18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-J03-4

LARGE FIRE SCENARIOS IN RELATION TO SABOTAGE OF NUCLEAR INSTALLATIONS

Paolo Contri
Department of Nuclear Safety and Security
International Atomic Energy Agency
Phone: 43 1 2600-26426
Fax: 43 1 2600-7
E-mail: P.Contri@iaea.org

Aybars Gürpinar
Department of Nuclear Safety and Security
International Atomic Energy Agency
Phone: 43 1 2600 22671
Fax: 43 1 2600-7
E-mail: A.Guerpinar@iaea.org

Ulrich Schneider
Technical University of Vienna, Austria
Phone: 43 1 58801 20600, Fax: 43 1 58801 20699
E-mail: ulrich.schneider+e206@tuwien.ac.at

ABSTRACT

The analyses of sabotage scenarios carried out in recent years identified two major damaging mechanisms associated with such scenarios, namely: the mechanical interaction of solid bodies or pressure waves with the installations and the fire-related effects from burning substances. While the former effect may be addressed by available analytical tools developed for accidental scenarios, the latter deserves a new, specific engineering effort. In fact, all nuclear facilities are designed in relation to accidental fires; even so, they need to be assessed in relation to sabotage induced fire scenarios due to the special characteristics of such scenarios, not addressed by the current engineering practice for the design of nuclear installations. Conventional fire hazard analysis is based on the hypothesis of the presence of combustible materials in the buildings and limited number of contemporaneous sources of fire. In addition, conventional fire safety assessment relies upon the presence of mitigation measures and fire related operational procedures. In a sabotage event the validity of all these assumptions need to be checked and if the assumptions cannot be supported, then the analysis should be revised and other alternatives of protection should be developed. Also the implementation of emergency planning should be reviewed to take account of this concern.

This paper collects state-of-the-art experience from some Countries, which represents the background information for the development of new IAEA documents in this field. The paper reviews how the current design practice for nuclear installations can cope with large fire scenarios caused by malevolent actions and provides recommendations to designers and operators on how to address these issues in a reasonable framework.

Keywords: sabotage, fire, nuclear power plants, fire protection.

1. GENERAL BACKGROUND

Recent terrorist events highlighted the vulnerability of structures to large fire scenarios. They triggered a review of the conventional procedures for the design of fire protection systems in large industrial complexes, as they showed that large fires may also be the consequence of accidental (i.e. non-terrorist) acts.

The generic lesson learnt from recent destructive events on conventional buildings, (see for example [1]) can be summarised as follows:

- Fire protection features (active systems, compartments, etc.) are designed for internal fire sources. The external source (fuel entrance) may imply substantial modifications to the design process;
- The thickness of the fire coating is crucial. The behaviour of heated connection should be understood with care;
- Less-brittle fireproofing (passive resistance) should be considered for steel structures considered vulnerable to blasts and attacks (it represents the third line of defence after the active systems and the manual suppression). Experts might also reconsider location of fire stairs and the strengthening of the bearing structure;
- Fire induced collapse should be re-considered;
- A structural redundancy able to provide some degree of load redistribution is beneficial;
- Egress systems should be evaluated for robustness and redundancy; Performance of adequate, conventional fire protection features (active system, but also structural fire protection and fire compartments which avoid fuel spreading) may improve the overall building capacity.

These conclusions are also valid for nuclear installations and should be considered in relation to the physical separation of large areas affected by fires, as well as the fire suppression systems and the operator action that can also be affected.

Therefore nuclear power plant designers, regulators and operators need to review the engineering practice in this field, aiming at a better integration between physical protection, operation and design measures. This review needs to be carried out with reference to both accidental and sabotage scenarios. The recent IAEA safety guides issued in 2003 [2,3] already incorporates some of these ideas, but a series of Technical documents is under development to address these issues more specifically, in connection with the IAEA reference document on security [4,21]. This paper discusses some of the more technical background issues, with the intent of collecting feedback.

The two major damaging mechanisms associated with “large fire” scenarios involve the mechanical interaction of solid bodies or pressure waves (originated by explosions, crash of aircrafts, etc.) with the installations, and the fire-related effects from burning substances on large areas.

The definition of the “mechanical” and the “fire” related challenge is not easy, as many aspects are connected to the threat and the plant characteristics, see for example [5]. However a very general evaluation carried out on an envelope of the credible threat scenarios and on generic plant configurations indicate, that the “fire” deserves a significant effort for some quantification of the associated potential effects.

This led the IAEA to carry out a special effort in gathering the available knowledge in this field. Two main tasks have been identified in this respect:

- A generic evaluation of potential fire-related scenarios, with understanding of the main physical issues and analysis of the available scientific knowledge in terms of simulation tools and validation of data;
- A detailed evaluation of the implications of fire-related scenarios on plant safety through impact on current practice in equipment qualification, fire protection design issues and operational procedures.

