*Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (***SMiRT 17)**
Prague, Czech Republic, August 17 –22, 2003

Paper # WHJKP01-3

Protection of nuclear power plants against external events of malevolent origin

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ABSTRACT

The evaluation of external hazards in relation to nuclear power plant design is traditionally considered a two-step process. The detailed evaluation is preceded by a screening phase where potential scenarios are identified. Many scenarios are screened out on the basis of different criteria, such as distance from the site, probability of occurrence, expected consequence on the plant, or because their effects on the plant are expected to be enveloped by some others. The screening process needs to use conservative criteria in order not to leave out any credible scenarios. Also the detailed siting and design phase provides some degree of conservatism in the design in relation to external events. Methods of ensuring a reserve capacity in nuclear installations siting and design are: the introduction of a minimum deterministic design basis for external events, ductile design, structural redundancy, high quality in design and construction, low sensitivity to variation in design parameters, consideration of beyond design basis scenarios, high and demonstrable conservatism and selection of an appropriate layout. An additional margin against radiological consequences is guaranteed through the application of the single failure criterion and the defence in depth approach to the design and management of the nuclear safety of the plant.

In case of unexpected changes in the hazard or its perception during the plant lifetime, the availability of some reserve capacity in the design may make the safety upgrading easier or even unnecessary. This advantage proves particularly useful when events of malevolent origin have to be accommodated by the design at a later stage. However, a specific analysis needs to be carried out to quantify the relevant safety margin.

The paper intends to explore methods to assess the amount of this reserve capacity which is available in the design of NPPs, in general, and to review its use in the protection of NPPs against external events of malevolent origin, in particular. The final goal is a better quantification of both the uncertainties in the hazard evaluation of events of malevolent origin and the engineering measures that can be put in place to cope with them, at all stages of the operating life. In particular, the hazard evaluation methodology, the design methodology, the selection of layout, the material selection and other generic engineering choices are reviewed in this perspective.

KEY WORDS: External events, terrorism, sabotage, aircraft crash, explosion, design basis threat, robustness, structural capacity, vital areas, malevolent acts, administrative measures, plant protection, other nuclear installations

INTRODUCTION

The events of September 11, 2001 have highlighted the need to review the basic assumptions used in the protection of nuclear power plants against malevolent external events. There is general agreement among experts that current practice for plant siting and design provides such a level of “safety margin” and robustness to the plant that some scenarios not explicitly considered at the design stage may be accommodated by the nuclear facilities in their current configuration without significant radiological consequences. However, quantification is needed in order to understand with a high level of confidence which scenarios can be screened out in an evaluation process and which one deserves a detailed assessment at the material capacity level. This paper suggests the following three main steps:

1) The evaluation of the safety margin available in the plant design due to the inherent conservatism in the siting and design process
2) The analysis of the potential effects from the additional malevolent scenarios (AMS) and the way in which they challenge plant safety. A quantitative evaluation of the safety margin in relation to these scenarios is also needed
3) Identification of measures to protect the plant from AMS, taking into consideration feasibility and economic viability aspects.

The design basis events considered in this paper are: earthquake, aircraft crash, wind, explosion, fire and internal pressure.

Some malevolent scenarios such as cyber terrorism, contamination or poisoning of water and air, are excluded. The discussion here is mainly oriented to the protection of the nuclear power plants, but the concepts can easily be extended to other nuclear facilities, with suitable grading on the potential consequences.

The IAEA carried out a major effort in this field since September 11, 2001. The objective was the development of criteria and guidelines for the self-assessment of the vulnerability of nuclear facilities in relation to new scenarios not foreseen in the design basis. This effort, triggered by a resolution of the IAEA General Conference [1] could partially benefit from the broad experience gained in recent years from the re-evaluation of existing facilities in relation to external hazard upgrading, particularly seismic. It led to the development of a methodology for the “Vital area identification” [2] and a guideline for self-assessment of nuclear facilities in relation to terrorist threat [3]. The definition of the "design basis threat" is a State responsibility as it mainly depends on national issues on security, but guidelines have been developed by the IAEA to assist the Countries also in this task.

This paper is intended to provide guidance to support the engineering effort for the development of protection measures, which is the final outcome of the self-assessment phase. It provides some examples collected from the IAEA review experience in nuclear plants worldwide.

