘plastic’ or inelastic behaviour range of the structural element also have the property of reducing the effective natural vibrational frequency or increasing the fundamental vibrational period of the element. Local architectural elements and in particular non-bearing plaster or masonry walls tend to be rather brittle with little or no ductility. Global structural elements which make up the primary load path for the structure are normally made of reinforced concrete or structural steel, however. Their behaviour, if properly engineered to conventional building code requirements, is normally quite ductile and such an assessment is usually sufficient to prove their capacity. In fact, ductility and frequency effects tend to make primary load bearing elements more resistant to short duration blast loads, of the type associated with chemical detonations, than the local structural elements they support, which should be explicitly assessed.

6.38. Parameters typically necessary to define the response of a particular structure include the duration of the load and the natural period of the structural response, as well as the damping and maximum level of ductility exhibited by the structure during the response. Since the initial peak pulse is the loading of primary concern, damping normally does not play a significant role, unlike response to cyclic earthquake type loads, where damping has a significant effect. From these quantities, by using the blast wave and dynamic wind properties, it is possible to determine the equivalent static load pressure produced by the blast type forcing function, using standard engineering charts, to be checked and validated for the specific application.[30]

6.39. In addition to the energy absorbed by the ductile response of the structure, there is also energy absorbed as various parts of the structure respond to load. This form of energy absorption should be referred to as ‘per cent critical structural damping’ and is the phenomenon which causes cyclic response behaviour gradually to die down.

7. ASPHYXIANT AND TOXIC GASES

GENERAL DESCRIPTION

7.1. Asphyxiant and toxic gases may on release affect the nuclear power plant both externally and internally, damaging or impairing safety related systems and

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[30] In some States, plane reinforced concrete walls may be designed with equivalent static load pressure derived from the maximum overpressure multiplied by a coefficient of 1.4. This coefficient accounts for maximum dynamic amplification (equal to 2) and structural change to the plastic phase (plasticity factor equal to 0.7).

operator action. For example, this may occur by preventing startup of diesel or gas turbine powered equipment where the air intakes to prime movers have been blanketed by high concentrations of non-combustible gas, and by essential plant or control room operators being incapacitated (asphyxiated) or their movements restricted so that they are unable to perform safety related duties.

7.2. Reference [2] provides guidance and recommends procedures for characterizing the releases. The Safety Guide recommends precise identification and assessment of the characteristics of the potential hazard (flow rate, duration of emission and meteorological conditions). There also exist international and national standards and guides laying down requirements on releases.

DISPERSION

7.3. Toxic and asphyxiant gases may be heavier or lighter than air. On release their concentration in air will be high and the density difference will cause the cloud to rise or fall. Atmospheric turbulence will gradually dilute the gas cloud by mixing with air. Special consideration should be given to heavy gas clouds formed by cold gas–air mixtures (like liquid NH_3–air) which could travel far without dispersing. Reference [25] is concerned with the dispersion of gases or aerosols of the same mean density as air. Reference values for the toxicity limits are provided in Annex III.

DESIGN METHOD

7.4. Once a toxic or asphyxiant gas cloud has been postulated, calculations should be made of gas concentration as the cloud drifts or flows across the plant site. Extension of the cloud as well as interaction time should be decided case by case, depending on the source and meteorological conditions. If the concentration outside is known, the time dependent concentration of the gases inside the plant can be calculated, with account taken of air exchange rates.

7.5. To simplify the calculation, it can be assumed that the concentration in the cloud remains constant during the interaction time with the plant. Furthermore, equal gas concentrations in all rooms sharing one ventilation system may be assumed. These assumptions are conservative with regard to estimates of gas concentration but not for estimates of recirculation time or for determining the amount of bottled air supplies necessary: for this purpose, a more refined analysis should be carried out.

MEANS OF PROTECTION

7.6. Concentrations of toxic or asphyxiant gases within the control room area that may lead to loss of the operators' capability to control the plant should be prevented. Acceptable concentration levels for a given interaction time may be derived from industrial standards. Given a known source of toxic or asphyxiant gases, gas detectors should be provided. When gas concentrations exceed the prescribed levels, protective actions should be initiated with due regard to quick acting materials such as chlorine gas. These actions may include filtering the incoming air, prevention of ingress of air during the critical time period by use of recirculation air systems, and use of self-contained breathing apparatus.

7.7. In the most extreme cases a supplementary control room (SCR) remote from the main control room (MCR) and with a separate air supply from dedicated air intakes could provide an alternative location for shutting down and monitoring the reactor. Some types of toxic or asphyxiant gas, such as those that may be released along traffic routes (such as on land, sea, rivers and railways), cannot be identified in advance. Although the provision of detectors capable of detecting all types of toxic or asphyxiant gas is not practical where multiple sources of gases could be a hazard, consideration should be given to providing detectors that would be as versatile as practicable (capable of detecting groups of gases such as halogens or hydrocarbons) and also able to detect a decrease in oxygen levels.

7.8. The routing from the MCR to the SCR should be protected to allow the movement of the operators, or alternative arrangements should be made for personnel access via a control point at which breathing apparatus is issued.

7.9. For such situations, means of protection such as geometric separation of control room air intakes may be necessary; their placement at a high level may also be beneficial, particularly if heavy gas clouds have to be considered. However, the effectiveness of geometric separation may depend upon the ability to detect or otherwise become aware of the presence of a toxic or asphyxiant gas in a timely manner. Thus, selection of a specific means of protection should be performed for each particular site.

8. CORROSIVE AND RADIOACTIVE GASES AND LIQUIDS

GENERAL DISCUSSION

8.1 The release of corrosive gases or liquids (including hot steam and gas) from industrial plants close to the site or in transit, such as in accidents and spills from shipping or trains, constitutes a potential hazard. Leakage of corrosive gases and liquids may also occur from stores of chemicals on the site. Usually, since gaseous releases from such sources are required to be within toxicity limits, which are well below corrosive levels, they will not pose a serious threat to the equipment.

8.2. Among the principal gases for which releases are considered are chlorine, hydrogen sulphide, ammonia and sulphur dioxide. Salt water, carbon dioxide, boric acid and steam used in plant operation may also be considered to be corrosive gases and liquids. Corrosive liquid effluents may have the potential to enter and do damage to the plant cooling system. Additionally, particles from oil spills or corroded pipes may adversely affect the function of heat exchangers, pumps and valves, potentially affecting safety related items.

8.3. The release of radioactive gases and liquids from adjacent operating nuclear units, from vehicles containing new or spent fuel and from other on-site and off-site sources constitutes a potential hazard. The release of radioactive substances may affect the nuclear power plant externally and internally, damaging or impairing safety related systems and operator action.

DESIGN METHODOLOGY

8.4. Reference [2] provides information concerning releases of corrosive and radioactive fluids and recommends procedures for dealing with them. That Safety Guide should be used together with other applicable reference documents for identification of the corrosive and radioactive fluids to be considered in the design of the plant to ensure that the design requirements are met.

8.5. In the case of a cloud of corrosive or radioactive gas or corrosive vapour, the gas concentration inside the plant should be calculated on the basis of air exchange rates, with assumed meteorological conditions taken into account, thus giving a time dependent concentration. Extension and interaction time of the gas or vapour cloud should be determined on a plant specific basis.

8.6. For cases in which a corrosive or radioactive liquid mixed with water may enter the cooling water intake, the time dependent concentration should be calculated on the basis of the concentration in the cooling water just before the intake.

MEANS OF PROTECTION

8.7. Section 7 discusses means of protection for personnel against asphyxiant and toxic gases. This guidance should be followed as appropriate in considering control room habitability issues and other related concerns.

8.8. Corrosive or radioactive fluids may enter the plant via the cooling water system. Special attention should be paid to systems that dissipate heat from the plant.

8.9. Corrosive or radioactive fluids may also enter the plant via ventilation system intakes. Special attention should be paid to releases of radioactive gases to air intakes for the control room and other locations where personnel are present. Special attention should be paid to electrical and electronic equipment, which is known to be vulnerable to corrosion.

8.10. Corrosive fluids may also affect outside areas, such as switchyards, and consideration should also be given to outside electrical and electronic equipment.

8.11. It should be demonstrated that even at the maximum possible rate of corrosion the inspection intervals are such that safety systems could not be impaired to the extent that loss of a safety function could occur before the affected system could be repaired. Protection of systems may be achieved in a number of ways: by preventing standing contact between corrosive agent and corrodible surface; by providing corrosive gas detectors that activate closure valves; by means of protective coatings; by providing additional wall thickness to allow a certain amount of corrosion; or by reducing intervals between inspections. Specific protection measures, possibly by combining some of these methods, should be determined on a case by case basis. In particular cases it might even suffice to keep the air temperature or humidity within specified limits, thus slowing down corrosion rates.

