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Methods to assess effects of cable failures caused by fire

Keywords

cable failure, fire, probabilistic risk assessment, FMEA

Abstract

It is state-of-the-art that a Level 1 PSA also includes a fire PSA for all plant operational states. In performing Fire PSA not only the malfunction of the components has to be assessed but also all supply systems and cables have to be traced for a given component. In the past it was assumed in the case of a fire in a compartment that all components and cables in that compartment are not functional anymore. However, this is in many cases a too conservative approach and could lead to overestimated fire induced core damage frequencies. Therefore, a method is necessary to assess in a more realistic manner the effects of cables failures caused by fire. Such a procedure requires a sound data base on equipment, list of cables and their properties as well as cable routing. Two methods are described which are currently developed. One of them is a cable failure mode and effect analysis which is easier to apply in practice.

1. Introduction

Fire risk assessment has become an integral part of probabilistic safety assessment (PSA). Moreover, fires have been recognized as one major contributor to the risk of nuclear power plants depending on the plant specific fire protection concept. A state-of-the-art Level 1 PSA meanwhile includes Fire PSA as part and supplement of the internal events PSA for all plant operational states.

One of the important parameters in a fire probabilistic risk assessment (PRA) is the conditional probability of a specific failure mode (e.g., loss of function, spurious actuation) of a selected component, given (assuming) that a postulated fire has damaged an electrical cable connected to that component.

In general, evaluation of this parameter can require the analysis of a number of cable failure scenarios, where each scenario involves a particular fire induced cable failure mode and the propagation of the effects of this failure through the associated

electrical circuit. The cable failures of interest cover the following conductor failure modes:

- Loss of continuity,
- Short-to-ground, and
- Conductor to conductor short.

There are three primary functional types of cables in a nuclear power plant: namely, power cables, instrumentation cables, and control cables (cf. *Figure 1*).

Cables can also be categorized by their physical configuration. The most common types are single conductor, multi-conductor, and triplex. Cables are generally routed horizontally through the plant on raceways (in principle on cable trays or conduits) with vertical runs used as required between different elevations in the plant. The cables are generally segregated by type (power, control, and instrument) but cables of various voltages and functions can be found together in the same raceway for some plants (generally older plants).

While short-to-ground or open circuit failures may render a system unavailable, a hot short failure

might lead to other types of circuit faults including spurious actuations, misleading or faulty signals, and unrecoverable losses of plant equipment. These circuit failures, taken individually or in combination with other failures, may have unique and unanticipated impacts on plant safety systems and on plant safe shutdown capability being not always reflected in current Fire PSA studies. In most of the Fire PSAs performed to date, circuit analysis has been performed in a simple manner.

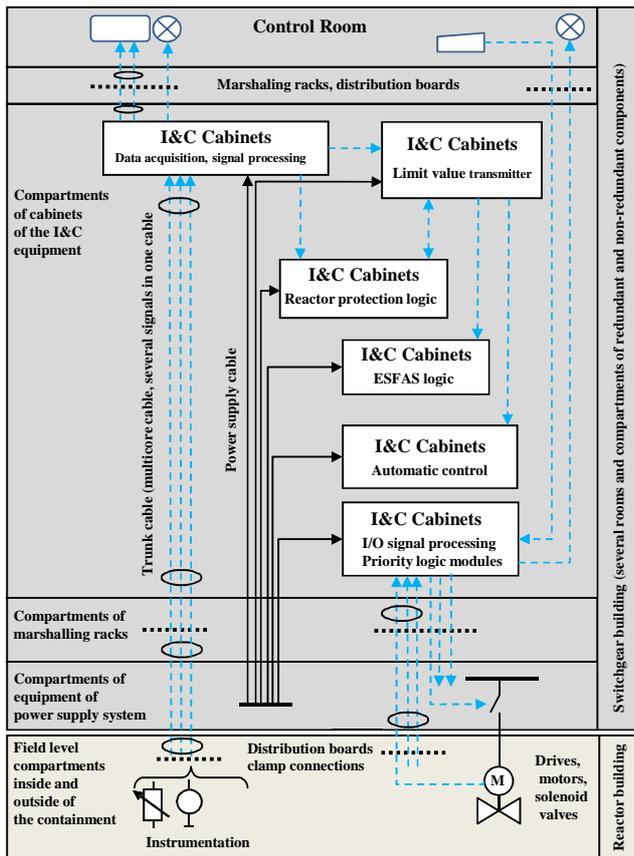


Figure 1. Schematic drawing of I & C (blue, dashed) and power cables (black, solid)