EVALUATION OF THE AVAILABLE SAFETY MARGIN

Current practice for siting and design of nuclear power plants in relation to external events aims at providing the final design with a high level of "safety margin" with reference to the potential radiological hazard posed by the NPPs to workers, public and the environment [4, 5]. However the definition of the external event scenarios is affected by large uncertainties [6], mainly due to the intrinsic difficulty in the forecasting of the characteristics of very low probability events. The design is carried out on a deterministic basis and therefore the uncertainty in the definition of the design basis is not considered throughout the design process itself.

A probabilistic approach such as PSA could be used to quantify the effect of this uncertainty. However this calculation is usually carried out only at the end of the design process, as a confirmatory tool [5, 6, 7, 8].

As a confirmation of the fact that the deterministic siting and design process may leave some vulnerability into the plant, an analysis of recent incidents at NPPs was carried out [7]. It revealed the following set of initiators:

- Inaccurate screening of scenarios at the very beginning of the siting stage. Screening criteria based only on the probability of occurrence proved to be very weak. Scenarios with potentially serious consequences on plant safety have been screened out only on the basis of purely probabilistic criteria.
- Inappropriate evaluation of the probability of combination of events: in one case, for example, an unfavourable combination of meteorological, hydrological and oceanographic scenarios, each of them quite below the design level, led to significant and challenging events for the plant.
- Exclusion of some effects from a scenario due to the limited historical experience on the event. A typical example is the evaluation of the fire/explosion effects induced by an aircraft crash, which often neglected the effects from the fuel.
- Underestimation of parameters related to scenarios due to the uncertainty in extrapolation techniques to low levels of probability of occurrence.

Other uncertainties may affect the design process through the choice of the analytical methods, the assumptions in the material properties, etc. Usually this set of uncertainties is dealt with in the probabilistic safety assessment of the plant.

The engineering community is aware of the above mentioned difficulties intrinsic in the design process and therefore the guidelines for siting and design are continuously updated, as in the case of the IAEA Safety Guide Program, particularly in the direction of a more systematic use of full probabilistic techniques. In addition to that, recommendations for a "robust" design have been recently incorporated in design codes together with the requirements for having an appropriate safety margin [9, 10]. The intent is to provide the final design with some capability to accommodate "unforeseen", but limited deviations from the design basis. Robustness is usually embedded in the design through the introduction of a set of minimum deterministic design basis for parameters related to external events (regardless of their real hazard) [9, 10, 11], the preference for a ductile design [10], the preference for structural redundancy [9, 10], the explicit requirement for low sensitivity to variation in design parameters [5], the consideration of beyond design basis values (particularly to avoid "cliff edge effects") [5, 9], and the selection of a "favourable" layout [9, 10]. The application of the single failure criterion and the defence in depth are integral elements of nuclear safety and will not be further discussed in the following.

Operational procedures are also available in case of extreme events. A typical measure is the requirement for plant shut down and post-earthquake actions in case of a major earthquake. This provides additional robustness to the plant. These procedures are usually implemented through a suitable structural or event monitoring, preventive operational procedures, and post event operator actions [6, 9, 10, 12, 13].

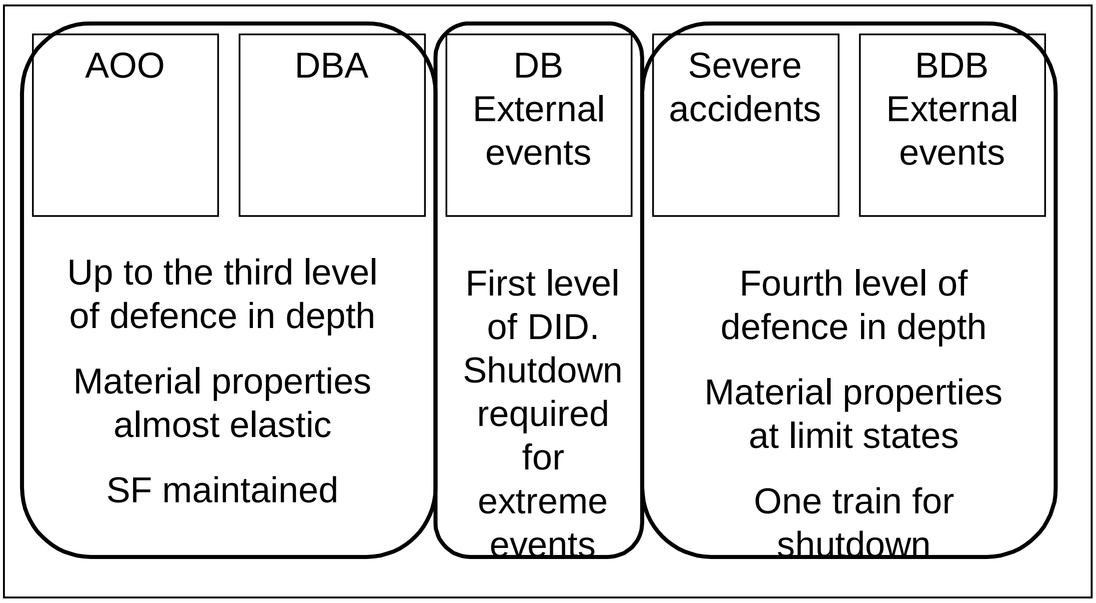
Additional reserve capacity is embedded in the design as a consequence of the conservatism applied in the different steps of the siting and design process. It is usually inserted to compensate for rough assumptions in material properties or calculation methods and, again, is not explicitly quantified.