9. ELECTROMAGNETIC INTERFERENCE

GENERAL DESCRIPTION

9.1. The initial assessment, described in Ref. [2], should identify any potential sources of electromagnetic interference that could cause malfunction in or damage to safety related equipment or instrumentation. If such interference is possible, protective measures should be allowed for in the design of the plant.

9.2. Experience from operation indicates that the interference can be initiated by both on-site (high voltage switch gears, portable telephones, portable electronic devices and computers) and off-site (radio interference and telephone network) sources.

DESIGN METHODS

9.3. The safety related equipment sensitive to electromagnetic radiation should first be identified. The equipment should be qualified by testing to show that it can withstand the electromagnetic environment in which it should work. Alternatively it should be shielded or moved from that environment.

9.4. The noise level should be identified for any I&C equipment, even if not safety related, to avoid any potential interaction with safety related items.

MEANS OF PROTECTION

9.5. Protection from on-site sources (high voltage switch gear and supply cables) could be provided by appropriate shielding of the potential sources and by administrative measures (such as in the case of telephones). Protection from off-site interference should be assessed by means of appropriate qualification of equipment [12]. Special attention should be paid to the installation of qualified equipment in order to fulfil the requirements for emissions and immunity.

9.6. For highly sensitive equipment, appropriate cable shielding should be provided, in particular for safety related I&C items.

9.7 Attention should be paid to potential interaction between items via electromagnetic interference, including also non-safety-related items.

10. FLOODS

GENERAL DESCRIPTION

10.1. Reference [3] gives guidance for a site specific review of the potential risk of flooding of a site due to diverse initiating causes and scenarios (and relevant potential combinations), namely:

- Rain precipitation at the site;
- Runoff of water from off-site precipitation;
- Snow melt — seasonal or due to volcanism;
- Failure of water retaining structures (hydrological, seismic and from faulty operation);
- Failure of natural obstruction created by landslides, ice, log or debris jams and volcanism (lava or ash);
- Sliding of avalanches and/or landslides into water bodies;
- Rising of upstream water level due to stream obstructions (see scenarios above);
- Changes in the natural channel for a river;
- Storm surge due to tropical or extra-tropical cyclones;
- Tsunami;
- Seiche, also combined with high tides;
- Wind induced waves.

10.2. All these scenarios induce a transient in water level at the site, static effects (water weight) and dynamic effects (from water, debris and ice).

10.3. Both the external barriers and natural or artificial plant islands should be considered features important to safety and should be designed, constructed and maintained accordingly.

10.4. Any human implemented solution for site improvement (dam structures, levees, artificial hills and back-filling) can affect the design basis for the plant. They are therefore included in a site evaluation framework, as discussed in Ref. [3].

10.5. The so called 'incorporated barriers' directly connected with the plant structures (special retaining walls and penetration closures) are dealt with in Ref. [26], since they are not considered part of the site protection as such.

10.6. There are many operational records of experience of external flood induced accidents in which the functionality of safety related equipment has been impaired. Most of these are related to insufficient measures for site protection, to poor maintenance of the drainage systems and to effects of ice on river sites.

10.7. Much evidence has also been recorded recently on in-leakage, essentially through poor sealing in structural joints or cable conduits and inspec-tion openings. The provisions for such events are mainly design related, but attention should be paid to the possibility of the groundwater table rising as a con-sequence of a flood, as its maximum level is a true design basis for the plant [25].

LOADING

10.8. If external barriers and natural or artificial plant islands are part of the site protection system, the design basis flood for the site affects primarily the site protection structures and the water intake structures.

10.9. As an additional measure against site flooding from off-site sources [3], owing to its 'cliff edge' characteristics in the event of overtopping of protection, the protection of the plant against extreme hydrological phenomena should be augmented by waterproofing and by the appropriate design of all items necessary to ensure the capability to shut down the reactor and to maintain it in a safe shutdown condition. All other systems and components important to safety can be protected against the effects of a design basis flood lesser than the one used for the design of the site protecting structures and essentially related to the performance of the site drainage system.

10.10. Special operational procedures should be defined, on the basis of real time monitoring data for the identified causes of flooding. This approach is acceptable if the following conditions are met:

(1) A warning system is available that is able to detect a potential flooding of the site in sufficient time to complete the safe shutdown of the plant, together with the implementation of adequate emergency procedures;
(2) All items important to safety (including warning systems, powered with a protected off-site power supply) are designed to withstand the flood producing conditions (such as wind and landslides) that are considered characteristic of the geographical region of the site (excluding extremely rare combinations).

10.11. The action of water on the site protecting structures and on the plant structures may be static or dynamic, or there may be a combination of effects. In many cases the effect of ice and debris transported by the flood and the waves (or surge) are important variables in the evaluation of pressure.

10.12. In case of precipitation at the site, only the drainage system may be relied on and therefore an adequate safety margin should be ensured.

10.13. Other factors relating to floods should be considered in the design basis evaluation, mainly for their potential action on the plant operation and the integrity of water intakes and protection structures. These are:

- Sedimentation of the material transported by the flood, usually occurring at the end of a flood (such as on estuaries);
- Modification of water salinity;
- Erosion of the front water side and of the site boundary in general;
- Blockage of intakes by ice or debris;
- High mud content suspended in the water [3].

10.14. The design basis flood should be appropriately combined with all the various design basis events generating the flooding itself [3].

10.15. Availability of cooling water and drought hazard can be evaluated with methods similar to that presented in Ref. [3] for flood.

DESIGN METHODS AND MEANS OF PROTECTION

10.16. Site protection measures are discussed in Ref. [3] as part of the site qualification procedure and conditions affecting the definitions of the design basis flood itself.

10.17. In general all EE classified items should be protected against flood either by protecting structures or by adequate drainage systems, active or passive. Their functionality during a flood accident should be guaranteed as part of the defence in depth approach, through an adequate environmental qualification programme.

10.18. Adequate emergency procedures should be implemented on the basis of the environmental monitoring and the structural monitoring of the flood protection items. Communications should be established with any flood warning systems in the vicinity to enable the plant to be put in a safer condition where appropriate.

11. EXTREME WINDS

GENERAL DISCUSSION

11.1. Reference [4] gives guidance for a site specific review of the potential risk of tropical (typhoons and hurricanes) and extra-tropical cyclones, both generated on the ground (tornadoes) and on seas or large water bodies (waterspouts).

11.2. In this section, only wind coupled with abrasive effects by sand and dust or corrosive attack by a salty atmosphere are discussed: related effects such as rain and wind induced missiles are dealt with in other sections.

11.3. Operating experience in nuclear power plants has shown that extreme winds mainly affect the power supply and availability of the electricity grid; however, sometimes, damage is sustained to the switchyards. The accidents typically evolved into turbine trip and loss of off-site power. In a few cases the pressure differential created some false signals to instrumentation. At sites close to the marine environment, heavy salt sprays from the sea in the form of a precipitation during the most violent phases created shocks in exposed electrical equipment (bushings and switchgears) and, later, deep corrosion and malfunctions.

11.4. High winds have been known to cause collapse of cooling towers as a consequence of a ‘group effect’, while they were individually designed to withstand an even higher wind speed.

LOADING

11.5. The derivation of wind and pressure profile is discussed in Ref. [4]. The evaluation of the local wind and pressure on the building should be carried out with reference to the movement of the originating cyclone, it being borne in mind that the damaging effects of such strong winds are produced by a combination of their strength, their gustiness and their persistence. These quantities should be included in the loading parameters.

11.6. The group effect from the combination of the influence of neighbouring buildings should always be evaluated [4].

11.7. Standards and codes developed for the effects of winds on normal buildings should be used for the evaluation of the local effects, with special care taken for the dynamic effects exerted by the wind on the roof, curtain walls and glass openings. The reference values for nominal wind velocity should be consistent with the selected DBEE policy.

11.8. The combinations of wind induced loads with other design loads should reflect the characteristics of the maximum probable cyclone, as described in Ref. [4].

DESIGN METHODS AND MEANS OF PROTECTION

11.9. Wind can affect the structural integrity of light surfaces, but can also be the root cause of dangerous effects other than missiles and rain as discussed in the appropriate sections. The pressure differential could affect the ventilation system; dust and sand carried by the wind could damage exposed surfaces and prevent the functioning of components and equipment. Salt water precipitation could jeopardize the functionality of electrical equipment.

11.10. Extreme winds can give rise to high local pressure gradients and also to missiles that could affect the performance of cooling towers. However, extreme local pressure gradients are expected to be transitory and their effects are not expected to lead to unacceptable reactor conditions. This assumption should be evaluated with care.

11.11. The UHS and its directly associated transport systems should be examined to ensure that any changes in water level caused by an extreme wind cannot prevent the transport and absorption of residual heat. Credible combinations of effects should be considered when appropriate.

11.12. The interaction effects from wind on safety related structures could be of concern: heavy and high rising cranes parked outside the containment might fall over, as well as chimneys and cooling towers. A dedicated analysis should be carried out and adequate separation provided in case they represent a hazard.

