A fire risk analysis method for nuclear installations

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Abstract:
A fire safety analysis (FSA) is requested to justify the adequacy of fire protection measures set by the operator of a nuclear facility. An IRSN document outlines a global process for such a comprehensive fire safety analysis and focuses on compliance with performance criteria for fire protection measures. These performance criteria are related to the vulnerability of targets to effects of fire, and not only based upon outside radiological consequences caused by a fire.
In his FSA, the operator has to define the safety functions to be preserved in the case of a fire in order to be compliant with nuclear safety objectives. Then, the operator has to justify the adequacy of fire protection measures, defined according to defence in depth principles.
One of the key points of the fire analysis is the assessment of possible fire scenarios in the facility. Given the large number of possible fire scenarios, it is then necessary to evaluate "reference fires" which are envelope of all possible fire scenarios and which are used by the operator for the design of fire protection measures.

1 INTRODUCTION

This document presents the IRSN process for a comprehensive analysis of fire hazards in nuclear installations.

The purpose of the analysis process described in this document is to provide the required steps to prove that the fire protection measures in the facility are acceptable and sufficient. The justification of the measures retained should be based on the fulfilment of technical criteria considering the fire hazard analysis. On the basis of the safety functional requirements in combination with the protection requirements for safety targets[1], the operator shall therefore determine the performance criteria that shall be met by the fire protection measures. Compliance with these criteria ensures that the safety objectives will be met.

This guide is a tool explaining the analysis process of the fire hazards in nuclear installations. Considering its general nature, the process described in this document may require to be adapted to very specific configurations.

[1] The elements needed to perform a safety function or to protect against the effects of a fire. Targets can be diverse in nature: radioactive materials, radioactive materials containment systems, criticality units, material and human resources that play a role in the safety functions, escape routes and access routes to equipment which has to be operated to put and keep the installation in safe conditions.
Structures that accommodate or support safety targets are to be protected against the fire. Equipment and structures, different from those mentioned above, are also to be protected against the fire and its effects if their deterioration (in the form of a domino effect) caused by a fire could affect the safety of the installation.

2 FIRE AND NUCLEAR SAFETY CONSIDERATIONS

In the room a where fire breaks out, the fire will cause a temperature increase as well as a change in the room gas pressure. Hot gases and combustion aerosols toxic, corrosive and possibly flammable will be generated by the fire. Fire is often the source of opaque and explosive atmospheres.

It is important to consider all the effects of the fire in the analysis, on the one hand to assess the vulnerability of the targets that need to be protected against the effects of fire and, on the other hand, to establish the fire protection measures.

Considering only fire characteristics is not enough to determine and design the fire protection measures needed for a satisfactory level of safety. It is also essential to consider the unfavourable effects of the fire extinguishing systems selected (excess pressure due to the release of an extinguishing agent, malfunction of safety equipment due to the extinguishing agent used, criticality accident caused by a mechanical or moderating effect, etc.) and the mechanical effects induced (behaviour of confinement barriers, etc.).

2.1 Fire in the presence of radioactive materials

In the presence of radioactive materials, a fire can scatter the materials, thereby producing a situation in which the workers' exposure cannot be controlled and even not a release of radioactive materials into the environment. A fire can also trigger a criticality accident by damaging the measures and systems used to control the criticality units. Furthermore, specific measures are necessary to deal with the effluents produced by the extinguishing systems or the fire fighting, which could lead to a contamination (dispersion of radioactive materials) or criticality accidents.

2.2 Fire in the presence of safety equipment

The fire and the extinguishing systems used can significantly damage safety equipment. Even at a distance from the fire and in different ways, the corrosive materials and the soot contained in the smoke may produce equipment malfunctions which differ from those caused by the simple thermal effects of a fire. Because of the toxicity and visibility effects for employees, smoke may jeopardize actions to tackle the fire and to put the installation in safe conditions.

2.3 Structural stability in case of fire

In nuclear installations, the structural stability of buildings containing targets shall be guaranteed to lead and maintain the facility in safe conditions. This stability is requested for a fire occurring inside or outside these structures. Consideration also has to be given to the consequences of any interactions between buildings caused by a fire that grows up in a contiguous building.

To demonstrate that the structural stability in case of fire is sufficient, the actual stress (temperature and pressure fields) that these structures are likely to experience, including the cooling phase after extinction, and the structures' behavioural requirements during a fire have to be known.

The analysis process defines the fire scenarios, leading to the worst effects on the structures.