Robustness and conservatism are usually not quantified and they represent the main reserve capacity for events exceeding the design basis. However, inherent plant robustness and conservatism need quantification when AMS are to be evaluated.

A schematic picture of the categorisation of load conditions is shown in Table 1 [5, 9], where the defence in depth levels are defined in [5]. The most relevant aspect of such categorisation is the special treatment of the beyond design basis conditions (BDB) which allows for some important exceptions to the requirements for the first levels of defense in depth. In particular:

- The protection or qualification of a single shutdown path (with redundancy)
- The consideration of a single plant status in case of BDB (typically the operational one, excluding the accident state, but including maintenance, refueling, etc.)
- The use of margin approaches for the evaluation of the residual capacity instead of design approaches, without an explicit quantification of the safety margin, limited to an estimation of a lower bound
- The use of more realistic values for material properties (typically best estimates.)

Table 1. Categorisation of loading conditions, according to [9]. (AOO=anticipated operational occurrences, DBA=design basis accidents, DB=design basis, BDB=beyond design basis, DID-defence in depth, SF=safety factor)



THE DESIGN BASIS SCENARIOS

The IAEA recommendation for the hazard evaluation as well as the general tendency in the engineering community promotes the use of a probabilistic approach [4]. However, in many countries the safety objectives are still defined deterministically. There is a very broad range of practice in the countries on both the record length to be used for the evaluation of the maximum historical value and the amount of additional margin to be applied on top of the maximum historical data to compensate for the uncertainties in the data and the shortness of the observation duration.

Any evaluation of the available safety margin needs to be carried out in relation to a specific country (for the country dependent requirements) and to a specific plant (for site and plant specific aspects). In the following, reference is made to a common basis of this evaluation, as recommended by IAEA documents, with the intention to provide a background for a detailed plant specific analysis.

Concerning the strategy for protection of the plants suggested in [9], two basic approaches are recommended:

(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, 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 and physical separation).

The solution should represent the best balance among safety, operational aspects and other important factors. To provide additional defense in depth to the basic forms of protection defined above, for some external events administrative measures can also provide safety benefits. Examples of such measures include the reduction of fire loading materials adjacent to or on the nuclear site, the diversion of air and maritime traffic routes, the definition of an exclusion zone, the installation of additional barriers (damboards) or the closure of watertight gates in anticipation of flooding. While these measures are not normally as reliable as passive engineered systems, they nevertheless can provide additional safety benefits. The effectiveness of administrative measures is strongly dependent on their enforcement level, particularly when different administrations are involved.

The following summarizes the international practice for plant protection in relation to external events.

Aircraft crash

One of the most common (and severe) scenarios is represented by a deformable missile of 1750 Kg with diameter 0.8m impacting the plant at 215 m/s.

The impact on concrete slabs (concrete strength 350 Kg/cm^2) with two layers of reinforcement (0.4% in total) yields in general the following design features:

1. Slab thickness
   - 80 cm: perforation, damage in an area of 3m radius
   - 100 cm: penetration+scabbing
   - 140 cm: penetration+spalling in an area of 2m radius
2. Longitudinal reinforcement
   - No significant contribution to the overall capacity, only retention of debris
3. Stirrups
   - Reduction of damaged area (up to 1m radius)

Explosion (without significant fire effects) One of the most common scenarios is represented by a triangular dynamic load, with duration ~100 ms, a peak dynamic pressure of 0.01-0.03 bar ([14] assumes 0.1 bar static) and an equivalent static pressure of 0.01-0.4 bar (dependent on the impulse and the first natural period of the structure).