12. EXTREME METEOROLOGICAL CONDITIONS

GENERAL DESCRIPTION

12.1. Reference [4] gives guidance for a site specific review of extreme meteorological events, grouping the following natural hazards:

- extreme temperature,
- extreme atmospheric moisture,
- snow precipitation (also blizzards) and ice pack,
- lightning.

Other hazards may be connected with these, such as frazil ice, frost and hail.

12.2. Most of these hazards affect very specific plant systems and are not usually considered in the structural integrity evaluation of the buildings, namely:

- The availability of the UHS, as discussed in Ref. [9], which is mainly affected by ice and drought;
- The availability of off-site power, as discussed in Ref. [11], which is mainly affected by wind, snow, frost and lightning;
- The functionality of safety related equipment, and particularly the I&C equipment, as discussed in Ref. [12], which is mainly affected by temperature, moisture and lightning.

12.3. Extreme low temperature has been the root cause of many malfunctions in nuclear power plants, particularly affecting I&C systems, which on many occasions have generated spurious signals. Low temperatures have at times created moisture condensation in closed rooms, with consequent dropping of water onto electrical equipment causing short circuits and malfunctions. Low temperatures have also prevented the air ventilation system of some nuclear power plants from working properly, hindered proper operation of diesel generators where the fuel showed separation of paraffin, damaged the external power supply system and limited the availability of service water.

12.4. Snow induced damage is usually represented by the unavailability of the power supply or the electrical grid, but snow could also affect ventilation intakes and discharges, structural loading, access by the operator to external safety related facilities and mobility of emergency vehicles.

12.5. The damage caused by lightning has been shown to be very extensive: it has mainly affected electrical equipment, but very often developed into explosions of transformers, serious fire accidents and spurious signals to valves with consequent flooding and loss of off-site power.

LOADING

12.6. The definition of the environmental parameters follows the evaluation of the extreme values for the quantities of interest, which define also the duration of such conditions, their periodicity and their reasonable combination with other load cases, such as wind or precipitation, and biological conditions.

DESIGN METHODS AND MEANS OF PROTECTION

12.7. Structural design should follow the standards and codes for conventional buildings, while equipment should be qualified according to its safety and EE classification.

12.8. Special protection from lightning should be designed and implemented, with periodic assessment of a proper earthing system and regular inspections of the insulation of exposed equipment. In general a comprehensive Faraday cage should be put in place by means of narrow mesh thin rebars in the outer skin of the building walls. Moreover, special care should be taken in the protection of conductors at short distances from each other and/or protruding from the cage protected volume.

12.9. Intake structures for the heat transport systems directly associated with the UHS should be designed to provide an adequate flow of cooling water during seasonal water level fluctuations, as well as under credible drought conditions.

12.10. Due allowance should be made for the effects of extreme weather conditions on make-up supplies, even when these do not necessitate any extensive off-site capability. Thus such aspects as freezing of supply pipework should be considered and trace heating provided where appropriate.

12.11. Measures should be taken, by testing and/or analysis, to confirm that the facilities provided to reject heat to the UHS still retain their capability under extreme meteorological conditions, particularly if there are long periods when the facilities are not used. These measures would include, for example, monitoring the operability of spray nozzles to check that they do not become frozen or intake screens blocked by ice.

12.12. Alternative path(s) for water cooling should be provided to counter the formation of frazil ice at the service water intake, if justified by site conditions. In this case, provision should be made for adequate instrumentation and alarms and relevant procedures and training.

13. BIOLOGICAL PHENOMENA

GENERAL DESCRIPTION

13.1. Biological phenomena mainly affect the availability of cooling water from the UHS and the service water system as consequence of excessive growth of algae, mussels or clams, or clogging by exceptional quantities of fish or jellyfish. Very often malfunctions have also been recorded in ventilation systems because of clogging by leaves or insects in the filters. In some cases, attacking of I&C cables by rats and by bacteria have been recorded. Corrosion effects and accelerated ageing of steel structures exposed to the marine environment can be induced by sulphate reducing bacteria.

13.2. Reference [9] provides guidance on how to deal with such hazards in the design of specific safety related systems.

13.3. Such scenarios have usually been found to be combined with flooding, which can cause the sudden removal of marine growth (deposited in different areas) and clogging into the water intake, and strong winds which can cause the clogging of air intakes by leaves or insects in unusual seasonal conditions.

13.4. Recently some biological contamination problems have been recorded in the UHS of modern power plants, mainly owing to the warm temperature, which facilitates the rapid growth of dangerous and infecting bacteria.

DESIGN METHODS AND MEANS OF PROTECTION

13.5. Analysis of the environmental conditions should be the starting point for the evaluation of such hazards. An inspection regime should be established which takes due account of the need for passive or active control measures and of the rate of growth of the biological matter.

13.6. Specific design provisions should be set up to prevent the clogging of air and water intakes. Screens or redundant paths for clean cooling water for safety related heat exchangers should be provided to protect against failures of intake.

13.7. Measures should also be taken to exclude vegetable matter and other organisms from entering cooling systems. Major blockages may occur as the result of rare accumulations of vegetable matter or seaweed loosened by a storm, shoals of fish which can rapidly block the screening systems, or flotsam of a biological or manufactured type. The intake structure should be designed to inhibit marine organisms and plant life from approaching close enough to be caught in the suction flow and trapped against the intake screens. Alternative intakes may be considered.

13.8. Fixed screens may be provided on the intake canals or at the pump house to prevent the ingress of large fish or clumps of seaweed. The outer screens should be designed with sufficient strength to prevent large debris, mammals, fish and alligators or other reptiles from entering the cooling water system. In addition a second screening stage using such measures as rotating drum screens should be considered to provide further cleaning of the intake water. A third stage of filtration using fine strainers is also likely to be needed.

13.9. Despite these precautions, a total blockage may still be possible. If the type of event postulated extends over a considerable surface on the site or shoreline, even alternative intakes might not suffice to prevent the blockage. For such events, a diverse UHS or water intake should be provided.

13.10. Cooling water used in condensers and in heat transport systems directly associated with the UHS should be adequately treated in order to inhibit the growth of organisms within cooling circuits. Further design features should be provided to ease the cleaning of air and water intakes.

13.11. There should be provision for frequent biological monitoring of the UHS to give early warning of changes which might significantly affect its performance. For example, the introduction of new strains of seaweed with different growth habits or greater tolerance to cooling water conditions can affect the availability of water.

13.12. Dedicated operating and maintenance procedures should be developed for the proper monitoring of the phenomena and the prevention of induced accidents. Active control measures may involve treatment using biocides or the use of sacrificial systems.

14. VOLCANISM

GENERAL DESCRIPTION

14.1. Volcanism can affect the site acceptance phase but can also be the source of design basis events.

14.2. The manifestation of volcanic activity that may affect the site can be listed as follows [27]:

- Launching of ballistic projectiles;
- Fallout of pyroclastic material such as ash or pumice;
- Lava flows, including debris avalanches, landslides and slope failures;
- Lahars, maars and floods induced by snow melt;
- Air shocks and lightning;
- Release of gases (including 'glowing avalanches');
- Earthquakes;
- Ground deformation;
- Tsunamis;
- Geothermal and groundwater anomalies.

A detailed description of such phenomena is provided in Ref. [27].

14.3. No operating nuclear power plant has yet suffered from strong volcano induced effects (only ash rains and earthquakes have been recorded), but in some States it is planned to build new plants in rather volcanic areas, where such issues should be an essential part of the considerations for the design basis.

LOADING AND MEANS OF PROTECTION

14.4. Most of the volcano induced scenarios can be treated in the same way as similar scenarios initiated by other root causes. This is the case for projectiles, floods, earthquake and tsunamis, hazardous gases, landslides and lightning.

14.5. Some other scenarios are more specific: ash precipitation, for example, is one of the most widespread phenomena and can cause a static load over the roof, but can also cause clogging of air and water intakes for particular combinations of particle size, density and accumulation rate. Operator access to safety related external facilities could also be impaired in the event of deep ash drifts.

14.6. Debris flow and floods can threaten the site, which should be protected from the preliminary siting phases, for example with the design solution of the 'dry site'. In any case the design against such phenomena should take into account the extremely short warning time available after the onset of the phenomena, which excludes any defence based on operating procedures alone and therefore necessitates specific passive design protection measures such as protecting walls, trenches and dykes.

14.7. Such load conditions for the plant should not be combined with other extreme scenarios, but a realistic combination of the design loads for the plant originating from the same volcanic source should be specified (gases, floods, missiles and earthquakes).

14.8. A key component of the plant protection system is the monitoring system, usually in operation before the siting phase, which should be maintained and operated throughout the plant's operating lifetime, with specific procedures for alerting and evacuation. It should have some basic components for the measurement of microtremors, ground deformation, weight (gravimetry), geomagnetism, volcanic gases, and groundwater level and properties.

