THE FRENCH FIRE PROTECTION CONCEPT.

VULNERABILITY ANALYSIS

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Abstract

The French fire protection concept is based on a principle of three levels of defence in depth: fire prevention, fire containing and fire controlling. Fire prevention is based on arrangements which prevent the fire from starting or which make difficult for the fire to start. Fire containing is based on design measures so that the fire will have no impact on the safety of the installation. For fire controlling, equipment and personnel are on duty in order to detect, to fight and to gain control over the fire as early as possible.

The French fire protection concept gives priority to fire containing based on passive structural measures. All buildings containing safety equipment are divided into fire compartments (or fire areas) and fire cells (or fire zones). Basically, a compartment houses safety equipment belonging to one division (or train) so that the other division is always available to reach the plant safe shut down or to mitigate an accident.

Because there is a large number of fire compartments and fire cells, deviations from the general principle can be observed. For this reason the RCC-I (Design and Construction Rules applicable for fire protection) requires to implement an assessment of the principle of division. This assessment is called vulnerability analysis.

The vulnerability analysis is usually performed at the end of the project, before erection. It is also possible to perform a vulnerability analysis in an operating nuclear power plant in the scope of a fire safety upgrading programme.

In the vulnerability analysis, the functional failure of all the equipment (except for those protected by a qualified fire barrier, designed or able to withstand the fire consequences) within the fire compartment or cell, where the fire breaks out, is postulated. The potential consequences for the plant safety are analysed.

These consequences are mainly loss of both divisions of safety function by common mode failure. Some of them can cause a core meltdown. In vulnerability analysis, these consequences are classified according to 4 criteria:

- common mode failure concerning redundant components of the same safety function,
- Common mode failure concerning support systems of redundant components of the same safety function,
- Selectivity failure,
- Failure of mitigation systems in case of accidental transient phase caused by the fire.

These potential failures are then assessed from the safety point of view, by a functional analysis. If these failures have an impact on the means to reach the safe shut down or to mitigate an accidental phase, the potential common mode failure is confirmed and must be treated individually, mainly by wrapping cables with insulation fibres.
A vulnerability analysis is being implemented on all the French operating plants.

Computerised cable data files are required to select the common mode failures. Functional and fire risk analyses are performed, on a case by case basis, to justify the common mode failures as they are or to provide modifications for the others. An overview of the first results of the vulnerability analysis is given including a typical description of the modifications proposed to improve safety at optimal cost.

## INTRODUCTION

This document recalls the main stages of the fire protection concept applied by EDF and then stresses one major point of the French fire protection doctrine: the vulnerability analysis. The vulnerability analysis mainly involves the identification and treatment of common mode failures and so prevents the fire from destroyed both trains of redundant safety systems necessary to reach the safe shut down or to mitigation accidental situations. The practical aspect of this methodology is then explained. The vulnerability analysis is carried out on new projects but also for upgrading operating plants. An overview of the first results of the studies and examples are given.

### 1. MAIN OBJECTIVES FOR FIRE PROTECTION

Fire protection aims to fulfil three objectives:

- to ensure the safety of personnel,
- to guarantee the availability of the safety systems which are used to shut down the reactor, to maintain long-term subcriticality, to remove the residual heat and to retain radioactivity,
- to limit damage to equipment which could result in long-term unavailability.

The vulnerability analysis brings a significant contribution to the second objective concerning safety systems.

### 2. FRENCH FIRE PROTECTION CONCEPT

The French fire protection concept is entirely deterministic. It is based on the following two hypotheses:

- a fire may break out anywhere but only one fire at a time,
- the fire may break out whatever the normal operating status of the plant, under power or during shut down, or in a post-accident situation.

The fire protection concept is based on a three level defence-in-depth concept: fire prevention, fire containing and fire controlling.