A common assumption is the evaluation of the effects through a "TNT equivalency" where:

- Distance has an exponential type effect on the peak of the dynamic load
- The amount of the explosive has its major influence on the amount of air displaced and therefore on the equivalent static load

The application of this load yields in general design requirements for external surfaces (walls, windows, openings, air inlet) and slender structures (chimney, antennas, etc.).

Wind

One of the most common scenarios is represented by a maximum wind velocity of 30 m/s, static pressure 0.01 bar, corresponding to a return period of 50 years [15]. Other references assume max 50-60 m/s: pressure 0.04 bar, static (excluding tornadoes) [14, 16].

The application of these load conditions in general yields the following:

- Structural design of local protection structures
- 0.04 bar applied to a containment structure (diameter 40 m, H=45 m) induces a static resultant force of about 0.8 MN.

Internal pressure (only for reference)

One of the most common scenarios is represented by a design pressure for pressurised containments of 3.5 - 6.5 bar of relative pressure due to an internal accident. The application of this load condition yields in general a minimum thickness of concrete containment of 1 – 1.3 m

Earthquake

One of the most common scenarios is represented by a standard response spectrum with pga at 0.1 g. If applied to a heavy concrete containment structure (diameter 40 m, H=45 m, thickness=1m), it induces a resultant inertia force of 2 MN.

The application of this load conditions yields in general the following:

- Wall thickness of 1m for 0.1 g (reinforcement density 3%), 1.2 m is suitable for 0.3 g
- Vibration on components is a major concern
- Possibility of dynamic buckling for low values of thickness (~0.5 m)

Fire

The most common scenarios are:

- Fire from aircraft crash. It is still not very well understood (and usually not included in the Design Basis which refers to a standard scenario). Points of uncertainty involve:
  - The percentage of the fuel which goes into the plant (engines are expected to penetrate, but the tanks are expected to break outside)
  - Burning mechanisms and influence of the environmental conditions (stoichiometric ratio, ventilation, openings, confinement, size of drops, mixing with water from sprinklers, temperature, etc.). Fuel may burn in a pool, develop a fireball, deflagrate or detonate, partially inside and partially outside the buildings.Fire from

explosions. The effects are strongly dependent on environmental conditions (see above) which are rather unpredictableMany measures are put in place to protect a plant from fire effects [17, 18], usually with reference to some basic assumptions that are worth to mention:

- Fire protection measures (detection, mitigation, suppression); they are put in place with reference to the presence of combustible materials;
- External fire (external to the fence) is usually not considered (only peat or bush fire in some countries)
- Fire (and explosion) at the site, but external to the buildings, is seldom considered: from transformers, hydrogen or oil tanks, etc.
- Protection from external fire is usually achieved through protection against the potential sources (e.g. shielding of the containment).
- Usually fire PSA does not assume fire and smoke propagation to neighbouring rooms, neither combination with high mechanical loading

  Usually fire PSA does not assume contemporaneous fire in more than two areas

THE DEFINITION OF THE ADDITIONAL MALEVOLENT SCENARIOS

Twenty years of operating experience data for nuclear installations worldwide showed a number of serious challenges to the defence in depth system of these plants by some scenarios which were not part of their design basis [7]. However, in most cases they could be withstood by the existing engineering features. Examples are: abnormal biological growth in proximity of water inlet and outlet, electromagnetic interferences from cellular phones or actuation of high voltage switches, salty precipitation on electrical components with short circuits and corrosion, collapse of internal structures of cooling towers due to biological growth in the abduction channels, etc.

In some other cases, the scenarios were part of the design basis, but the effects were poorly estimated, as in the case of fuel effects in small aircraft crashes or in the combination of precipitation, storm surge and sea waves.

The AMS require consideration of additional scenarios, such as: crash of civil aviation aircraft, launch of small projectiles, impact by terrestrial or marine malevolent vehicles, etc. This category of events was often considered to be partially addressed by other load conditions such as accidental aircraft crash or accidental explosion, but an explicit inclusion in the design basis was very seldom carried out.