15. COLLISIONS OF FLOATING BODIES WITH WATER INTAKES AND UHS COMPONENTS

GENERAL DESCRIPTION

15.1. According to Refs [2, 3], water intakes and UHS structures[31] can be damaged by ship collision, ice or floating debris. Associated phenomena in the

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[31] The main components of a UHS (both active and passive) usually include water intakes, water ponds, cooling towers, heat transport systems and pump houses.

event of a ship collision should be considered, such as oil spills or releases of corrosive fluids, which could affect the availability or quality of cooling water.

15.2 The UHS and the water intake for service water are exposed to the same DBEEs identified for the safety related buildings at the site, but their design in relation to external events may present some peculiarities owing to the fact that some components may be beyond the site boundary and they can be spread over a wide area.

15.3. Recent experience from operation shows a significant number of occurrences of damage to water intakes and UHS components: ice blocks and floating debris have damaged water intakes, pump houses were flooded and there was some have damage to cooling towers, often associated with flood debris and low temperatures (see also the relevant sections).

LOADING

15.4 The collision of floating bodies with water intakes and UHS structures either is the result of specific scenarios (e.g. a ship collision) or is associated with more complex external event scenarios (e.g. ice and logs during a flood) as described in Refs [2–4]. Loads from colliding ships and/or impact of debris ice may be combined with other loads depending on the originating scenario (mainly flooding according to experience).

15.5. For sites for which a safety related intake of water from navigable water bodies is designed, the effects of shipping accidents on the capability to provide the UHS safety function should be considered [2]. Of primary concern is the potential for blockage of the intakes of the heat transport system directly associated with the UHS, which might be caused by sinking or grounding of ships or barges, and the resulting obstruction of intake structure bays, canals or pipes that provide a conduit for water to the intake.

DESIGN METHODS

15.6. The design against ship collision should be capable of providing an adequate level of performance under various environmental conditions and for all the related potential consequences, such as oil spills or releases of corrosive fluids.

15.7. For debris and ice, the dynamic action derived from the event analysis should be applied to the structures that should guarantee integrity, but also the availability of water to the plant should be investigated.

15.8. For coastal sites, adequate protection measures should be designed according to the codes and standards developed for the traditional mooring and ship protecting structures.

MEANS OF PROTECTION

15.9. The survivability of the SSCs important to safety associated with the water intakes should be based on considerations relating to separation by distance, diversity or redundancy, or by specific design.

15.10. Where a potential direct collision with the intake structure is of concern, measures should be taken to maintain the supply of cooling water and UHS safety functions. Examples of these means are as follows:

- Collisions may be prevented by providing protective structures, such as piling — properly engineered fenders or chains of adequately spaced vertical cylinders fixed at the bottom of the waterway and arranged so as to prevent the approaching vessel from colliding with the protected structure. Similar systems could also be developed to mitigate the consequences of debris impact or buildup of ice.
- The intake structure itself may be designed to withstand the effects of the impact without loss of function. The effects of a collision on components of the heat transport systems directly associated with the UHS should be considered in their design.
- The design should be capable of providing an adequate level of performance under various environmental conditions and for all the related potential consequences, such as oil spills or releases of corrosive fluids. In the case of liquids which readily mix with the intake water and which could result in damage to the heat transport system or could seriously degrade the heat transfer capability, adequate provisions should be made. For oil spills, protection can be provided by the proper submergence of pump intake parts. However, in cases involving shallow submergence, special measures such as booms or skimmers which keep the oil at a safe distance from the pump intake parts should be implemented. Such measures may also be necessary if the potential for ignition of the oil or other fluid is of concern.

15.11. If blockage of an intake is possible to the extent that the minimum heat transport system flow that is required cannot be ensured, then either redundant means of access to the UHS or diverse means of fulfilling the design objective for the UHS should be provided. In the event of a ship collision associated phenomena should be considered, such as oil spills or releases of corrosive fluids which could affect the availability or quality of cooling water.

15.12. In the case of a significant hazard for ice, the static and dynamic action on the intakes derived from debris and ice should be considered. Alternatively a different method of providing cooling water to the plant could be provided,[32] for example from a different source or by a closed loop air cooled system.

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[32] For example, pumping (warm) cooling water from a discharge basin when ice clogs the intake screens is the practice in some States.

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Annex I

AIRCRAFT CRASHES

The experience in some States is collected here for easy reference to current engineering practice since experimental data are not easily available and numerical simulation results are often affected by intrinsic difficulties in their own validation.

LOAD FUNCTIONS FROM REAL AIRCRAFT

I-1. Some examples of load–time functions are derived for an impact normal to the target surface of the shell or plate under consideration. A stable and stiff structure is assumed. An impact velocity of about 100 m/s is generally used because this velocity is not exceeded in the normal takeoff and landing of commercial aircraft and no records of accidents with large aircraft within a certain distance of an airport have shown higher velocities. However, if the probability of impact during a particular phase of flight is not low enough, then such an impact needs to be taken into account with the appropriate speed. In this regard, an impact velocity of about 215 m/s is used in some States for the flying conditions of a military aircraft.

I-2. Some load–time functions for large commercial aircraft have been derived. Load–time functions for the Boeing 720 and 707-320 at a typical velocity for landing and takeoff (100 m/s) are provided in Figs I-1 and I-2.

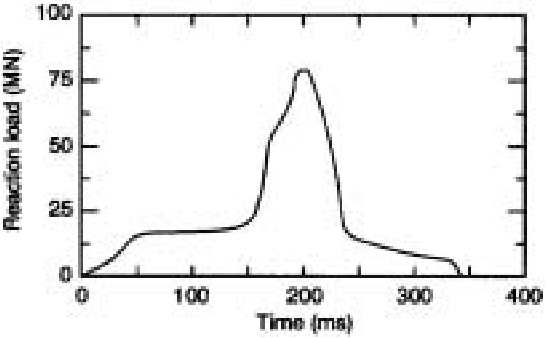

FIG. I-1. Load–time function calculated for a Boeing 720 airliner (adapted from Ref. [I-1]).

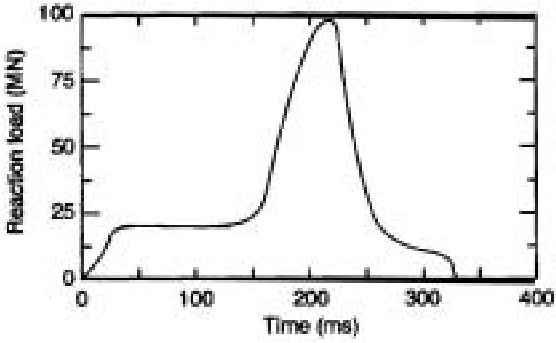

FIG. I-2. Load–time function calculated for a Boeing 707-320 airliner (adapted from Ref. [I-1]).

I-3. For use of these load–time functions for structural analysis, the impact area should be known. Figure I-3 gives the area as a function of time during impact for a sample aircraft. The average values of the impact area chosen for the calculations were about 37 m^2 for flat surfaces and about 18 m^2 for spherical surfaces.

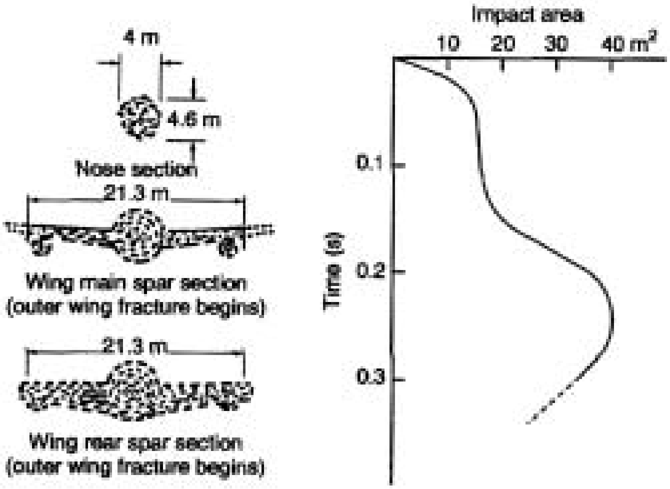

FIG. I-3. Impact area calculated as a function of time for a Boeing 707-320 airliner (adapted from Ref. [I-1]).

I-4. Another load–time function that was originally derived for the crash of a military aircraft (RF-4E Phantom with an impact velocity of 215 m/s) is shown in Fig. I-4. The effective impact area for this event was determined to be 7 m^2. This load–time function covers a wide range of military and commercial aircraft.

I-5. Other load–time functions that have been derived to deal with the impact of two civil aircraft, a Cessna 210 and a Learjet 23, are shown in Fig. I-5 for an impact velocity of 100 m/s. The average impact areas chosen for the calculations were about 4 m^2 and 12 m^2, respectively. A comprehensive set of load functions is presented in Ref. [I-5] for different aircraft and impact conditions.