In most cases, the analysis assumes that if any of the cables associated with a given circuit or system are damaged due to fire (i.e., the cables fail), then the circuit or system is rendered unavailable. This approach neglects the potential for spurious actuations entirely, and may represent an optimistic approach. Most of the common approaches apply a single-valued damage threshold of temperature and/or heat flux to predict the onset of cable failure. That is the case, when the cable reaches a predetermined temperature, and/or is exposed to a threshold heat flux, worst case failure of the cables inside the fire compartment is assumed. The worst case failure modes have been deduced by expert judgment.

Simplified assumptions on the failure modes could lead to an overestimation of specific event sequences whereas other effects such as spurious actuation of not directly connected components were neglected.

On that background in the U.S. and in Germany two approaches have been developed. In both cases the success of the method strongly depends on the quality and form of the prerequisite information on the cables and their properties. Therefore, several cable fire tests have been and are performed to gain the necessary data for the safety assessment.

For a more realistic picture of cable failure effects a cable failure mode and effect analysis (FMEA) methodology has been developed. It is intended to use this method as an integral part of Level 1 Fire PSA in Germany.

The main purpose of the methodology and its supporting tools is to improve the comprehensibility and completeness of cable failure analysis within the context of Fire PSA.

The computer aided methodology based on the principles of FMEA is supported by a plant specific database application named CaFEA (*Cable Failures Effect Analysis*) developed by GRS. The database CaFEA comprises all relevant data of the cables, such as cable routing within the plant, cable type as well as data on the connected components. Availability of such information is a prerequisite for the implementation of a state-of-the-art FMEA methodology.

2. Procedure of risk evaluation developed in the U.S.

During the 1990s, both the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) were active in the development of methods for fire risk analysis. U.S. NRC and EPRI initiated a collaborative project to document the state-of-the-art for conducting Fire PSA. The principal objective of the Fire Risk Study is to develop a technical basis and methodology that will clarify issues affecting application of fire risk methods.

The project was designed to culminate in a joint EPRI/RES publication of state-of-the-art Fire PRA methodology. The report NUREG-CR-6850 [3] is a compendium of methods, data and tools to perform a fire probabilistic risk assessment and develop associated insights. This report is intended to serve the needs of a Fire PSA team by providing a structured framework for conduct and documentation of the analysis in four key areas:

- Fire analysis,

- General PRA and plant systems analysis,
- Human reliability analysis (HRA), and
- Electrical analysis.

One finding of the investigations outlined in the report was that the selection, routing, and failure analysis of cables and circuits have not been covered generally by past Fire PSA methodology. The issue of circuit analysis, including the spurious operation of components and systems, continues to be an area of significant technical challenge.

The approaches recommended in the report [3] provide a structured framework for the incorporation of fire-unique cable failure modes and effects in the Fire PSA. The circuit analysis issue impacts Fire PSA methods and practice broadly. Circuit analysis affects the following steps:

- Identification of Fire PSA components and cables,
- Mapping of Fire PSA components and cables to fire analysis compartments,
- Development of the plant post-fire safe shutdown response model,
- Incorporation of circuit failure modes in the quantitative screening analysis,
- Detailed analysis of cable failure modes and effects,
- Detailed analysis of circuit fault modes and effects, and
- Quantification of human actions in response to a fire.

A U.S. NRC report [3] proposing process for including circuit analysis into a fire PSA is shown in Figure 2.