In case an evaluation is needed, the special character of the AMS needs to be addressed. While accidental scenarios can be analysed and forecasted with improved simulation tools, operating experience record and improved statistical tools, events of malevolent origin require a special approach in their quantification, due to two main reasons

- Their probability of occurrence may be difficult to estimate (the high level of uncertainty could make the estimation meaningless) and in some cases useless, as evidence of the protection has to be provided regardless of the probability of occurrence, mainly for public acceptance reasons
- The scenario is affected by many social, political, security, military conditions that may make the hazard evaluation highly unreliable because of the complicated data retrieval

In conclusion, most countries prefer to define the “design basis threat” (DBT) in a deterministic way.

PROTECTION AGAINST ADDITIONAL MALEVOLENT SCENARIOS

The protection against AMS may be designed following three steps:

1) An evaluation to determine whether a complete envelope of all the effects from the AMS is available by the existing design basis. If so, the scenario can be screened out as a single event but kept for the development of load combination and operational procedures. The relevant safety margin can be assumed at least equal to that of the enveloping scenario.
2) The design of a suitable protection provided by additional engineering measures or the use of an existing protection designed for other scenarios. This requires analysis of the effects of the AMS on structures, systems and components. A special methodology has been developed to identify SSC’s and associated areas where protection is needed with respect to a set of prescribed requirements. The methodology is called “vital area identification” and can serve the double purpose of identifying locations that should be protected both in the sense of engineering and physical protection [2].
3) The capacity evaluation of the items in vital areas in case a shielding is not provided. This requires an analysis of the effects of the AMS on the SSCs in vital areas. Considerations on diversity and physical separation may lead to reducing the items for upgrades.

A flow chart representing this process is shown in Fig. 1 [3].

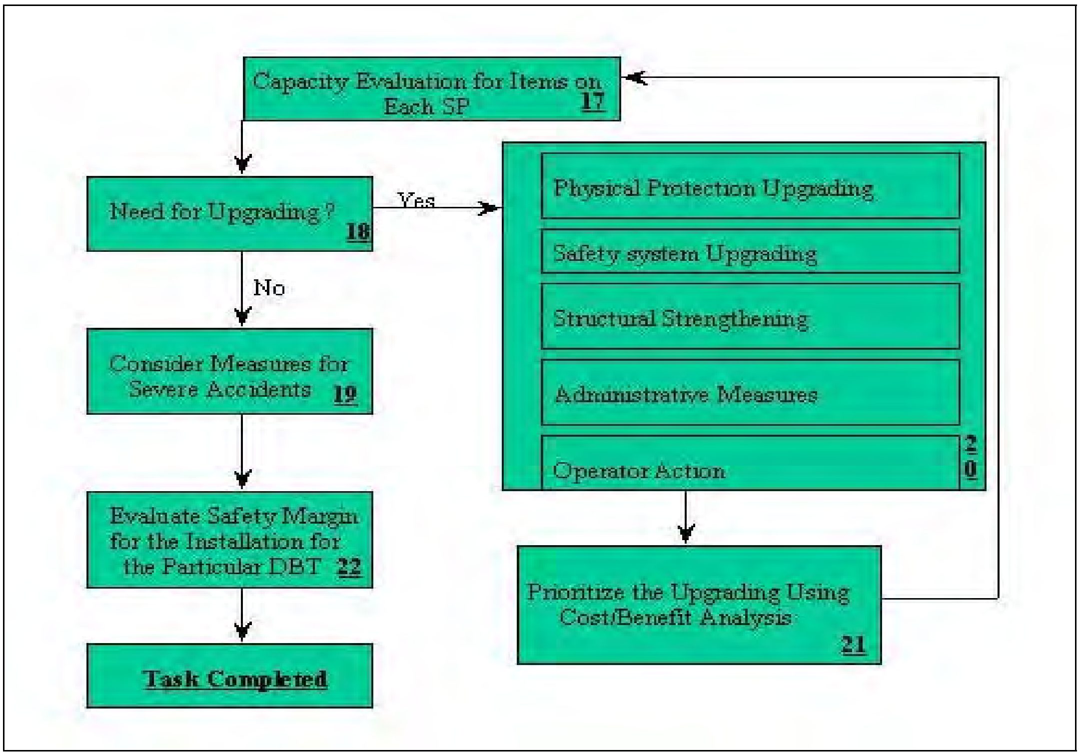


Fig. 1. Flow chart of a possible procedure to assess the plant capacity against Additional Scenarios

The procedures described above can be applied in two alternative frameworks:

1) The AMS is treated as an additional design basis condition. The robustness and/or the conservatism embedded in the original design are spent to accommodate the AMS with the same safety factor (and safety approach) used for all the other design basis conditions in the original design
2) The AMS are treated as additional beyond design basis conditions. The inherent robustness and the conservatism are spent as at the previous point, and, in addition, special limitations to the general defense in depth are developed, agreed with the regulator, and applied. Additional administrative and operational procedures may provide some degree of protection for the facility. However, they may need to be complemented by engineering measures.