UNIFIED LOAD FUNCTIONS

I-6. An example of a unified load function, not related to any specific aircraft, is provided in Fig. I-6. It represents an agreement between many European utilities for a unified nuclear power plant design [I-4].

I-7. Another approach, also not related to a specific aircraft, has been defined for the European pressurized reactor [I-6]. This approach leads to a bunker type layout (see Fig. I-7), which can survive a wide range of scenarios relating to the potential crash of a military or large commercial aircraft.

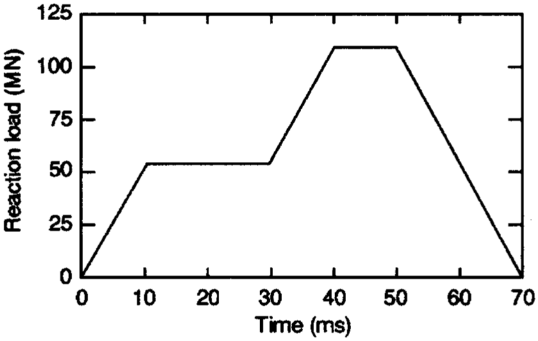

FIG. I-4. Idealized load–time function for an RF-4E Phantom military aircraft (adapted from Ref. [I-2]).

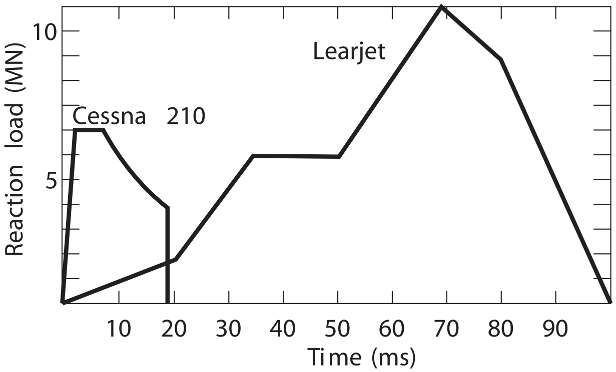

FIG. I-5. Idealized load–time function calculated for a General Aviation Learjet 23 and a Cessna 210 aircraft (adapted from Ref. [I-3]).

I-8. The outer walls of the reactor building, the fuel building and two of the four safeguard buildings of the European pressurized reactor are designed against penetration. For these buildings, the internal structures are decoupled from the outer walls in order to reduce induced vibrations, and the fixing of sensitive or safety relevant systems onto the outer walls is avoided.

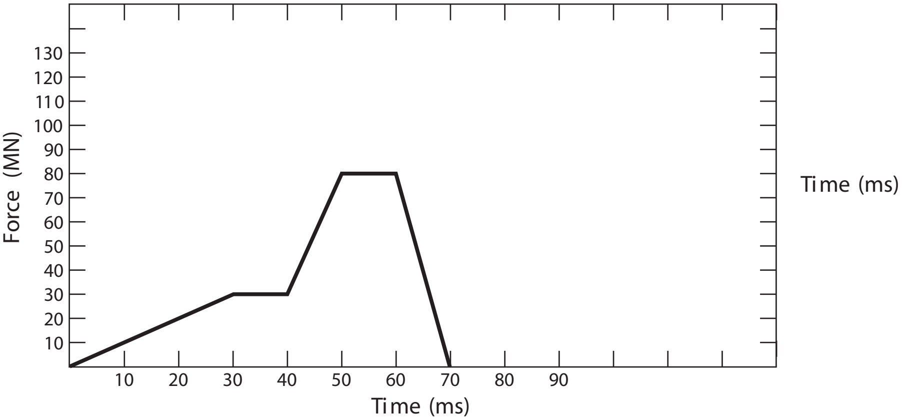

FIG. I-6. Unified load–time function for the structural design of unified nuclear power plants with pressurized water reactors (adapted from Ref. [I-4]).

I-9. The design is based on the load–time diagrams C1 and C2 (see Fig. I-8) applied to a circular area of 7 m^2, with the aim of ensuring the protection of equipment needed to shut down the reactor and to prevent core melt without redundancy:

- The load–time diagram C1 is used for the design of the inner structures of these buildings against induced vibrations, on the assumption of linear elastic material behaviour and impact in the centre of each outer protecting wall. The corresponding floor response spectra to be considered for equipment design are generated for the main structural elements of the buildings only.
- Regarding protection against penetration, the load–time diagram C1 is used for the design of the outer shells of the same buildings against the direct impact loads, so as to ensure that neither penetration nor scabbing occurs and that deformation (of rebars and concrete) is limited.
- In addition, the load–time diagram C2 is used for the design to the ultimate limit state of:
  (a) the reactor building so as to ensure that perforation is prevented and scabbing that could occur would not jeopardize the shutdown of the reactor and the prevention of core melt,
  (b) the fuel building so as to ensure that there is no uncovering of the spent fuel.

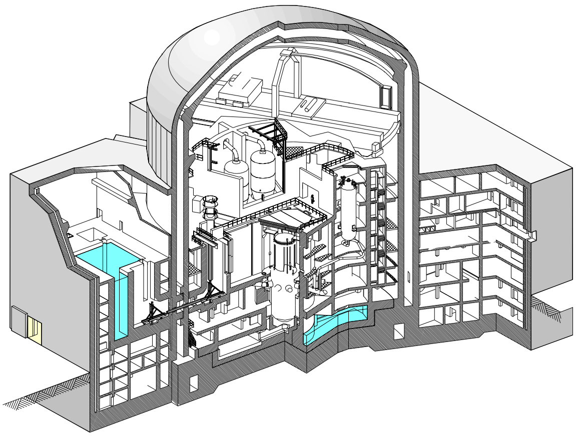

FIG. I-7. European pressurized reactor: outer shells for protection against aircraft crashes [I-6].

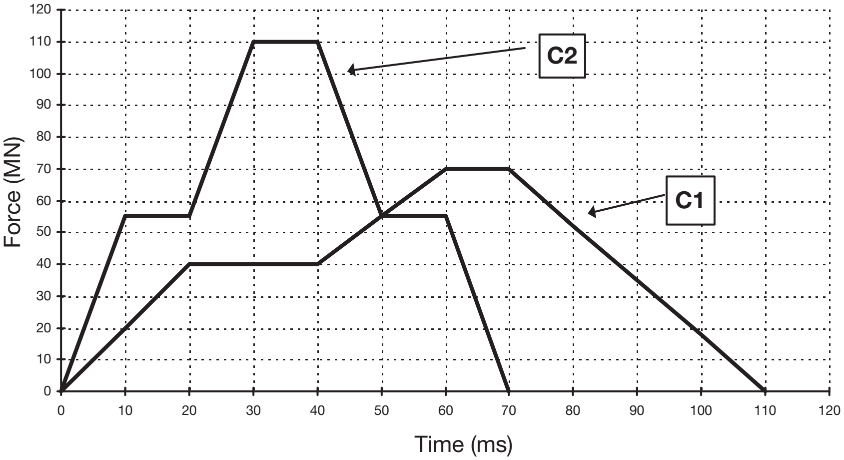

FIG. I-8. Load–time diagrams.

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Annex II

DETONATION AND DEFLAGRATION

INTRODUCTION

II-1. The experience in some States is collected here for easy reference in a discipline in which chemistry, physics and engineering have to be considered in providing a consistent approach to the plant design, and which is not easily recovered from the literature and not usually oriented to the design of nuclear power plants.

II-2. Explosion as defined here consists of detonation and deflagration. The difference between a detonation and a deflagration is primarily the burn rate of the explosive material in question. In general, solid detonating materials have burn rates in excess of 4000 m/s. The characteristics of several detonating types of solid explosives are given in Table II-I.

II-3. Deflagrating materials are typically in gaseous or vapour form. Whether they detonate or deflagrate depends primarily on the concentration in air of the gas or vapour. In general there has to be a threshold volume of explosive gases or vapours in air before a deflagration can occur. Annex II is applicable primarily to conservative first order screening type evaluations. In cases where loads of these types govern design, more rigorous design procedures are recommended [II-1–II-4].

DETONATIONS

Solid material

II-4. A relationship between peak blast wave incident or side-on pressure and dynamic wind for a TNT equivalent detonation is shown in Fig. II-1. The limiting design basis wind loading (exclusive of tornado prone regions) is typically less than about 3 kPa, which compares with a peak blast wave pressure of 30 kPa as defined in some States. For structures less than 50 m in depth (parallel to the direct blast wave travel) the dynamic wind loads are usually ignored. For side-on or incident blast waves with peak pressures greater than 30 kPa or for structures greater than 50 m in depth, dynamic wind effects and the timing relationship with the passage of the blast wave should be evaluated.