The objectives of this paper are summarised in the following:

- To collect a state-of-the-art of the knowledge on fire-related scenarios;
- To review the current design practice for nuclear installations in view of these new scenarios;
- To evaluate the impact that the lack of knowledge on the scenarios may have on the safety of the nuclear installations.
- To select areas with priorities where further investigations, R&D and safety analyses are needed to improve installation safety.

Potentially near surface nuclear installations are considered in this paper, with emphasis on the most hazardous ones for workers, population and environment (nuclear power plants, fuel re-processing plants, etc.).

The design basis threat (DBT) is not covered by the discussion. The reference scenario is a collection of different components (e.g. fire, explosion, mechanical impact) whose absolute intensity and relative percentage is not defined. However, large fires are typically the results of the impact of large aircrafts, fully loaded with fuel; therefore, this scenario is explicitly covered in this paper.

Fire-relevant aspects receive the highest emphasis on this paper due to their innovative character. Mechanical issues (impacts and explosions) are considered only as contributors to the fire issue.

2. THE CHALLENGE TO PLANT SAFETY

The following statement was issued by the IAEA just a few days after the “September 11” event [6]:

“Nuclear facilities are protected by well trained security forces and are extremely robust, designed to withstand, for example, earthquakes, tornado-force winds and accidental crashes of small aircraft. Although it is not automatic that any attack would result in a release of radioactivity, they are however industrial facilities and as such are not hardened to withstand acts of war."

This statement indicates the need for a plant specific analysis of the capacity of the installation to withstand a terrorist scenario.

The IAEA Safety Guide [7] on design of nuclear plants in relation to accidental fire relies on well-established engineering practices that can be summarized as follows:

- Fire protection measures (detection, mitigation, suppression) are put in place with reference to internal fire according to presence of combustible materials internal to the buildings;
- External fire (external to the fence) is not considered (only peat or bush fire in some countries)
- Sometimes fire (and explosion) at the site, but external to the buildings is considered: from transformers, hydrogen or oil tanks, etc.;
- Protection from external fire is achieved through protection against the potential sources (e.g. shielding of the containment). However, this strategy assumes a scenario, which may prove inadequate;
- Fire PSA does not assume fire and smoke propagation to neighbour rooms, neither its combination with high mechanical loading;
- Fire PSA does not assume contemporaneous fire in more than two areas ignited at the same time.

Therefore, general nuclear design safety criteria should be evaluated to assess their effectiveness in relation to such malevolent scenarios: i.e. the width of the affected area may be much larger than the usual assumption of a few square meter damage induced by a mechanical impact. This means also that the usual assumptions used for physical separation may not be valid any more.

The impact associated with fire may destroy most of the fire suppression systems and therefore different design and operational approaches may be needed.

Conventional fire hazard analysis is based on the hypothesis of the presence of combustible materials and limited number of contemporaneous sources of fire. In addition, conventional fire safety assessment relies upon the presence of mitigation measures and fire related operational procedures. In a sabotage event the validity of all these assumptions need to be checked and if the assumptions cannot be supported then the analysis should be revised and other alternatives of protection should be developed. Also the implementation of emergency planning should be reviewed to take account of this concern.

3. SOURCES OF LARGE FIRES

The collection of basic information on potential sources related to sabotage acts is a difficult task that has to address confidentiality issues and should involve different engineering sectors, traditionally isolated, to learn from their broader experience, namely: the oil and chemical industry, the aeronautical industry, and the construction industry. The IAEA collected some recommendations on the development of the design basis threat in [5].

Recent events highlighted the need for consideration of the mutual interactions among the different contributors to complex scenarios, such as: the complexity of potential scenarios composed of mechanical impacts, pressure waves and fire, smoke, toxic releases etc., all acting on very wide areas. Moreover, the consequences may be very much dependent on the proportion of the different contributions, for example a fuel aerosol can lead to detonation or to a deflagration according to the ventilation, the stoichiometric ratio and other boundary conditions. In this framework, the challenge to the installation should be expressed as a result of these potential interactions. A possible approach is to associate a probability value to different scenarios derived by the same initiating event. Such a definition for a design basis scenario is not usual and its impact on design procedures should be evaluated with care.

4. FIRST INTERACTION BETWEEN EXTERNAL SOURCES AND PLANT

The partitioning of the fuel following an impact deserves a better clarification or at least the development of some conservative assumptions.

Also the penetration path of the combustible in a plant should be better understood. Recent evidence clarified that the worst scenario is usually associated with the penetration of combustible material in liquid and/or aerosol form through openings and fractures generated by the mechanical impacts.

The interactions between the damage induced by the mechanical impacts and the boundary conditions for the development of fire-related scenarios is another issue that needs clarification to support a reliable analysis (i.e. the fire protection measures, including the structure coating, can be damaged and washed away by the explosion).