3 HAZARD ANALYSIS PROCESS FOR A FIRE IN A NUCLEAR INSTALLATION

According to the defence in depth, the safety of a nuclear installation in case of fire shall be demonstrated for all of the operating states, including shutdown states, with the operating ranges associated to each operating state. The measures retained to meet the safety objectives have to be described. However, the measures' adequacy has to be justified in particular.

The analysis process shall be based on the verification of the fulfilment of the technical performance levels which are justified through a fire and safety hazard analysis. The operator has to define the safety functions to be protected, the associated functional requirements, the technical performance levels of fire protection measures (FPMs) retained, and to demonstrate the adequacy of these performance levels in relation to the needs and how they are assured by the design adopted. Justification of the measures therefore concerns compliance with technical performance criteria. Calculation of the potential radiological consequences of a fire will only be carried out in a verification step of the safety demonstration.

3.1 Principles to be met

3.1.1 Goals of the fire protection measures

The control of hazards linked to an event such as a fire in a nuclear installation requires the examination of both plausible fires and targets to be protected as part of nuclear safety.

The goals of the protection measures implemented on the basis of this examination are to:

- prevent fires and limit their number, spread and duration,
- maintain functional safety requirements,
- limit the radiological consequences of the fire.

3.1.2 Defence in depth applied to fire protection

To fulfil the aforementioned goals, the fire protection is defined and designed according to the defence in depth principle. These measures are therefore implemented and organized in successive levels that are as independent as possible. Each level of defence against the fire shall prevent the situation from deteriorating and moving to the next level and limit the consequences of the failure of the previous level.

Applied to fire hazards, the levels of defence in nuclear installations can be defined as:

- preventing fires from starting,
- detecting and extinguishing quickly those fires which start, thus limiting the damage,
- preventing the spread of the fires which have not been extinguished, thus minimizing their effects on the installation's safety and their consequences.

It may also be necessary to have an additional levels of defence including the ultimate protection measures inside the installation and the protection of the population in case of a radioactive materials release. These last levels are generally specified in the installation's internal emergency plan and the corresponding external emergency plan. These levels are not covered in this document because fire is not the only initiating event to be considered when defining the corresponding measures.

Fire protection means shall be designed and dimensioned to meet the goals of the aforementioned defence in depth levels as well as possible.

3.1.3 Combination of events

A combination of events is the occurrence that several events are able to affect the same installation in the same period of time. If there is no link between these events, they are independent events. Otherwise, depending on the strength of the correlation, the dependence of the events is potentially proven.

This section looks at the combination of fires with other events to be considered when designing and dimensioning fire protection measures (FPMs). These events may be internal events caused by the failure of equipment involved in a safety function or caused by internal or external hazards.

As a general rule, the combinations shall be explicitly considered whenever there is a proven dependency and no design solution can rule out such a dependency. Any absence of dependency shall be justified. Excluded combinations of events shall be specified and their exclusion shall be justified with regard to their frequency and consequences.

Combinations with a potential dependency shall be examined to determine whether they should be considered. The following situations are to be examined in particular lightning and fire, airplane crash and fire, explosion and fire, earthquake and fire.

Furthermore, an independent fire is to be considered

- in conjunction with each event with a high frequency that is likely to affect the fire protection measures (freezing, loss of external power supply, etc.),
- after an event that undermines the safety of the installation over a long period without any compensatory measures.

For entire combinations of events considered, all of the direct and indirect effects brought about by the initial event are to be studied. Therefore, the effects of these events on the fire protection measures and the associated back-up elements as well as the possible intervention of the external emergency services shall be assessed. If necessary, these fire protection measures will have to be protected against the associated hazards and qualified on the basis of the specific conditions induced.

3.1.4 Margins and uncertainties

The hazard analysis process needs an assessment of the different effects of fire and a comparison with the performance criteria while taking into account the failure conditions of the targets to be protected.

The modelling of the fire scenarios and the evaluation of the scenarios' effects comprise uncertainties that are linked to the input data used to model the scenarios, the values associated with the data, the tools used to determine the effects, the models implemented, etc. These uncertainties shall be assessed and taken into consideration. Furthermore, the margins considered when defining the performance criteria of the fire protection measures shall cover the variability of the situations examined in the installation's safety analysis, which are finally represented by a small number of studied scenarios (“reference” fire scenarios).

The margins selected and the parameters used to determine them shall be presented and justified in the analysis.