#### FIRE PREVENTION

Fire prevention is based on arrangements which prevent the fire from starting or which make it difficult for the fire to start. In concrete terms, this means choosing uninflammable or hardly inflammable equipment and fluids. Ignition sources have to be controlled.
FIRE CONTAINING

If, as a result of human error or of equipment failure, a fire should break out, design measures are taken so that the fire, whatever the effectiveness of the fire-fighting facilities, will have no impact on the safety of the installation. The subdivision of buildings into fire compartments and fire cells and the fire barriers set up must therefore confine the fire so that the two redundant trains of a safety system cannot be simultaneously endangered by the fire.

FIRE CONTROLLING

If a fire breaks out, the fire barriers confine it to the fire compartment concerned, thus preventing any direct impact on plant safety. It is nevertheless necessary in order to limit the risks of spreading of the fire and to preserve the availability of the plant, to gain control over the fire as early as possible with automatic detection and fire-fighting actions.

3. SUBDIVISION OF BUILDINGS

Containing the fire requires adequate subdivision of the plants into fire compartments and fire cells, a proper qualification of all the items used as fire barriers and a maintenance and periodic test programme which ensures the continued operability of the corresponding components.

To meet this objective, it is necessary to use layout rules based on physical or geographical separation of components. For plants involving two redundant trains A and B, that means that basically a fire compartment or a fire cell contains equipment of train A or equipment of train B but never A and B together.

Subdivision of buildings is the key-point of fire protection programme and no vulnerability analysis can be performed in a plant where the subdivision of buildings into fire compartments and fire cells has not been properly done, reviewed and finally approved.

4. VULNERABILITY ANALYSIS (REQUIREMENT)

VERIFICATION PROCEDURE

Verifications (studies and on-site visits) are performed on each installation as it is finished. Any singularity which does not conform to the design arrangements mentioned above is identified.

This analysis must list the calorific loads in each room, assess the fire duration by fire compartment or cell and assess the efficiency of the physical or geographical separation of redundant trains.

Because there is a large number of fire compartments and fire cells, deviations from the general principle can be observed. For this reason the Design and Construction Rules applicable to fire protection (RCC-I) requires to implement an assessment of the principle of separation of redundant trains. This assessment is called vulnerability analysis. The vulnerability analysis is carried out on new projects but also for upgrading operating plants. The vulnerability analysis mainly involves the identification and treatment of common mode failures and so prevents the fire from endangering both trains of redundant safety systems necessary to reach the safe shut down or to mitigate accidental situations.
COMMON MODE FAILURE IDENTIFICATION

The vulnerability analysis is carried out in each fire compartment or fire cell. A potential common mode may be identified when a, b, c or d criteria are fulfilled in the same fire compartment or fire cell:

**CRITERION a)**

Safety mechanical components or electrical connections belonging to two redundant trains of the same system performing a safety function,

**CRITERION b)**

Safety mechanical components or electrical connections belonging on the one hand, to the train of a system performing a safety function, and on the other hand, to systems required to operate the same system of the redundant train,

**CRITERION c)**

Electrical connections which are supplied by redundant electrical switchboards, and the number of which is such that the selectivity of the protection of these switchboards is likely to be jeopardised. The criterion c) relating to the non-selectivity of electrical protection is only taken into account when a fire is able to reach both electrical connections simultaneously (only the electrical connections present in the same room shall be taken into account).

**CRITERION d)**

Components, the failure of which, in the event of a fire, is likely to result in an accident or additional operating conditions and components required to perform a safety function necessary for mitigating this accidental event.

COMMON MODE FAILURE TREATMENT

If a potential common mode is detected, it will be necessary to install one or more qualified fire protections or to demonstrate the existence of a functional redundancy, non-affected by the fire, able to perform the safety function endangered by the fire.

EXAMPLES OF IDENTIFICATION OF COMMON MODE FAILURE ACCORDING TO CRITERIA a, b, c or d

**REDUNDANT COMPONENTS OF THE SAME SAFETY FUNCTION (a)**

Example: safety pumps of redundant train located in the same room.