The development of fire, explosion, smoke, and toxic gases represents a series of secondary effects that should be better explored. Critical parameters in these evaluations are represented by the duration of the fire, its development mechanisms (pool fire, "dirty pools", explosion, etc.) and its transfer to combustible materials available at the plant.

Two types of fire scenarios may result from a given DBT or beyond DBT (BDBT). These scenarios assume that the fire is located only exterior to plant structures or that the fire may ignite simultaneously both inside and outside plant structures. For a fire scenario outside the plant only, it must be conclusively determined that impact and blast impulses will not result in the penetration of plant structures. Otherwise, it must be conservatively assumed that given a fuel source for the threat scenario evaluated that an interior plant fire(s) will result.

If a fire initiates simultaneously both inside and outside the plant, it can be assumed that the predominant impact to the safety systems will occur due to the interior fire. Therefore, it is recommended in this situation that an evaluation of the impact of interior fires only be performed and with the assumption that the entire quantity of flammables has penetrated interior to the plant. The potential for multiple simultaneous fires must be considered.

From this type of event several relevant fire scenarios may be derived to be considered:

- Pool fire outside the building;
- Pool fire and fire ball outside the building;
- Combined pool and cable fires inside the building;
- Pool fire interior and fire ball exterior the building;
- Combined pool and cable fires interior and fire ball exterior the building;
- Combined pool fire and fireball interior the building.

In the special case the fire source is associated to an aircraft crash, the following considerations may be developed [13].

The type of airplanes, which are to be considered in this connection, may be divided into three groups. Group A comprises light weight passengers planes like Boeing 737 and Airbus A 320. The average number of passengers in a plane is about 160 and the take-off weight is below 100 tons.

Group B passenger planes comprise medium weight planes like Boeing 757 and Airbus A 300. The number of passengers at maximum is 280 and the take-off weight is below 200 tons. Boeing 757 is the lightest plane in this group.

Group C passenger planes comprise heavy weight planes with take-off weights between 230 and 400 tons. The heavy weight planes like Airbus A 340 and Boeing 747 provide about 400 passenger seats. The plane A 330 has only two jet power plants, its weight is 230 tons, whereas the others generally have four power plants.

The fire loads of planes have been estimated as in Table 1.

Table 1: Fire loads of passenger planes at take-off

Plane	**Fuel** **kg / MJ**	**Lining Seats** **kg / MJ**	**Luggage clothes** **kg / MJ**	**Combustible materials** **(Sum) kg / MJ**
Group A < 100 tons	20 000 864 000	4 500 180 000	4 800 144 000	29 300 kg 1 188 000 MJ
Group B < 200 tons	56 000 2 440 000	8 800 350 000	8 400 250 000	73 200 kg 3 040 000 MJ
Group C < 400 tons	182 000 7 860 000	12 000 480 000	12 000 360 000	206 000 kg 8 700 000 MJ

Table 1 indicates that the amount of kerosene compared to the total fire loads lies between 73 and 90%. In group C the energy of kerosene is about 90% of the total energy of the combustible materials in the plane. It is therefore sufficiently accurate to assume in BDBT calculations that the amount of kerosene at take-off is relevant for fire investigations.

During the ACC the plane fire loads are dispersed inside or outside the facility building and may burn as fire balls, fire pools or both. Fire balls outside the building may cause fires and fire spread in adjacent buildings due to radiation effects. Fire pools outside the building may lead to fires in underground cable channels and supply shafts, i.e. for HVAC systems or else. Inside the building the spread of kerosene leads to uncontrolled ignition of all fire loads being involved. The burning may be controlled by the limited natural air supply, which leads to long fire durations. Explosions in certain areas of the affected building cannot be excluded without extended investigations.

The amount of kerosene, which is dispersed and burns in a fire ball depends on the amount of fuel penetrated into the target building and the residual amount outside. The latter is determined by the wall thickness (see Table 2).

The fires inside buildings may be estimated according to the fuel, which is penetrated through the walls, plus the permanent loads in the buildings. The percentage of fuel penetrated according to Table 2 refers to that amount of fuel at take-off of the aircraft (see Table 1). The ventilation is given by the opening A_v (wall destroyed) of the building (see Table 2). More details on the rate of combustion are available in the IAEA document [13].

Table 2: Estimated wall area destroyed and fuel penetrated into a building after an ACC

Aircraft	**Wall thickness**		
	200 cm	**100 cm**	**50 cm**
Group A < 100 tons	Penetrated fuel 0% Wall destroyed $A_v = 0\ m^2$	Penetrated fuel 0% Wall destroyed $A_v = 0\ m^2$	Penetrated fuel 50% Wall destroyed $A_v = 25\ m^2$
Group B < 200 tons	Penetrated fuel 0% Wall destroyed $A_v = 0\ m^2$	Penetrated fuel 0% Wall destroyed $A_v = 0\ m^2$	Penetrated fuel 75% Wall destroyed $A_v = 75\ m^2$
Group C < 400 tons	Penetrated fuel 0% Wall destroyed $A_v = 0\ m^2$	Penetrated fuel 25% Wall destroyed $A_v = 75\ m^2$	Penetrated fuel 100% Wall destroyed $A_v = 150\ m^2$

The fires outside the buildings may be estimated as follows. From the amount of non-penetrated fuel, about 50% may be used estimating a pool fire with a pool size according to geometrical considerations. If no special considerations are available it is suggested to use the pool sizes according to Table 3. The size of the fire balls should be calculated with respect to the residual amount of fuel. An upper limit of 300 m for the diameter of a fire ball is proposed if no special information is available. The proposed fire ball diameters are given in Table 3.