3.2 Fire hazard analysis

The fire hazard analysis shall prove that the performance level of the FPMs meets the safety objectives and prove the robustness of the operator's safety demonstration. For the "reference" fire scenarios, this means that the operator will have to show that:

- the fire protection measures (defined according to the defence in depth process) are adapted to the fire hazards,
- their global design ensures, despite the failure of one of these measures, that the consequences for the installation's safety are controlled and the consequences for individuals and the environment remain acceptable.

The performance level of the FPMs is defined according to specific conditions. The hazard analysis shall be updated in case of modification of the installation or for the safety reassessments required by regulations.

The analysis shall reveal the key parameters of the safety demonstration. Then, minor modifications and those likely to significantly undermine the safety demonstration's conclusions can be easily pointed out.

As part of the final verification of the design, the operator shall show that consequences would remain acceptable, even in case of fire in a given room despite the FPMs taken.

3.2.1 Demonstration of the sufficiency of the fire protection measures

3.2.1.1 Elements required for the analysis

This chapter lists the elements which shall be known in addition to the description of the installation's characteristics (dimensions, organization of rooms, layout, procedures, etc.) for the fire hazard analysis.

Functions to be safeguarded and associated functional requirements

The operator identifies the safety functions and the associated support functions to be maintained or to be restored within a relatively short period in case of fire. The operator associates the functional requirements needed to ensure that the corresponding systems and components work correctly during the various operating states.

Targets to be protected against the fire and its effects

The operator identifies the targets to be protected so that the functions defined previously can be safeguarded in case of fire. These targets include, in particular: radioactive materials, material confinement systems, criticality units, SSCs (structures, systems and components) important for safety, material and human resources that play a role in the safety functions to be safeguarded in the event of a fire, escape routes and access routes to equipment which have to be operated to put and keep the installation in safe conditions.

Structures that accommodate or support safety targets are to be protected against the fire. Equipment and structures, different from those mentioned above, are also to be protected against the fire and its effects if the safety of the installation can be affected due to domino effects.

Performance criteria to be met

A nuclear installation operator shall demonstrate by a fire safety analysis that the functional safety requirements are met thanks to the fire protection measures put in place. Considering the process, the effectiveness of these measures has to be compared with quantitative performance criteria. These technical criteria may be threshold values based on, for example, data on the failure of equipment (temperature and thermal flux values that trigger a malfunction, soot particle or toxic particle concentration levels, etc.); whenever possible, they shall include a margin in relation to the experimental or theoretical data.

These performance criteria vary according to the goal of the operator's demonstration. For example, if the operator seeks to demonstrate the resistance of the last stage filter, the performance criteria can be defined in relation to the failure criteria of the filtering system during a fire (i.e. the maximum temperature values and the difference in pressure at the filter terminals).

Furthermore, specific attention shall be given to the fire stability requirement for structures that accommodate or support safety targets. Attention shall also be given to the associated performance criteria, because this functional requirement is generally a priority condition for the compliance with all of the other requirements.

Fire hazards

The fire hazards within the installation, which are likely to impact on the targets, have to be identified for all of the installation's operating states (normal, maintenance, shutdown states, etc.). These fire hazards are linked to the products and materials used and also to the installation's equipment and operating conditions.

The fire hazards outside of the installation, which form part of the industrial, human activities or natural environment (such as lightning, external road or railroad hazards, etc.) shall also be identified in order to define the fire protection measures needed to control external fire hazards.

Fire protection measures

The operator specifies the reliable FPMs for its safety demonstration. The operator justifies the fire protection measures' ability to fulfil their functions (fire detection, heat insulation, smoke tightness, access and extinction of the fire in a room, etc.). The justification of these measures can be based on the fact that they comply with different reference documents or standards, as long as the associated conditions and qualification criteria are adapted to the situation.

With regard to the response to a fire, whether it relies on human or technical actions, the response time to be used for the safety demonstration is the sum of all of the amounts of time needed for the effective implementation of the intervention means.

3.2.1.2 "Reference" fire scenarios

The selection of "reference" fire scenarios is an important part of the safety demonstration. These scenarios justify the suitability and the sufficiency of the fire protection measures retained, considering the fire hazards, by comparing the performance levels of these fire protection measures with the performance criteria.

In practice, numerous fire scenarios could arise in an installation. Nevertheless, it is usually necessary to reduce the possible fire scenarios to a manageable number of credible “reference” fire scenarios.

Two stages are therefore necessary:

- identification of the fire scenarios,
- selection of "reference" fire scenarios for the design of the fire protection measures.

Definition of fire scenarios

The definition of deterministic fire scenarios is carried out by room or group of rooms. Conservative assumptions are to be retained with regard to the parameters used in the scenarios' development (ventilation flow rates, diagnosis and response times, etc.). As part of a deterministic approach, the outbreak of a fire will always be considered.