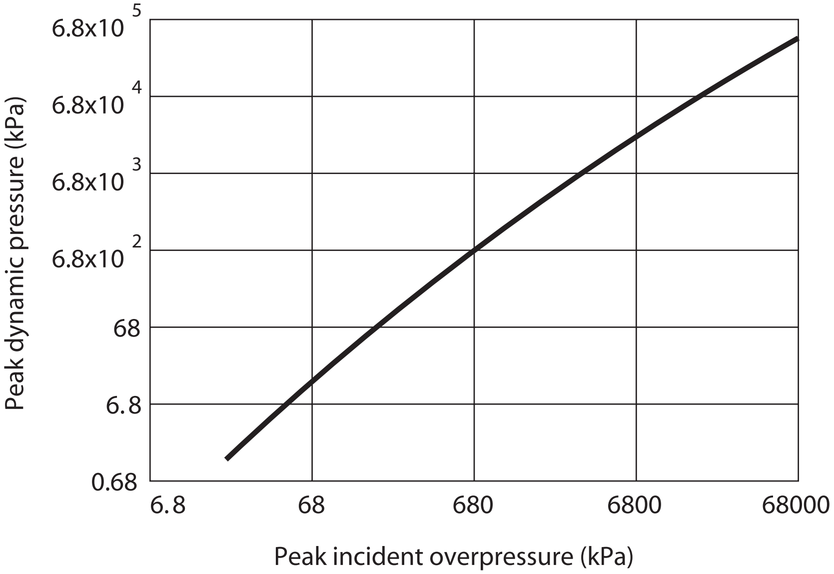

FIG. II-1. Peak incident overpressure versus peak dynamic pressure (kPa).

II-5. When the blast wave impulse encounters an obstruction it results in a reflected wave typically two to four times the magnitude of the side-on peak pressure, but of shorter duration, impinging on obstructions perpendicular to the free field or side-on blast wave's direction of travel. As the positive blast wave traverses a building structure, in addition to the reflected pressure on the windward side, it exerts a positive pressure on all walls and the roof of the structure as it passes. Dynamic winds following the blast wave exert a positive pressure (inward) on the windward wall and negative pressures on the side and leeward walls and roof.

II-6. The design parameters for some solid detonation type TNT equivalent explosions are indicated in Table II-1. Simplified versions of the charts used to compute the associated design values are shown in Figs II-2–II-4 [II-3, II-5].

Detonation of gas and vapour cloud

II-7. Although vapour cloud explosions have received considerable attention, most attention has been focused upon phenomenology; few experimental pressure–time data have been reported. Some empirical models are based upon

TABLE II-1. CHARACTERISTICS OF DETONATING TYPE SOLID EXPLOSIVES

Name	Relative effectiveness as external	Velocity of detonation (m/s)
TNT	1.00	7000
Ammonium nitrate[a]	0.42	4500
Dynamite (commercial)		
40%	0.65	4500
50%	0.79	5500
60%	0.83	5800

[a] Ammonium nitrate, with the addition of certain widely available materials, can result in a relative effectiveness as an external charge equal to 1.07 times that of TNT.

measurements obtained from devices using either ethylene oxide or propylene oxide as the detonating material. The fuel is dispersed into 'pancake shaped' aerosol clouds prior to detonation. The L/D (height/diameter) ratio of the clouds is usually between 0.15 and 0.20. These models are based on data from firings of a large number of devices with gas or vapour weights ranging from 1.5 to 720 kg. The resultant design parameters are presented in Refs [II-3, II-4].

DEFLAGRATIONS

II-8. Provided that a deflagration mode can be guaranteed, in most cases it is permissible to reduce the weight of deflagrating material to one tenth of its actual weight, as suggested in Ref. [II-3], for the purpose of determining the deflagration blast wave pressure.

DESIGN OR ANALYSIS OF SSCs TO RESIST BLAST WAVES

General

II-9. The resultant simplified shock loadings for a TNT equivalent ground surface detonation are shown in Figs II-2–II-4.

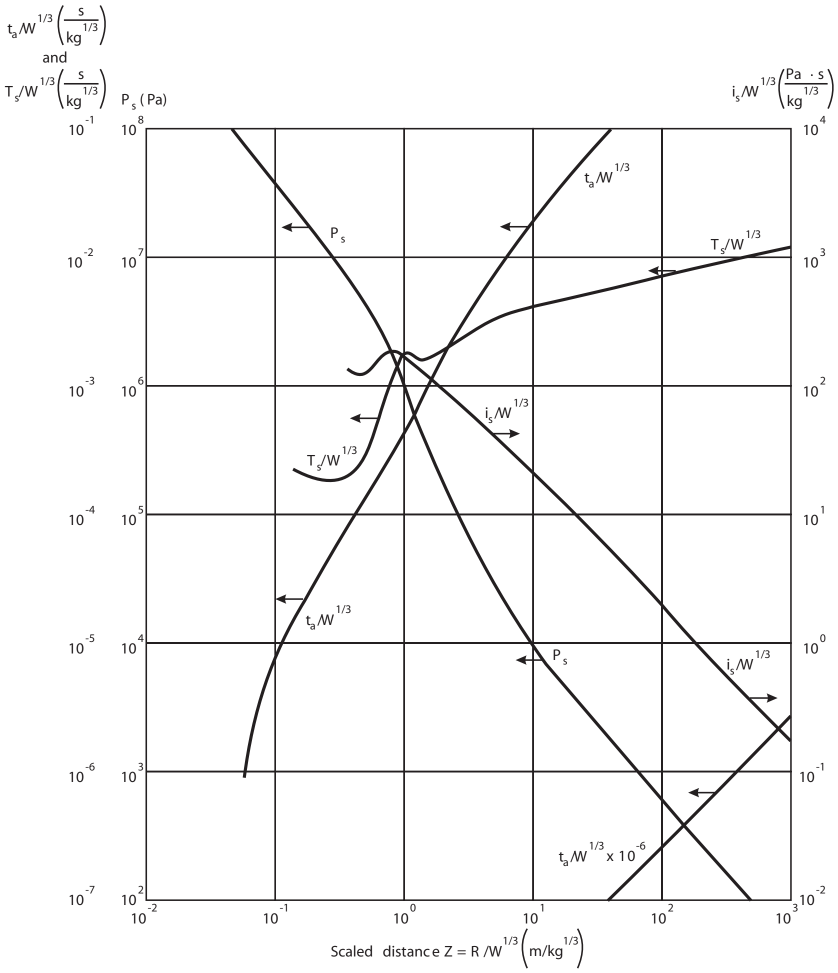

FIG. II-2. Side-on blast parameters for TNT. W: charge mass (kg); R: distance (m); P_S: peak positive incident pressure (Pa); T_S: duration of positive phase of incident pressure wave (s); t_a: time of arrival of blast wave (s); i_S: incident impulse (pascal seconds/kg$^{1/3}$); Z : range/mass to the 1/3 power (m/kg$^{1/3}$).

Frequency or period

II-10. Local elements tend to have relatively high fundamental frequencies or short periods of response typically in the 5–20 Hz or 200–500 ms period range. Individual primary load path elements such as individual beams or columns making up load bearing frames tend to respond in the 2.5–15 Hz range. Global assemblies of load bearing or primary load path elements such as frames or bracing typically respond in the 0.5–10 Hz range.

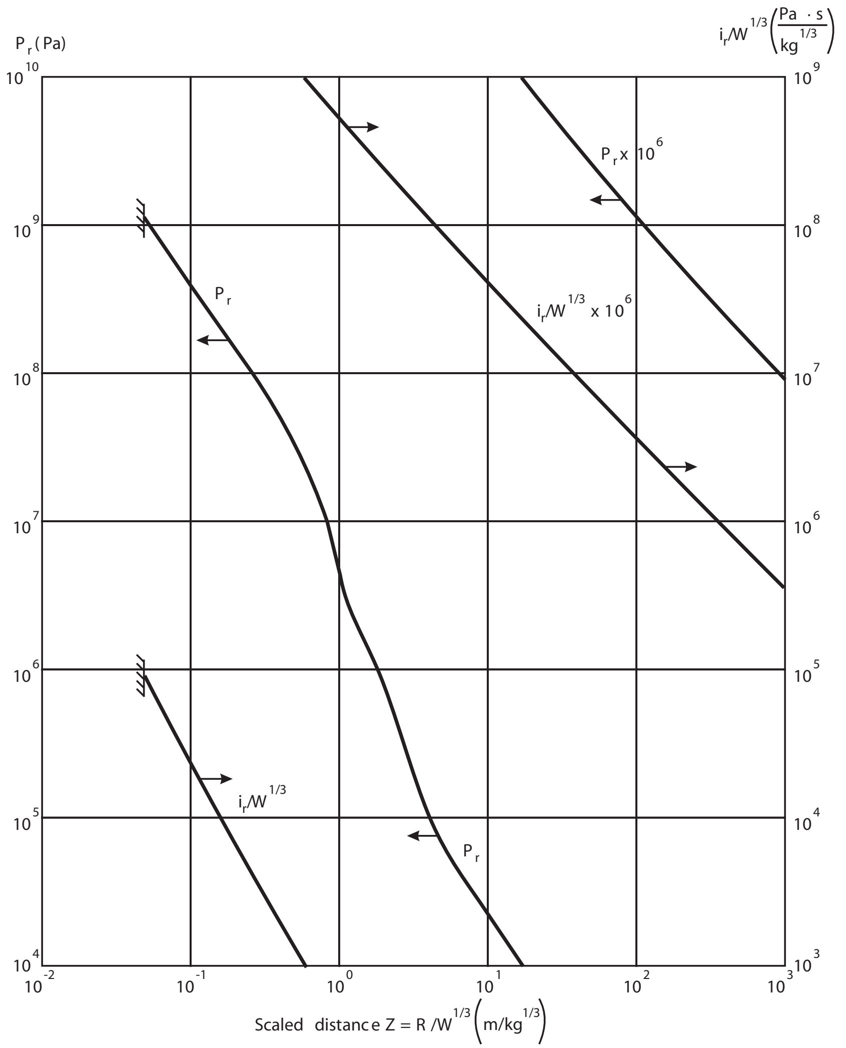

FIG. II-3. Normally reflected blast parameters for TNT. P_r: peak reflected pressure (Pa); i_r: reflected impulse (pascal seconds/kilogram$^{1/3}$); W: charge mass (kg).