Table 3: Suggested pool fire sizes after an ACC

	Aircraft type		
	Group A	**Group B**	**Group C**
A_{pool}	100 m	300 m	800 m
$2\ R_O$	45 m	100 m	300 m

The duration of fires may be calculated according to the available fire load and the average rate of burning. Details are available in [13].

5. SIMULATION OF THE EFFECTS AT THE PLANT SITE

For evaluation of fire impacts interior to the plant structures, many fire modeling codes are available. Typically, these codes employ zone models for the fire area where the fire initiates. These zone models predict a hot gas layer temperature and depth as a function of time with the non-impacted lower level of the fire area assumed to increase slidely in temperature. Also, models are available for multi-compartment fire modeling. Any model chosen should be used with a great deal of caution and experience because in many cases, predictions of non-physical temperature conditions and potential impacts to safety related equipment may result. When predicting fire effects in compartments other than where the fire originates, additional caution should be employed when evaluating the results of the modeling effort.

The fire effect to safety related structures (SRSs) and SSCs are calculated using the latest methods of fire safety engineering. There are two methods, which are more or less generally accepted in fire engineering design. These methods are:

- zone models (CFAST, MRFC)
- computational fluid dynamic models (FDS, FLUENT)

Zone models were developed during the 80ies and the 90ies and are still in use in the field of fire safety engineering [8,9]. The models typically describe the fire development, temperatures and smoke flows near the origin of the fire initiation [10]. The models predict hot gas layer and "cold" gas layer temperatures and the smoke layer depth as a function of time. From this one may derive the fire performance of structural elements and SSCs in the fire areas or areas adjacent to the fire.

Advanced zone models like CFAST from NIST and MRCF from the University of Technology Vienna are used for multi-room-fire-modelling ([9], [11], [12]). It is possible to calculate the fire spread and smoke flow to adjacent areas, i.e. the codes can be applied to estimate the performance of SSCs in large compartments and compartments which are integrated in a larger building area.

In [9], [10], [11] and [12] different zone model fire codes are described. Compared to the computational fluid dynamic codes their application is simple and leads to appropriate results within calculation times in the range of minutes. The application of multi-room-zone-models is possible up to more than 20 rooms or compartments.

Experience with zone models suggest that the calculation results in multi-room-zone-modeling are less reliable in rooms, which are situated far from the fire origin. Generally it is proposed to limit the number of rooms to 15 or less. In the sense of zone modeling a “room” may be a part of a large compartment, i.e. large areas in a building may be divided into several virtual rooms. Any model chosen in this way should be used with caution, and needs a lot of experience of the modeler.

From the zone model the hot gas temperatures near SSCs may be derived and its performance can be estimated if adequate performance criteria are known. The long term performance of SSCs may be estimated after heating and cooling, as well as corrosion effects due to fire extinguishing systems, the effects of corrosive fire gases and acids like, e.g. HCl or HCN.

The fire simulation with zone- or CDF-models requires realistic input data with respect to the

- geometry of the building or compartments;
- natural and mechanical ventilation system during fire simulation;
- fire scenario according to the fire loads and its energy release.

The natural ventilation should be estimated according to the damage after a malevolent attack. In Table 3 typical damage areas A_v after Aircraft crash (ACC) are given. The mechanical ventilation and filter systems may be out of operation after the attack due to physical or electrical effects, which can be easily verified with respect to the sabotage scenario.

The fire scenario should be based on the building damage and the effect of penetration of fire loads and ignition sources, especially in the case of an ACC. Four types of building damage are possible according to the following definitions:

Case 1: Little building damage, acceptable cracks, no perforation or penetration of combustible materials, the fire is limited to areas outside the building;

Case 2: Building damage with limited perforation and little penetration of combustible materials, large fires inside the building are possible;

Case 3: Larger building damage with large areas for the penetration of combustible materials, large fires inside the building are possible;

Case 4: Loss of buildings and building functions after a malevolent attack due to mechanical and fire effects.

If the fire investigation requires a detailed analysis of temperatures and smoke flows in safety related areas or outside of buildings (e.g. due to underground cable channels or ducts) Computational Fluid Dynamics (CFD) codes may be applied. Compared to multi-room-fire-codes which are able to simulate fires in calculation times which are less than the real time of the fire duration, the fire simulation with CFD codes is done within days or even weeks, depending on the size of the building involved.