Selection of "reference" fire scenarios

The fire scenarios thereby identified may be grouped in accordance with their specific characteristics and similarities as long as the fire hazards are of the same nature. The rooms or groups of rooms concerned are covered by the same type of fire protection measures (similar nature and performance levels) and their fire effects are alike.

For each fire scenario group, one or more representative scenarios are selected if they are likely to have the most harmful direct or indirect effects on the targets. These scenarios will be used to check the design of the fire protection measures. They are specified as "reference" fire scenarios. Each reference scenario shall be chosen to ensure that the fire protection measures can also ensure compliance with these objectives for all of the other scenarios of the group.

The conclusions issuing the examination of each reference scenario apply to all of the rooms or groups of rooms covered by a same “reference” fire scenario.

3.2.1.3 Quantification of the effects of "reference" fire scenarios

For each "reference" fire scenario, a quantitative assessment of the characteristic factors of the fire is necessary to assess the effects that the fire can have on targets and the effectiveness of the fire protection measures.

The methods and tools used for this quantification process shall be adapted to the scenarios and the parameters studied. The input parameters and groups of hypotheses shall be reasonably inclusive.

Selection of methods and tools

When the assessment of the characteristic factors under investigation is based on a numerical tool or an analytical calculation method, the capability of the selected tool to match the degree of complexity of the phenomenon studied must be proven. The accuracy, the physical factors to be characterised and the performance criteria are also to be considered. For these tools, a validation and a demonstration of their use in the relevant area shall be provided.

If quantification is carried out on the basis of experimental results, the experimental results shall be presented if they were obtained under conditions that are sufficiently representative of the scenarios. The test results shall be analysed to make sure that the conclusions drawn apply to the cases considered.

In certain specific cases (for example, in case of a lack of adapted calculation method or experimental data), the opinion of experts can be sought. However, a prudent approach should guide the reflexion. In any case, resorting to an expert's opinion shall be clearly mentioned and justified.

Characteristic factors investigated

The characteristic factors to be quantified vary with the "reference" fire scenario(s) retained and the requirements. Aside from the temperature reached in the room and the duration of the fire, factors such as pressure, thermal flux received by the targets, the quantities of soot and unburned materials produced, the toxicity of the smoke, etc. and their associated uncertainties (inherent to the input data, the modeling tool, etc.) may be factors to characterise.

Input data and groups of hypotheses

Regardless of the quantity of input data needed to forecast the characteristic factors of the fire under investigation, some of them may significantly affect the results. They shall be identified and their values justified (physical parameters, values of thresholds for automatic actions, criteria for manual actions, time required for manual actions, etc.). The uncertainties associated with these values shall be assessed.

3.2.1.4 Verification of the performance level of the fire protection measures

The characteristic factors of fire effects in the "reference" scenarios shall therefore be compared with the criteria retained. Then, two situations can ensue:

- one or more criteria are not met: corrective measures shall be taken (new design of fire protection measures, additional measures, modification of initial project, etc.) and the demonstration shall be reconsidered,
- all of the criteria are met: justification of the performance level of the fire protection measures is provided for the reference scenarios; the robustness of the demonstration shall now be proven.

3.2.2 Verification of the robustness of the safety demonstration

The robustness of the safety demonstration, and therefore the sufficiency of the fire protection measures and their design, is proven on the basis of the fire scenario study whose effects could prove to be more harmful than the "reference" scenarios retained at the dimensioning stage; this involves:

- "aggravated" scenarios based on a fire protection measure failure,
- one or more “maximum possible fire” scenarios.

Within the scope of checking whether the consequences for safety, people and the environment remain acceptable.

3.2.2.1 Aggravated scenarios based on a fire protection measure failure

The failure of a fire protection measure can result in fire scenarios that are more harmful than those retained during the dimensioning stage. Consequently, the performance criteria of some of these measures may no longer be respected. This stage therefore consists of checking the robustness of the safety demonstration while making sure that the consequences remain acceptable despite the hypothetical failure of a fire protection measure.

The acceptability of the demonstration is assessed on a case by case basis, while taking the installation, its specific characteristics and its environment into consideration. To test the robustness of the demonstration, two approaches are possible:

- a deterministic approach,
- a probabilistic approach.

Deterministic approach

On the basis of the "reference" fire scenarios, this approach aims to determine the plausible failures of the fire protection measures. Then these failures, considered separately, shall not allow the development of a fire whose effects would result in unacceptable consequences. It is important to recall that in certain cases, the lack of effectiveness of one fire protection measure can impact on the effectiveness of one or more of the other fire protection measures. These cases shall be clearly identified and considered in the demonstration.