Ductility

II-11. Ductility is a measure of the ability of an element to deform without rupture. It is not unusual, for example, to see a structural frame still standing, even though the curtain walls are badly damaged or even obliterated as a result of a detonation blast wave.

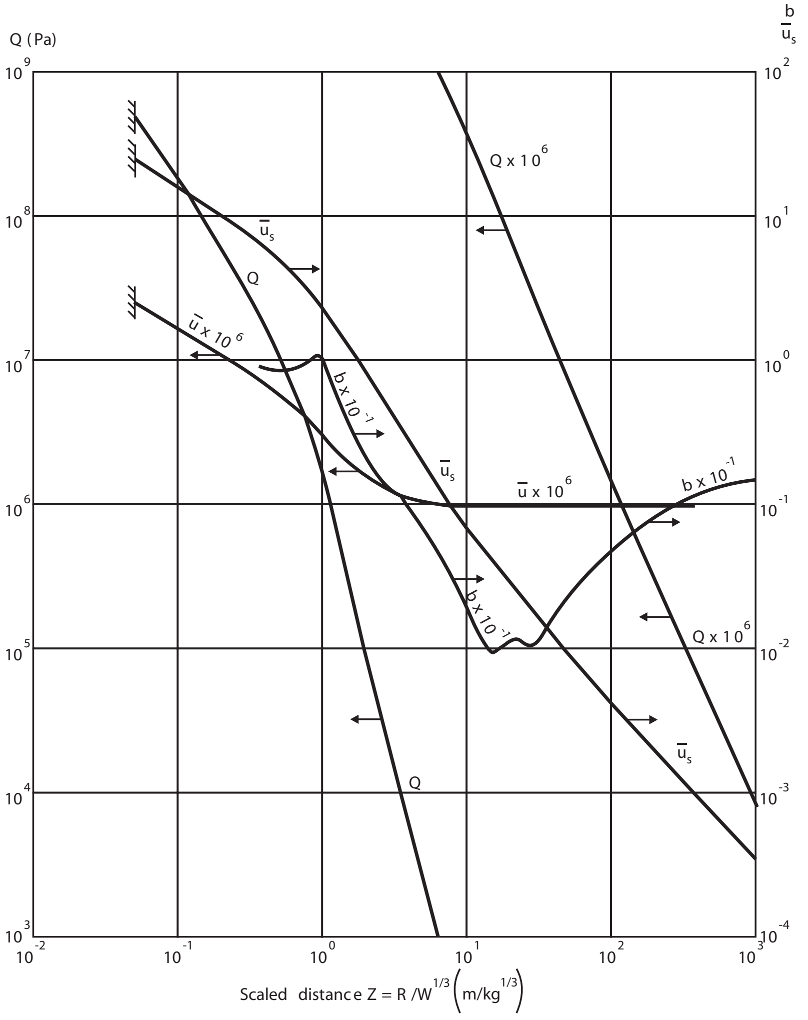

FIG. II-4. Additional side-on blast parameters for TNT. $\bar{U}$: shock front velocity (m/s); $\bar{u}_s$: particle velocity behind the shock wave (m/s); Q: dynamic wind pressure (Pa); b: decay constant.

II-12. In Fig. II-5 the static pressure requiring the same load capacity as is required by a triangular shaped dynamic forcing function applied to a one-degree-of-freedom ductile system (dynamic load factor) is shown as a function of its ductility and duration divided by period of response. Parameters typically necessary to define the response of a particular structure include the duration of the load and the natural period of the structural response, as well as the damping and maximum level of ductility exhibited by the structure during the

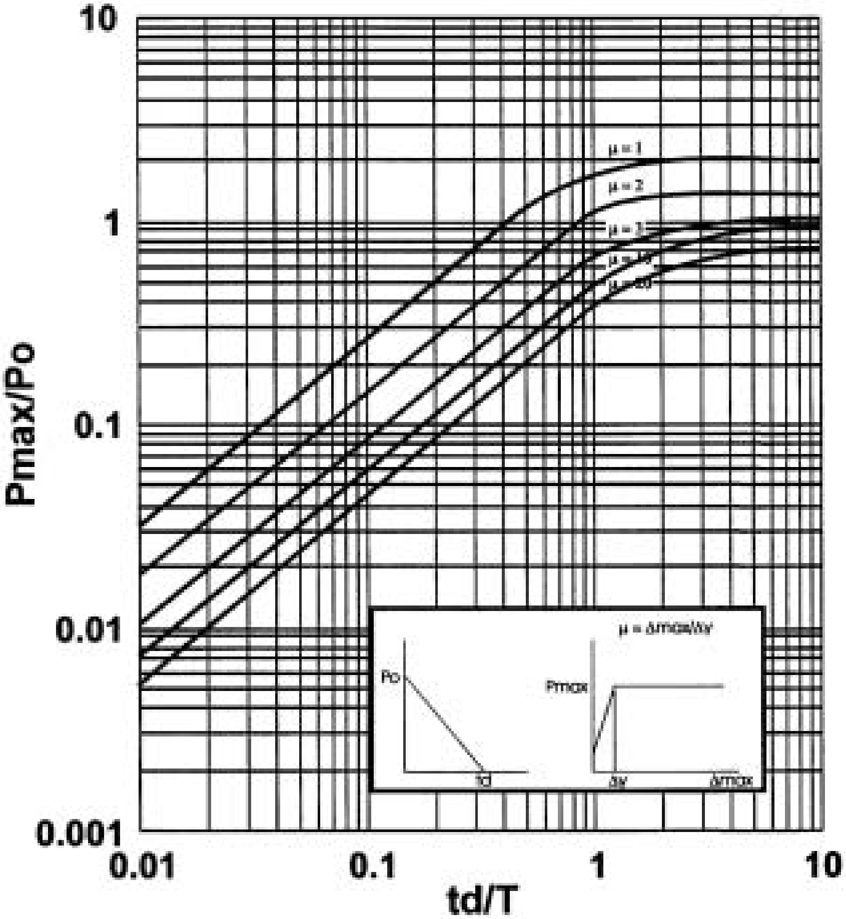

FIG. II-5. Conversion of a triangular dynamic pressure into an equivalent static load. P_0: peak of the dynamic triangular pulse (Pa); P_{max}: static pressure (Pa); t_d: duration of the triangular pulse (ms); T: first excited period of the one-degree-of-freedom structure (ms); Δ_{max}: maximum displacement at failure (m); Δ_y: maximum elastic displacement (m); μ: maximum ductility.

response. However, since the initial peak pulse is the loading of primary concern, damping does not normally play a significant role, unlike the response to cyclic earthquake type loads in which damping has a significant effect. From Fig. II-5, by using the blast wave and dynamic wind properties for the incident and reflected waves as evaluated in Figs II-2–II-4, it is therefore possible to determine the equivalent static load pressure produced by the blast type forcing function. Figure II-5 can be used with P_r and t_r (defined as $2i_r/P_r$) to

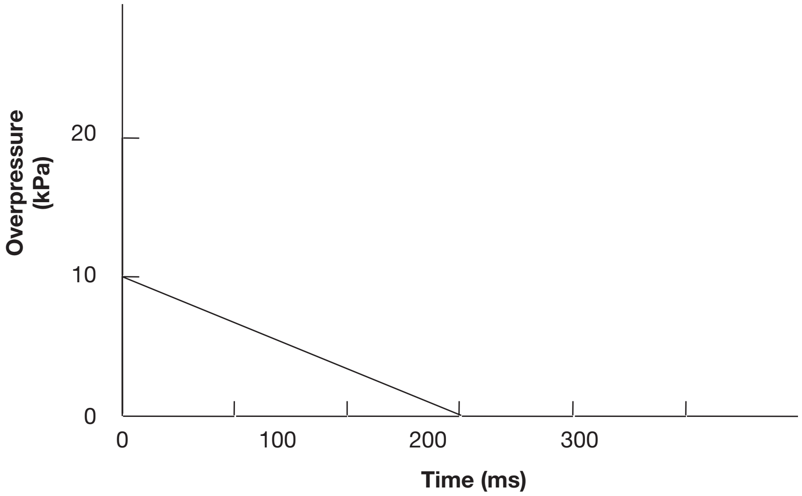

FIG. II-6. Standard load–time function for explosion pressure wave (adapted from Ref. [II-5]).

determine pressures on a reflective surface (facing or at an angle to the direction of blast propagation), and with P_s and t_s (defined as $2i_s/P_s$) to determine pressures on a 'side-on' surface (parallel to the direction of propagation of the blast wave).