The application of CFD fire codes is limited to fire experts with additional knowledge in fluid mechanics. In spite of the great mathematical and physical sophistication of CFD fire codes the results of calculation are strictly pre-determined by the fire scenario, which is chosen by the expert, i.e. the fire scenario is mainly part of the input parameters, irrespectively which CFD-models are employed.

6. THE ASSESSMENT OF FIRE SAFETY

A plant walk-down can be performed to obtain vital information for computer fire simulations. This information includes the location and type of critical equipment and cable trays, separation between redundant trains and shielding and fire barrier that may be present. A list of typical parameters for fire calculations is shown in Table 4. These parameters were selected based on common data used in fire safety engineering (see [8,9]).

Table 4 - Fire load input parameters for fire simulation models

PVC Cable Parameters		Oil Parameters	
Density	**1715 kg/m^3**	**Density**	**900 kg/m^3**
Spec. heat	**1045 J/kgK**	**Spec. heat**	**2100 J/kgK**
Conductivity	**0.092 W/mK**	**Conductivity**	**-**
Heat of combustion	**18.5-23.1 MJ/kg**	**Heat of combustion**	**46.7 MJ/kg**
Surface controlled (tray) burning rate	**300-390 kW/m^2**	**Surface controlled (pool) burning rate**	**1470 kW/m^2**
Radiation fraction	**0.3 to 0.5**	**Radiation fraction**	**0.3 to 0.7**
Smoke alternation	**1.4**	**Smoke alternation**	**-**
Reflectivity	**0.1 to 0.3**	**Reflectivity**	**-**
Kerosene		**Gasoline**	
Density	**830 kg/m^3**	**Density**	**810 kg/m^3**
Spec. heat	**2100 J/kgK**	**Spec. heat**	**2200 J/kgK**
Conductivity	**-**	**Conductivity**	**-**
Heat of combustion	**43.2 MJ/kg**	**Heat of combustion**	**43.7 MJ/kg**
Surface controlled (pool) burning rate	**1700 kW/m^2**	**Surface controlled (pool) burning rate**	**2100-2300 kW/m^2**
Radiation fraction	**0.3 to 0.7**	**Radiation fraction**	**0.4 to 0.8**
Smoke alternation	**-**	**Smoke alternation**	**-**
Reflectivity	**-**	**Reflectivity**	**-**

It should be noted that the surface controlled burning rates may vary with air flow rates and flow direction.

The parameters in Table 1 may be used for a first estimate in fire calculations in ventilated areas.

It should be considered that the threat scenarios usually lead to large (pool) fires and large fireballs. Experiences show that small fires must be very close to the components as to yield damage. Large fires, however, can and do yield damage in most cases. This is due to the large fire volume, i.e. normally all safety related components will be damaged by the direct impingement of flames. Equipment or components will be ignited aspect will be ignite and/or destroyed by the high radiation fluxes of the flames. This is especially the case in small spaces with a sufficient air supply.

For the evaluation of fire impacts exterior to the plant structures, typically fires are modeled as pools, which are situated adjacent to plant structures unless it can be demonstrated that the fire location is elsewhere. As it is the case for the evaluation of interior plant fires, modeling should be performed using conservative input parameters (pool size, fire load) as to achieve results, which are on the safe side.

A railway or truck crash is an example of an exterior plant fire threat. For the fire scenario, it is typically assumed that all the fuel from the vehicle leaks and the fuel pool size is the result of an instantaneous spill of flammable liquid. The quantity of fuel can be defined as the maximum amount that may be present in a given vehicles fuel tanks. The definition of simultaneous fire balls (vapour cloud fires) is not possible if no experimented proof is available.

A methodology, which has been developed to calculate the average diameter for an instantaneous spill, is based on [13]. The primary mechanism for damage from such fires is thermal radiation. Depending on the circumstances and conditions leading to such an event, different types of open fires may result. For example, ignited releases can produce pool fires, jet flames, vapour cloud fires, or fire balls, all which behave differently and exhibit markedly different radiation characteristics.

The potential for these different types of impacts should be evaluated for the given threat scenario. Once the relevant fire scenario is determined, correlations provided in [13] can be utilized to determine the potential for structural failure of adjacent plant structures. In this approach, the probability of structural failure and the propagation of fire impacts interior to facility buildings can be determined. If it is found that the propagation of fire impact to the interior of a building is likely to occur, then an evaluation of interior plant fires, as outlined above, should be performed.

7. ENGINEERING APPROACH TO FIRE SAFETY ASSESSMENT

It should be noted that extensive modelling experience for small fire simulations, except for zone of influence cases, has not found damage to critical components in most fire areas. Engineering experience [15] shows that a small fire must be very close to its target to yield damage. Large fires, however, can and do yield damage in most cases.