**SUPPORT SYSTEMS (b)**

Example: cooling systems of safety pumps of redundant train located in the same room.
SELECTIVITY FAILURES (c)

Example: Five medium voltage (380V) cables are running through the fire cell 81 (900MW series). They supply a pump, 3 fans and a heating resistance. Each cable is fed by a circuit breaker. The overall amperage of breakers (380V) is 8950 A. The rate of the breaker of the emergency power supply (6600V) is 8000A. In this case the fire can cause loss of emergency power supply by selectivity failure.

Assessment: emergency power supply feeds two other safety fans which are not located in this fire cell. The cables supplying the redundancies of these 2 fans are not running through this fire cell.

Conclusion: loss of emergency power supply does not involve any new common failure mode.

MITIGATION SYSTEMS IN CASE OF ACCIDENTAL TRANSIENT PHASE INDUCED BY FIRE (d):

Examples:
- spurious activation of a pressuriser relief valve,
- opening of a main steam line relief valve caused by the effect of the fire on cables of pressure sensor.

5. VULNERABILITY ANALYSIS (PRACTICAL METHODOLOGY)

The plant has been properly divided into fire compartments and fire cells. It is assumed that the fire will not propagate from one cell or compartment to another. So this vulnerability analysis is performed inside each compartment or cell and common mode failures are identified inside the cell or the compartment.

The vulnerability analysis only deals with equipment and cables necessary to perform safety functions. In practice the vulnerability analysis is performed, at the first stage on all the safety-related equipment and cables.

CABLE DATA FILES

To perform the vulnerability analysis it is necessary to know exactly which pieces of safety equipment are lost if a fire breaks out in a compartment. For mechanical components it is possible to do it manually from drawings and on-site visits, but for fire compartments and fire cells containing hundreds of cables, computerised cable data files are required.

The files report the following information for each cable:
- cable route: fire compartment or fire cell, race, tray,
- system involved, division, voltage, power,
- reference of the equipment at both ends of the cables.
These data files are implemented as follows:

Basically several cable files are available at the Instrumentation and Control Engineering Companies which use them for on-site implementation. These files must be updated with modifications.

For old plants, these files do not cover all the safety cables and they must be upgraded by existing drawings. If no drawings exist, the file must be built by on-site visual observation. Some special tools have been developed to follow the cable route through penetrations or in trays involving a high number of cables by a French Company AINF. These tools allow us to carry out the work of detection even during full operation of the plant.

The files must be reviewed and approved as follows:
- it must be verified that all the safety cables are registered on the files,
- a test is made on a random selection of cables. A comparison is made between on-site arrangement and files. The deviations are analysed and classified into several categories according to safety impact. The rate of deviation must be less than a few per cent.

**IDENTIFICATION OF POTENTIAL COMMON MODE FAILURES**

By processing data, it is easy to list all the equipment and cables which are running in one fire compartment or fire cell.

This data processing is done for all the fire compartments and fire cells. Basically, a compartment or a cell contains a majority of equipment of one train: A for instance. The operator must then focus on equipment of train B which must be carefully and completely listed.

The potential common mode failures are generated from this list by using criteria a and b with the conservative assumption that all the equipment and cables (except for those protected by a qualified fire barrier, designed or able to withstand the fire consequences) within the fire compartment or fire cell, are lost.

In addition, through this process, the operator is able to know precisely which safety functions are lost, or could be lost in case of fire in a given compartment. This is useful for implementing detailed procedures for operating the plant in case of fire.

**COMMON MODE FAILURE PROCESSING AND ASSESSMENT**

At the beginning of the use of this methodology a few years ago, the operator picked out the equipment of the train in the minority and systematically protected it by fire-rated wraps. Today there are four steps of study before deciding to protect the common mode failure. The aim of each step is to examine if the common mode failure could be accepted as it is or not, and in that case to identify cost optimised modifications.

**STEP 1: POTENTIAL COMMON MODE FAILURE**

Potential common modes which are identified by data file processing are called potential common modes.
Example: Fire cell 280 in Nuclear Auxiliary Building:
- 2 fans train A and B in that fire cell,
- cables supplying these 2 redundant fans are running in the fire cell.