II-13. The angle of incidence between the direction of propagation of the blast wave and the reflecting surface has some effect on the level of reflected pressure level. For chemical explosions producing overpressures of the magnitude discussed here, as long as this angle is equal to or greater than 45°, the reflected pressure is generally the same as for a normal (90°) reflective surface. As the angle of incidence approaches a side-on (0°), the reflected pressure can be assumed to approach linearly the side-on pressure level for angles of less than 45° (Fig. II-6).

II-14. As indicated in Fig. II-5, the effective blast loading on a structure, as represented by the dynamic load factor, is strongly dependent upon the ductility capacity μ (mm) exhibited by the structure. This figure is applicable provided that the natural frequencies of the structure are far from the major frequency content of the load function and therefore no significant dynamic response is excited. A structure exhibiting a ductility level of approximately 5, for example, would typically require only of the order of 33% of the load capacity of a brittle structure with the same frequency characteristics in order to survive the same explosion.

Structural damping

II-15. Structural damping typically ranges between 5 and 10% of the critical.

Overall load on the structure

II-16. The overall load on a structure is also a function of the size of the structure. The effect of the lateral distribution of load local to an obstruction (front wall of a structure facing the blast) should be carefully analysed. For structures with depths less than about 50 m parallel to the direction of travel of the blast wave, the blast load would have largely passed the structure before the structure had time to respond to the blast wave since the wave is always travelling at or above the speed of sound. For a 50 m deep structure, the peak blast wave front would only engage the structure for about 0.02 s, which is typically well below the global fundamental natural period of the structure but not necessarily the local element response period.

II-17. For structures with depths between 50 m and 75 m, it is reasonable (and conservative) to assume that equivalent static blast wave loadings on the structure, to include leeward wall, sides and roof, are occurring at the same time. For structures deeper than about 75 m the time phasing of the blast wave as it traverses the structure should be considered, although it would be conservative not to do so, with the conservatism increasing as a function of the increased depth of the structure.

Typical equivalent static load capabilities of local and global structural elements

II-18. Table II-2 shows typical equivalent static load capabilities of structural elements designed to 10^{-2} per year wind velocities of 30–35 m/s (sampled at 3 s).

USE OF A UNIFIED PRESSURE CURVE

II-19. In some States a pressure–load curve is provided without reference to the originating source. It has to be applied to all the exposed structures. At the preliminary stage of the project, this curve can be taken as standard minimum load. However, when a site has been chosen, it should be verified that the incoming pressure wave produced by explosive sources located in the vicinity of the site does not exceed the standard pressure wave, or that the probability of exceeding this value belongs to the residual risk (10^{-7} per reactor per year).

TABLE II-2. FAILURE OF STRUCTURE ELEMENTS AND COMPONENTS DUE TO EQUIVALENT STATIC LOAD PRESSURE

Structural element or component	Failure pressure: equivalent static load (kPa)		Dynamic characteristic period	Ductility		Failure mode
	HCLPF[a]	Median	m/s	HCLPF[a]	Median	
(a) Ordinary window glass	1.4	3.4	40	1.0	1.0	Shatter
(b) Doors	2.8	5.1	50	1.0	2.0	Displace
(c) Interior plaster board and stud partitions						
1. unanchored	3.4	6.8	100	1.0	2.0	Displace and overturn
2. anchored	6.8	13.6	67	1.5	3.0	
(d) Concrete or concrete block walls, 20–30 cm thick						
1. unanchored	6.8	13.6	100	1.0	2.0	Displace and overturn
2. anchored	10.2	20.4	67	2.0	4.0	
3. reinforced	13.67	27.2	67	3.0	5.0	Rupture
(e) Brick wall						
1. unanchored	5.1	10.2	125	1.0	2.0	Displace and overturn
2. anchored	6.8	13.6	80	2.0	4.0	
3. reinforced	10.2	20.4	80	3.0	5.0	Rupture
(f) Corrugated asbestos, steel or aluminium siding or panelling	3.4	6.8	100	3.0	5.0	Rupture
(g) Conventional reinforced concrete shear walls and slabs	20.4	34	100	5.0	10.0	Large cracks; no longer capable of carrying or transferring load
(h) Conventional reinforced concrete and structural steel beams and columns						
1. non-moment-resist connections	13.6	27.2	200	3.0[b]	5.0[b]	Large cracks; no longer capable of carrying load
2. moment resist connections	20.4	34	200	5.0[b]	10.0[b]	Large cracks; no longer capable of carrying load
(i) Furniture						
1. not positively anchored	2	3.4	200	2.0	4.0	Slides or overturns if aspect ratio greater than about 2.0
2. positively anchored						

TABLE II-2. (cont.)

Structural element or component	Failure pressure: equivalent static load (kPa)		Dynamic characteristic period	Ductility		Failure mode
	HCLPF[a]	Median	m/s	HCLPF[a]	Median	
(j) Mechanical and electrical cabinets, switch-gears, motor control centre						
1. unanchored	3.4	6.8	200	2.0	4.0	Slides or overturns
2. anchored	13.6	27.2	200	2.0	4.0	after anchors fail
(k) Rugged mechanical components: pumps, valve, vessels, heat exchangers	68	170	40	3.0	5.0	
1. anchored						
(l) Mechanical and electrical distribution system						
1. piping	20.4	40.8	200–1000	6.0	12.0	
2. conduit	13.6	34	50–1000	3.0	6.0	
3. cable tray	10.2	20.4	330–1000	3.0	5.0	
4. duct	6.8	13.6	330–2000	2.0	4.0	

[a] HCLPF means high confidence low probability of failure or threshold probability of failure, 1% probability of failure with 50% confidence.

[b] The ductility of a structural steel column is limited to 2.0.

Note: Failure of significant quantities of the elements or components would occur at about 2.0 times the equivalent static threshold pressure.

II-20. This evaluation should consider different parameters such as:

- — the mass of explosive substances liable to be released or involved in the explosion;
- — the nature of the substances and their physical form (gas or liquid);
- — the decreasing effect of the distance from the location of the ignition;
- — the statistical distribution of the wind, which may cause the explosive cloud to drift before ignition.

II-21. The fixed installations and also the transport routes — roads, railways and shipping routes — should be considered in the evaluation.

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Annex III

TOXICITY LIMITS

III-1. The dispersion of toxic gases is, to a high degree, site specific and toxicity is dependent on the chemical composition. However, for a preliminary evaluation, the values given in Table III-1 may be used [III-1]. These values are based on the Pasquill scheme (i.e. no buoyancy or heavy gas effect), with a short duration intake of air to the control room, and on the following assumptions, which also provide some conditions for their applicability:

- The toxicity limit of the gas is 50 mg/m^3 (this can be used for chlorine, whose toxicity limit of 45 mg/m^3 is very close to this figure);
- The air exchange rate of the control room is 1.2 volume/h (this is a typical value and may be adopted when the actual design value is not available);
- Modified Pasquill stability is Category F with wind speed 1 m/s.

These values are intended to provide a preliminary evaluation of the risk associated with the impairment of operator actions in the event of a release of toxic gases. In a more accurate evaluation, the specific nature of the chemical agent and more refined hypotheses for the simulation of their dispersion at the site should be considered.

III-2. If the toxicity limit and air exchange rates of the control room are significantly different from those assumed in items (1) and (2), simple corrections should be made as indicated below:

(1) *Toxicity limit.* The masses presented are directly proportional to the toxicity limit. For example, if a particular chemical has a toxicity limit of 25 mg/m^3, the weights given in the table should be decreased by a factor of two.

(2) *Air exchange rate.* The masses given are inversely proportional to the air exchange rate.

TABLE III-1. MASS OF TOXIC CHEMICAL TO BE CONSIDERED AS A FUNCTION OF DISTANCE

Distance (km)	0.5	1.0	1.5	4.0	8.0
Mass (t)	>0.04	>0.18	>0.40	>6.00	>30.0

REFERENCE TO ANNEX III

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