The failure can concern material that may belong to an active system, such as the automatic fire detection (failure of a sensor, for example) or an extinguishing system (failure of a valve, for example), or a passive system, such as fire area elements (doors, fire dampers, in particular).

Failure may be the result of human actions, such as the failure of an action or diagnosis or a delayed intervention (incorrect diagnosis by an operator, slow response and slow implementation of equipment by the emergency team).

If the operator provides proof of the robustness of certain fire protection measures, their failure may be ruled out. The operator shall, nevertheless, provide proof that the level of performance of the measures concerned and the measures' functional characteristics are maintained during the fire scenario conditions and for the period required.

Probabilistic approach

This approach allows situations comprising complex events and an accumulation of events to be studied. In particular, situations in which redundant systems are lost and situations involving the occurrence of an external or internal hazard such as a fire. The hazard in terms of the probability of occurrence of the undesirable event is assessed. It includes both failures of a material and of a human or organizational action.

The event tree method is commonly used to represent fire scenarios. It shows how each scenario will develop, determine the events to be studied, assess the influence of measures (fire protection measures, systems and support systems, behavioural procedures, etc.) and consider time-related and functional dependencies between events.

The addition of the values of the frequencies calculated for each sequence of the event tree that leads to the undesirable event gives then the total frequency of the undesirable event for the "reference" scenario. The frequency associated with the reference scenario is then applied to all of the scenarios covered by this reference scenario in order to exhaustively assess the hazard associated with this group of scenarios.

To assess the robustness of the demonstration, the following factors are cross-referenced:

- the total frequency associated with the group of scenarios considered,
- the contribution of the failure of each fire protection measure to the total frequency,
- the corresponding level of consequences.

The approach adopted to create the event trees and the input data retained shall be presented and justified as the robustness of the results of the probabilistic approach chiefly depends on the quality of the input data.

<u>3.2.2.2 Worst case fire scenarios</u>

Eventually, the robustness of fire compartmentation shall be assessed with a final stage in order to check that a fully developed fire in one room or a group of rooms cannot result in unacceptable consequences for safety, people and the environment,.

The rooms or groups of rooms concerned by this stage are those that accommodate mobile radioactive material and that contain - or are likely to contain for a transient period - permanent combustible loads.

The spreading of a fire to all of the loads is to be considered separately from any consideration of the quantity of air available (air tightness or possible ventilation) and fire extinguishing systems that may be present.

The boundaries of the rooms or groups of rooms to be retained for the maximum possible fire study are those for which a fire resistance and a radioactive material confinement capacity are justified. Where a facility is not subdivided by these areas, the maximum area should be defined by the exterior walls and roof of the facility.

3.2.2.3 Assessment of consequences for safety, people and the environment

The consequences of a fire are to be assessed by considering:

- the functional damage brought about by equipment failures,
- the radiological impact.

The failure of any equipment important for safety or the loss of back-up systems requested for these equipment due to the effects of a fire shall induce the operator to carry out a functional analysis in order to check the operability of safety functions required in case of fire.

If the time needed to recover a function is below the lead times needed to recover and maintain the installation in a safe state or if there is a possibility of a functional redundancy, the safety demonstration is acceptable.

The assessment of the radiological consequences of a fire combined with the dissemination of radioactive materials or irradiation exposure concerns both workers, surrounding population, rescue team and the environment.

The quantification of the effects of the fire scenarios shows the quantities of radioactive materials that could be involved. The fractions of the airborne materials are estimated while taking into account the nature of the radionuclides involved, as well as their physicochemical form and volatile character. For each radionuclide or each group of radionuclides, the retained airborne release fraction shall be justified. If results from experiments are used, it shall be guaranteed that the experiment conditions are sufficiently close to the case considered.

The various modes of transfer and deposition mechanisms in the buildings and ventilation systems are to be considered with specific attention to leakages into the environment.

If the radiological consequences thereby assessed are considered to be tolerable, the safety demonstration in the event of a fire is acceptable.

4 CONCLUSION

This document presents the process by IRSN for a comprehensive analysis of fire hazards in nuclear installations.

This document gives the required steps to prove that the fire protection measures in the facility are acceptable and sufficient. On the basis of the safety functional requirements in combination with the protection requirements for safety targets, the operator shall determine the performance criteria that shall be met by the fire protection measures. Compliance with these criteria ensures that the safety objectives will be met in case of a fire.