**STEP 2: CONFIRMED COMMON MODE FAILURE**

At this second stage a functional analysis is performed: a potential common mode failure is confirmed if it causes safety consequences. The loss of safety function must be analysed in normal state and post accident situation of the plant.

Example: Fire cell 280 in Nuclear Auxiliary Building

Step 1
- 2 fans train A and B in that fire cell
- cables supplying these 2 redundant fans are running in the fire cell.

Step 2

These fans are blowing fresh air in 2 rooms housing high pressure safety injection pumps. Failure of these 2 fans causes overheating of the pump room, failure of both pumps and unavailability of the high pressure safety injection system.

This common mode failure has safety impact so a fire risk analysis is performed at the next step.

**STEP 3: FIRE RISK ANALYSIS**

At this step, an assessment of the first assumption: "the functional failure of all the equipment (excepted those protected by a qualified fire barrier, designed or able to withstand the fire consequences) within the fire compartment or cell where the fire breaks out is postulated" is done. The mechanism of fire propagation is analysed considering the possibility of

- Flash over,
- Local fire (cables or equipment),
- Plume or heat radiation,
- Mutual aggression of components.

At this step, it could be decided to implement complementary fire protection measures (sprinklers, screen) to avoid the fire to endanger both trains.

Example: Fire cell 280 in Nuclear Auxiliary Building

Step 1
- 2 fans train A and B in that fire cell,
- cables supplying these 2 redundant fans are running in the fire cell.
Step 2

These fans are blowing fresh air in 2 rooms housing high pressure safety injection pumps. Failure of these 2 fans causes overheating of the pump room, failure of them and unavailability of the high pressure safety injection system.

This common mode failure has safety impact in mitigation of small size pipe failure. A fire risk analysis is performed at the next step.

Step 3

TABLE I. MECHANICAL AND CABLE COMMON MODE FAILURES

<table>
<thead>
<tr>
<th>Fire propagation</th>
<th>Remark</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash over:</td>
<td>Yes</td>
<td>The fire cell includes a room with 2 vertical cable races. This lay out condition can encourage fire propagation and flash over. These races are encapsulated in a metallic casing to limit the burning rate. The natural air cooling of the cables is possible</td>
</tr>
<tr>
<td>Local fire (fans)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plume</td>
<td>No</td>
<td>Fans are installed on the floor</td>
</tr>
<tr>
<td>Heat radiation</td>
<td>Yes</td>
<td>The fans can be endangered by heat radiation generated by local combustion of nearby horizontal cable race These cable races are encapsulated in a metallic casing to limit the burning rate and radiation heat</td>
</tr>
<tr>
<td>Mutual aggression of components</td>
<td>No</td>
<td>Fans are separated by a ventilation plenum</td>
</tr>
</tbody>
</table>

Cable common mode failure:

<table>
<thead>
<tr>
<th>Fire propagation</th>
<th>Remark</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash over:</td>
<td>Yes</td>
<td>The fire cell includes a room with 2 vertical cable races. This lay out condition can encourage fire propagation and flash over. These cable races are encapsulated in a metallic casing to limit the burning rate. The natural air cooling of the cables is possible</td>
</tr>
<tr>
<td>Local fire (cables)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plume</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Heat radiation</td>
<td>Yes</td>
<td>The cables supplying the fans can be endangered by heat radiation generated by local combustion of nearby horizontal cable race These cable races are encapsulated in a metallic casing to limit the burning rate and radiation heat</td>
</tr>
<tr>
<td>Mutual aggression of components</td>
<td>No</td>
<td>Cables are separated by distance</td>
</tr>
</tbody>
</table>

For this case there is no fourth step because a solution has been found in step three.
**STEP 4: DETAILED FUNCTIONAL ANALYSIS**

Step 2 has confirmed that a safety function has been lost. The functional analysis performed at this step is a detailed functional analysis whose aim is to find whether another safety system can perform the lost safety function.