Moreover, in the assessment of the enveloping scenarios for screening out the candidate AMS, the following issues need consideration:

- A comparison of AMS and design basis at the scenario level usually cannot be carried out, as the involved phenomena are of many different natures.
- A comparison at the load level can usually be done only on selected aspects of different scenarios, for example: pressure wave from explosion and pressure wave from wind, fire from different sources (explosions, combustions, etc.), etc. An example of a complex scenario is shown in Fig. 2.
- A bounding analysis may have no meaning at the scenario level, as some scale effects may take place. An example: if a small vapour cloud deflagrates, a larger one may have some volumes where the stoichiometric ratio is such to ignite a detonation, with completely different and unscalable effects.A comparison among structural effects from earthquake, aircraft crash, wind and explosion usually needs a selection of a reference structure, as it cannot be carried out at the scenario (or load) level.

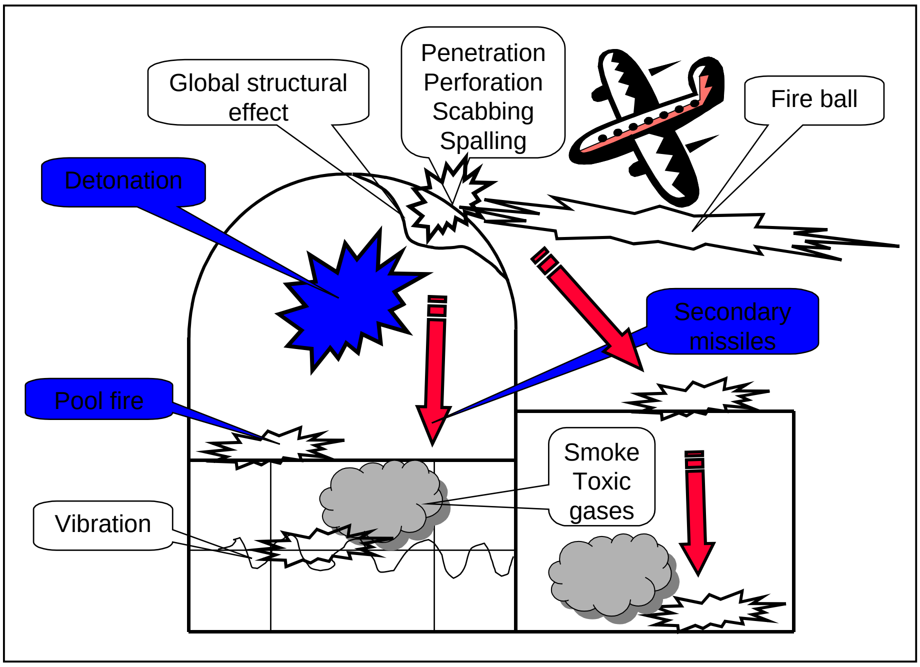


Fig. 2. Schema of the complexity of a typical Additional Scenario (aircraft crash)

When, as result of the preliminary assessment, the use of the available robustness and conservatism for new AMS is required, a more accurate and realistic structural evaluation needs to be carried out. Application of non-linear analytical methods, of limit analysis or of failure tests are typical examples of possible improved evaluation.

In conclusion, a safety assessment in relation to AMS usually requires the completion of steps 1 to 3 above, including a complete evaluation of the structural capacity. However, in practice, simplified methods can be applied relying on some general engineering evaluations, as shown in the following examples.