For evaluation of fire impacts exterior to the plant structures, typically fires are modeled as pools immediately adjacent to plant structures unless it can be demonstrated that the fire location is elsewhere. As was the case for the evaluation of interior plant fires, modeling results should be viewed with caution as the predicted fire impacts may be non-physical due to the large uncertainty in defining the precise scenario (i.e., whether only a flammable pool results or other impacts such as jet flames occur).

A vehicle crash is an example of an exterior plant fire threat. For this scenario, it is typically assumed that all the fuel from the vehicle leaks and the fuel pool size is the result of an instantaneous spill of flammable liquid. The quantity of fuel can be defined as the maximum amount that may be present in a given vehicle's fuel tanks. Other potential conditions such as jet flames, vapour cloud fires or fire balls have typically been beyond the scope of evaluation. With respect to ACC the occurrence of fire balls need to be taken into consideration.

A methodology which has been extensively employed to calculate the average diameter for an instantaneous spill is based on [13]. The primary mechanism for damage from such fires is thermal radiation. Depending upon the circumstances and conditions leading to such an event, a different type of open fire may result. For example, ignited releases can produce pool fires, jet flames, vapour cloud fires, or fire balls, all of which behave differently and exhibit markedly different radiation characteristics.

The potential for these different types of impacts should be evaluated for the given threat scenario. An event tree approach may be utilized to weight the potential for the different models, which result from pool fires, jet flames, vapor cloud fires, or fire balls. Once these fractions are determined for the various radiative heat flux models, the relevant correlations provided in [13] can be utilized to determine the potential for structural failure of adjacent plant structures. In this approach, the probability of structural failure and the propagation of fire impacts interior to plant buildings can be determined. If it is found that propagation of fire impact interior to plant buildings is likely, then an evaluation of interior plant fires as outlined above should be performed.

8. COMPONENT FRAGILITIES

When addressing component qualification issues it is important to note that thermal failure modes are not completely understood in terms of effects from temperature, smoke, aerosols, shock waves, lack of oxygen, etc.

In cases where a threat scenario either leads to a penetration of a plant structure(s) or occurs near openings of a structure(s), two or more fire areas may develop simultaneously. Components and cabling associated with components in those fire areas are attacked by the fire and may

- ignite and burn
- increase the fire hazard
- support the fire spread to adjacent areas
- fail after a certain time of exposure and/or burning

The time of failure may be different from the classified time of fire duration. This is due to the fact that the real fire development is different from the material fire test scenario. Especially the radiation of spill fires and material fire tests may be completely different. A classification of 90 minutes therefore does not ensure that the threshold of a component in reality is 90 minutes long. The threshold values of SSCs may depend on other parameters such as:

- surface temperatures; which may be less than 140 °C
- radiation effects; e.g. due to flame impingement
- flows of air and fire gases adjacent to the SSCs
- preheating of SSCs in adjacent areas before the direct fire exposure occurs
- mechanical stresses and deformations due to thermal strain, restraint forces and thermal bending

The component failure may be due to the combined effects of impact, blast and fire and/or smoke. Generally it should be assumed that all fuel associated with the threat scenario burns and may start multiple fires in the impacted fire areas and adjacent areas.

Electronic equipment is particularly sensitive to the impacts of smoke. However, the fragilities of plant components due to the impact of smoke is currently not well known. As a conservative approximation all electronic components in areas where heavy smoke results may be assumed to have failed. Additionally, loss of functionality or mal-operation of equipment outside of the impacted area due to hot shorts may result. The fire suppression system in the impacted fire areas is also assumed to fail due to impacts of blast or mechanical impact.

Credit may be taken for fire barriers that remain intact; however, the expected duration of the fire should be evaluated against the capability of the intact fire barriers to determine the potential for subsequent failure of these barriers.

The fire suppression system in the impacted fire areas is assumed to fail due to impacts of blast or mechanical impacts. It may also fail due to the loss of power or water supply in adjacent areas.

The fire detection system in the impacted fire areas is assumed to have failed. Spurious detection is to be expected in the fire areas and adjacent areas. Loss of power may lead to a total loss of fire detection capacity.

Electronic equipment is particularly sensitive to the impacts of fire and smoke. Actually the fragilities of electronic plant components due to the impact of fire and smoke are in most cases not well known. As a conservative approximation all electronic components in fire areas and in areas with heavy smoke may be assumed to have failed.

The cable insulation and damage thresholds depend on the type of material used. For PVC cables it is recommended to assume a cable insulation ignition temperature of 773 K. For large fires these thresholds are not critical for the fire damage calculations because the threshold levels are easily exceeded due to the radiation intensity of the flames. Usually the cables in fire areas are lost during a direct fire exposure, the resistance time is of the order of minutes rather than hours.

Cabling of components in fire areas may ignite and fail due to fire or it may fail due to mechanical or blast impacts. As a conservative approximation all cabling of components in fire areas may be assumed to have failed.