**TREATMENT FOR COMMON MODE FAILURES**

The Treatment for common mode failures requires high technology equipment. The most frequently adopted solution is to wrap the cables with insulation fibbers.

EDF's specifications have been written up for component testing. For cable wraps, fire tests in laboratories take into consideration the energy dissipated in the cable by the Joule effect, this energy being provided by an electrical resistance installed in the neighbourhood of the cable inside the wraps. Tests for assessing the long term behaviour and ageing are also required.

Most of plants use a soft wrap of mineral fibbers designed by the French Company Mecatiss. This equipment is easy to install in all the configuration met in operating plants. The rating is available in the range 30 to 180 minutes and is chosen according to the design fire duration of the compartment or cell.

**6. OVERVIEW OF VULNERABILITY ANALYSIS IMPLEMENTATION**

**RULES**

For French nuclear power plants under construction (N4 series), the design rules concerning fire protection have been issued by EDF, approved by the Safety Authority and implemented since the beginning of the design.

These rules are formalised in the Design and Construction Rules applicable to fire protection (RCC-I). For N4 series, the vulnerability analysis has been carried out at the design phase.

For operating plants (Fessenheim, Bugey and the series CP1, CP2, P4, P4'), the original fire protection had been designed in accordance with less complete rules.

The first revision of RCC-I, issued in 1983, only mentioned criterion a. Criteria b and c have been introduced in revision 2 issued in 1987. Criterion d was introduced in revision 3 issued in 1992.

An upgrading programme is in progress in all the operating plants to include most of the requirements of the RCC-I issued in 1992. The set of rules concerning fire protection which takes these developments into consideration is formalised in the Fire Directives applicable to each plant or series.

**IMPLEMENTATION: FIRST RESULTS**

The first results (see appendix for details) show that:

- 55% of the common mode failures are accepted as they are,
- 32% are treated with wraps,
- 5% are treated with different solution,
- 8% are still in process.
7. CONCLUSION

Protection against the risk of fire is based on requirements involving three levels of defence in depth.

To ensure that the design hypotheses are fulfilled, a verification phase including a vulnerability analysis is performed at the end of the project.

The vulnerability analysis assumes a conservative assumption that all the equipment and cables (excepted those protected by a qualified fire barrier, designed or able to withstand the fire consequences) within the fire compartment are unavailable and identifies the common failure mode.

Computerised cable files are required to perform this task. This methodology requires a significant contribution of functional and fire risk analyses and allows us relevant cost reduction on series.

The vulnerability analysis increases the operator's confidence for the efficiency of the compartmentation.

In case of fire this methodology guarantees the availability of the safety functions and provides information about availability of safety systems to plant operators.
Appendix

COMMON MODE FAILURE (CMF)

**FUEL BUILDING**

<table>
<thead>
<tr>
<th>Potential CMF</th>
<th>Confirmed CMF</th>
<th>Acceptable CMF</th>
<th>Treatment</th>
<th>Cable wrapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**NUCLEAR AUXILIARY BUILDING**

<table>
<thead>
<tr>
<th>Potential CMF</th>
<th>Confirmed CMF</th>
<th>Acceptable CMF</th>
<th>Treatment</th>
<th>Cable wrapping</th>
<th>Metallic wrapping</th>
<th>Cabinet wrapping</th>
<th>Sensor wrapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>9</td>
<td>0</td>
<td>9</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

**REACTOR BUILDING**

<table>
<thead>
<tr>
<th>Potential CMF</th>
<th>Confirmed CMF</th>
<th>Acceptable CMF</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>25</td>
<td>later</td>
<td></td>
</tr>
</tbody>
</table>

**SWITCHGEAR BUILDING**

<table>
<thead>
<tr>
<th>Potential CMF</th>
<th>Confirmed CMF</th>
<th>Acceptable CMF</th>
<th>Treatment</th>
<th>Wraps</th>
<th>Cable rerouting</th>
<th>Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>117</td>
<td>1</td>
<td>116</td>
<td>102</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>