APPLICATION EXAMPLES

Concerning the mechanical loads, some general observations can be made on the sizing loadcases for the most typical structures. Such considerations can suggest some engineering “shortcuts” to a comprehensive capacity evaluation, at least in reducing the number of items to be upgraded (i.e. only those for which the AMS is of “sizing” nature):

- Explosions (reasonably far from the target) and wind (excluding tornadoes) imply similar pressure values and therefore their effects can usually be compared
- Earthquake design for 0.1 g usually envelopes the maximum wind design (and explosion) for large cylindrical heavy structures (such as containment)
- The thickness of protecting walls is usually governed by aircraft crash loading, if applicable
- The thickness of the pressure retaining concrete walls is governed by the internal pressure which is more demanding than both the aircraft crash scenario and low seismic excitations
- In heavy containment structures the global stability of the building is governed by the earthquake, not by the ACC
- In framed structures ACC local effects are not enveloped by other loads
- The integrity of external closure panels is usually governed by wind and explosions
- If there is a concrete containment, internal pressure design and seismic design (>0.1g) usually envelope the effects of local aircraft crash loads. However effects on equipment are rather different (impulse load versus long vibration) and heavy scabbing may be developed if shear reinforcement is not appropriate
- Global aircraft crash effects on heavy containment structures are enveloped by seismic design (>0.1g)
- In framed structures aircraft crash loads are usually not enveloped by any other load, while explosions may still be enveloped by wind
- The safe shutdown path developed for seismic or fire events may be used for other events.

- The provisions for redundant and diverse systems needed to prevent common cause failures should make successful defence more likely. Also embedded redundancy in fire barriers may allow suppression actions to be taken in due time
- Fire loading may be very high and initiated in many areas at the same time. It may also be combined with mechanical loading.

An example of comparison among mechanical loads is shown in Table 2, with reference to a heavy concrete containment.

Table 2. Example study with comparison of capacities in relation to different loadcases on a heavy concrete containment structure

Thick ness	Local ACC	Earthquake (0.25 g)	Internal pressure (6 bar)	Explosion (0.1 bar, 200 ms)	Wind (0.02 bar)
1.4 m	Penetration with spalling	Reinf. density 2%	2% reinf. density+ prestressing	Min. reinf. Density (dead load)	Min. reinf. Density (dead load)
1 m	Penetration with scabbing	Reinf. density 3%	3% reinf. density + prestressing	Min. reinf. Density (dead load)	Min. reinf. Density (dead load)
0.8 m	Perforation	Reinf. density >3%	Not suitable	Reinf. density 1%	Reinforceme nt density 1%

Concerning, fire effects, aircraft crash (ACC) and explosion design, some general sizing considerations can be made such as:

- Concrete structures exhibit high fire resistance (in many experiments, after hours of confined fire, only the superficial layer was damaged).
- Steel structures are well known for their low fire resistance. However, both explosions and ACC are expected to be fast developing scenarios. Therefore, if most of the fuel is kept outside, the concern is shifted to the amount of combustibles which could be ignited.
- Equipment are very sensitive to fire and to smoke (particularly the electronics).
- Fire may develop in areas (e.g. through leakage of fuel) where few combustibles are present and therefore limited fire protection measures are available. In these areas ventilation may be different, as well as operator access for fire extinguishing.
- Personnel can be prevented from safety performing functions by smoke (even toxic), fire, temperature, flooding and debris from local failures.
- Fire brigade contribution may prove useless if the scenario has a fast development.Concerning other scenarios, initiated outside the fence, enveloped by “usual” design basis, sizing considerations are as follows:
- Malevolent vehicle impacting safety related structures at the ground level: limited experience is available, but usually it can be included into explosions and impacts, with some local protection upgrading, in terms of speed barriers and limiters.
- Contamination of service water: an accidental event recently alerted the international community. Specific protection is required on malevolent acts developing similar effects
- Cyber terrorism: special provisions are needed.
- Electromagnetic interference: protection is possible in some frequency ranges, but qualification practice is varied.

CONCLUSIONS

In general, the enveloping of the AMS by the design basis scenarios can be demonstrated as a result of a detailed evaluation of all the relevant effects of an AMS. However, a comparison between traditional design basis scenarios and malevolent ones may be difficult, mainly because of lack of information on the scenarios to be considered and related effects. Moreover, when the comparison has to be carried out at the material capacity level, it may prove to be time and resource consuming.

On the technical side, a combined use of well developed procedures and of the large engineering experience in the protection against accidental external events can drive the assessment safely to the target, without excessive expenditures.

On the organisational side, a combination of self assessment by the plant owner organisation driven by plant specific guidelines agreed with the regulator is probably the most suitable strategy to face the safety assessment in relation to AMS, as a consequence of the strong influence of plant dependent aspects.

For a more reliable and effective safety assessment, priority should be given to the AMS scenario definition, better if probabilistic; its consideration as "beyond design basis" (BDB) may avoid an excessive demand for additional protection to the facility.

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