Cable fires usually lead to the development of hydrochloride and a condensation of acid vapour at adjacent surfaces of concrete, steel and electronic equipment. The damage of hydrochloride is also possible in areas, which are far from the fire area due to rapid spread in ventilation systems. Failure mechanism of this kind should be taken into account. In this connection the behaviour of SSCs must be evaluated with respect to its short term, medium term and long-term behaviour. A fire attack may be non-dangerous for short periods after the fire but very dangerous for long periods after the fire, e.g. due to corrosion effects on SSCs.

Steel structures or components are sensitive to a fire exposure. Because of their high thermal conductivity and heat adsorption, steel failure may be assumed at 773 K for structural steel. This temperature is usually obtained within 10 minutes under heating rates of about 50 K/min. Liquid fires usually have heating rates of several hundred K/min, i.e. the supports of large components may fail in case of intensive fire exposure due to loss of strength of columns, hangers, ribs, supports, etc.

Concrete structures may also suffer from extreme heating rates. Due to the capillary water in which concrete explosive spalling may occur which leads to rapid loss of concrete cover and with it the possibility of a direct fire attack to the reinforcement. If the reinforcement reaches 773 K the steel plasticizes and the structure loses its load bearing function. Pre-stressed concrete members may even lose their load bearing function if pre-stressing cables reach 523 K.

It should be noted that the threat scenarios as a rule lead to large fires which are with respect to heating rates, radiation fluxes and temperature maxima beyond the temperature-time curves used in standard fire tests for the classification of structural member and structural fire protection measure and classifications. This means a structure with 90 minutes fire duration time according to its classification may fail in the case of a hydrocarbon fire within 30 minutes or even within 5 minutes.

Of course credit may be taken from fire barriers, which maintain their resistance. However, the expected duration of the fire should be evaluated against the capability of the fire resistance of the barriers in order to determine the potential for subsequent failure of these barriers.

9. PREVENTION OF FIRE INDUCED FAILURES AND PLANT UPGRADING STRATEGIES

As described in a previous paper [17], it is possible that nuclear installations designed using standards that do not consider sabotage acts are able to withstand some unanticipated scenarios, thanks to the “robustness” of the design, as per the IAEA design requirements [16]. 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 ones deserve a detailed assessment.

As a consequence of this design approach, 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 the real hazard) [2,3,18,19], the preference for a ductile design [10,20], the preference for structural redundancy and diversity [2,3], the explicit requirement for low sensitivity to variation in design parameters [18], the consideration of beyond design basis values (particularly to avoid “cliff edge effects”) [3], and the selection of a “favourable” layout [3,20] (e.g. physical separation). The application of the single failure criterion and the defence in depth are integral elements of nuclear safety and contribute largely to this robustness.

As consequences of these assumptions, the following can be said on the challenges to the safety of the installation posed by a large fire scenario:

- 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); unfortunately few qualification data are available;

- Fire may develop in areas (e.g. through leakage of fuel) where some combustibles are present and therefore corresponding fire protection measures are available, ventilation may be different, operator access for fire extinguishing may be different;
- Personnel can be prevented from safety functions by smoke (even toxic), fire, temperature, flooding and structural collapses;
- Fire brigade contribution may prove useless if the scenario has a fast development on a very large area.

A rough evaluation of the robustness embedded at the design stage is given in Table 5, developed on the basis of the review experience accumulated at the IAEA. For example, the structural capacity to withstand the seismic demand may be useful in protection against sabotage scenarios. The same comparison for the case of equipment qualification is not so straightforward.

A more general procedure for the comparison of the structural capacities is available in a previous paper [15].

Table 5: Comparison of structural capacities for the case of a concrete containment and a military jet impact ("local ACC").

Thickness	**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%	Reinforcement density 1%

In conclusion, the following strategies should be considered to prevent failures of equipment in adjacent fire areas:
- Investigate the potential for smoke and other blast/impact by-products to spread to non-impacted areas and mitigate to the maximum extent possible;
- Minimize the amount of combustibles in any given fire area;
- Protect fire barriers which remain undamaged;
- Utilize the fire brigade in the protection of fire barriers which remain undamaged;
- Investigate and correct any operational failures;
- Isolate damaged fire items;

The malevolent attacks generally will lead to fires which are mainly based on combustible liquid with high vapour pressures and which may not be suppressed by automatic fire suppression systems. Sabotage induced fires will usually be more dangerous than accidental fires in the facility and the stem or suppression of them needs to be carried out by the fire brigade, i.e. by manual fire fighting. The capability of the responsible fire brigade must be increased to a level, which allows for
- manual fire fighting of large pool fires;
- manual fire fighting of pool fires in facility buildings;
- manual fire fighting using special fire fighting systems, suppression agents and specific fire fighting operations.

It should be demonstrated in advance whether sufficient water for fire fighting is available and applicable in the assumed fire scenarios. Fires of liquids are usually suppressed by foam instead of water or a mixture of water and foam. Outside the buildings the spread of liquid fires in underground tubes and channels is a specific risk. The spread of fire should be limited by waterproof and fire resistant seals of underground channels. In any case the manual fire fighting capability seems to be a primary interest for the facility after a malevolent attack. It is important to prepare a special action plan for the responsible fire brigade with respect to possible malevolent attacks with serious consequences involving fire.

10. CONCLUSIONS

The paper identified some of the safety issues associated with large fire scenarios at nuclear sites. Some issues can be addressed by available methods, but most of them require the development of new engineering methods and response measures in order to provide a reliable protection.

Particularly, the modelling of the fire "loadcase" and the qualification of electric and mechanical equipment to the many effects of a fire scenario still require additional effort by the engineering community.

However, at the moment, sound engineering judgement can lead to a reliable assessment of the plant safety in relation to such extreme malevolent events, provided that the lessons learnt in recent non-nuclear accidents is analysed and transferred to the nuclear community. In most cases the robustness embedded into the plant design may be useful in dealing with sabotage scenarios. In other cases, specific upgrading may be needed.

The new technical documents under development at the IAEA will contribute to this dissemination effort.

REFERENCES

1. FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA), World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations, Federal Insurance and Mitigation Administration, FEMA 403, Washington, DC, May 2002.
2. INTERNATIONAL ATOMIC ENERGY AGENCY, External Human Induced Events in Site Evaluation for Nuclear Power Plants, Safety Standards Series No. NS-G-3.1, IAEA, Vienna (2002).
3. INTERNATIONAL ATOMIC ENERGY AGENCY, External Events Excluding Earthquakes in the design Nuclear Power Plant Design, Safety Standards Series No. NS-G-1.5, IAEA, Vienna (2003).
4. INTERNATIONAL ATOMIC ENERGY AGENCY, INFCIRC/225/Rev.4 (corrected), The Physical Protection of Nuclear Material and Nuclear Facilities.
5. INTERNATIONAL ATOMIC ENERGY AGENCY, TECDOC, "Guidance for the Development and Maintenance of a Design Basis Threat", Vienna, 2005.
6. INTERNATIONAL ATOMIC ENERGY AGENCY, Press release, November 1, 2001.
7. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Guide, Design of Fire Protection for Nuclear Power Plants, IAEA Safety Series No. SG-50-D2 (Rev.1), IAEA, Vienna 1992.
8. Schneider, U.: Ingenieurmethoden im Baulichen Brandschutz (Engineering methods for fire protection of buildings). 3rd Edition, Kontakt & Studium, Vol. 531, Expert Verlag, Renningen, 2004.
9. Schneider, U.: Grundlagen der Ingenieurmethoden im Brandschutz (Fundamentals of Engineering Methods in Fire Safety). Werner Verlag GmbH, Düsseldorf, 2002.
10. Lebeda, C.; Max U.: MRFC – Mult Room Fire Code (version 3), AGBI TC Vienna, Brechsal, Wien, 2000.
11. Jones, W.W. et al: A Technical Reference for CFAST – An Engineering Tool for Estimating Fire and Smoke Transport. NIST TN 1431, National Institute of Standards and Technology, Gaithersburg, Maryland, January 2000.
12. Joint Departments of the Army, Navy, and Air Force, USA, Structures to Resist the Effects of Accidental Explosions, TM 5-1300/NAVFAC P-397/AFR 88-22, Rev. 1, 1990.
13. INTERNATIONAL ATOMIC ENERGY AGENCY, TECDOC, Extreme external events including those of malevolent origin - Protection of existing Nuclear Installations, Vienna, 2005.
14. J. Lambright: "Design experience and reference standards in USA – Feedback from the experience", Proceedings from National Workshop on "Design requirements and industrial design standards for fire protection: an introduction to rulemaking techniques", IAEA, Beijing, China, September 15-19, 2003.
15. P. Contri and. A. Gürpinar: Protection of nuclear power plants against external events of malevolent origin, SMiRT 17, Prague, 2003.
16. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, Safety Standards Series No. NS-R-1, IAEA, Vienna (2000).
17. INTERNATIONAL ATOMIC ENERGY AGENCY, TECDOC 1341 "Extreme external events in relation to the design or assessment of NPPs", 2002.

18. INTERNATIONAL ATOMIC ENERGY AGENCY, TECDOC 1347 ”Design of nuclear facilities other than NPPs in relation to external events, with emphasis on earthquakes”, 2002.
19. INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Design and Qualification for Nuclear Power Plants, Safety Standards Series No. NS-G-1.6, IAEA, Vienna (2003).
20. INTERNATIONAL ATOMIC ENERGY AGENCY, Self-assessment guidelines of: the engineering safety aspects of the physical protection of nuclear facilities against sabotage, May 2005.