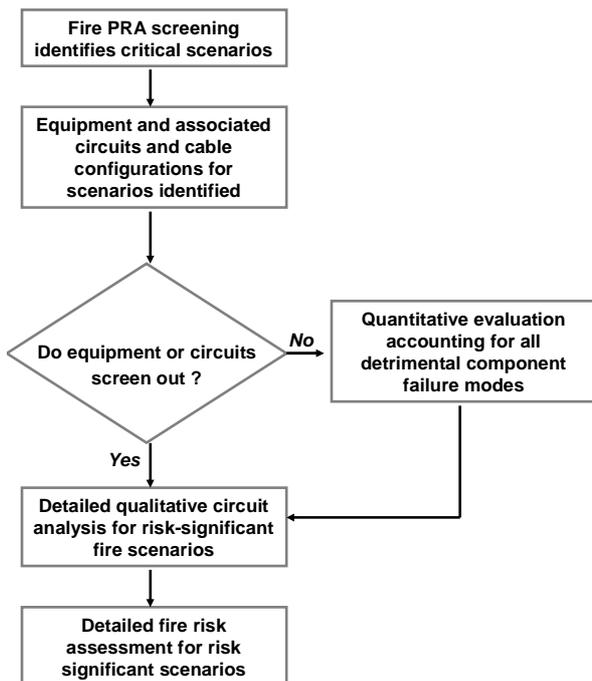


Figure 2. Circuit analysis for fire risk assessment

Another report of the U.S. NRC [6] presents a new methodology for the analysis of cable failure modes and effects (see Figure 3).

Electrical analysis involves circuit failure modes and affects the analysis conducted for specific plant circuits, including the selection of circuits and systems, cable and component routing, development of the Fire PSA database and quantification of failure mode likelihood values.

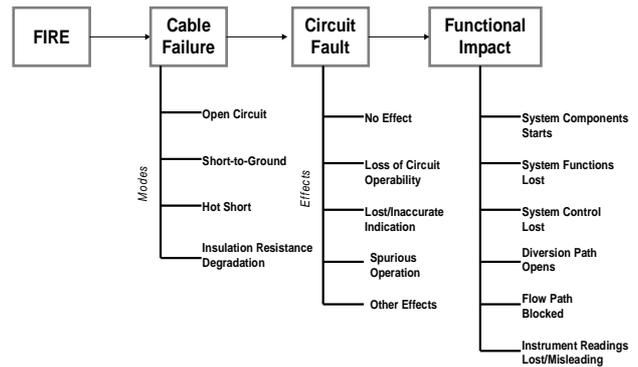


Figure 3. Circuit analysis process structure

Based on experience with the demonstration studies and the collective experience of the authors of the report, at least 4000 engineering hours would be needed to perform a complete plant-wide Fire PRA using the methods recommended in this report. This estimate is predicated on a large number of positive factors in terms of the quality of the plant analyses and the level of sophistication desired in the Fire PRA.

The low-end manpower estimate for the circuit and cable selection, tracing, and analysis efforts (600 hours) represents a case where the following three factors apply:

- The plant has a pre-existing state-of-the-art deterministic post-fire safe shutdown analysis.
- There is a pre-existing and well-documented electronic system for tracing cables and components-
- There is a pre-existing and well-documented Fire PSA safe shutdown plant response model.

The upper end of the manpower estimates for the circuit and cable selection, tracing, and analysis efforts (6000 hours) represents a case where the following conditions apply:

- The plant has a pre-existing deterministic post-fire safe shutdown analysis that has not undergone significant review.
- The plant has merely a paper (non-electronic) cable and raceway system and/or database.

- The Fire PSA model is intended to include at least all components that are credited in the internal events PSA.

The report also [6] provides findings regarding cable fire performance testing in the U.S. over the past three decades. From the viewpoint of cable failure mode likelihood estimation, the available information in these reports is sparse. This is because the bulk of fire-related cable research has focused on one of two areas:

- Most large-scale cable tests were designed to examine the flammability and fire behaviour of cables. In a minority of these tests electrical performance of a small sample of cables was monitored, but this was rarely a primary test objective. Even in those cases where electrical function was monitored, only a small subset of these tests explicitly sought information on cable failure modes.
- A second class of cable tests has sought to determine the failure thresholds of the cables. These are typically small-scale tests where cables are exposed to simulated fire conditions [11]. The time to failure for exposed cables is commonly monitored. The failure behaviour is commonly characterized based on the heat flux or atmospheric temperature in the test chamber and the time of exposure to these conditions.

A second potential source of information on fire-induced cable failure behaviour is actual fire experience. However, fire experience is relatively limited, and fire reports rarely focus on details of cable failures or the resulting circuit faults. The most significant exception to this observation is the 1975 Browns Ferry fire [9]. This fire damaged more than 1600 cables routed in 117 conduits and 26 cable trays. Various studies of that incident have noted that the fire resulted in spurious initiation of components, spurious control room annunciation, spurious indicator light behaviour, and loss of many safety related systems. Examples of the component and system behaviour observed during the fire are outlined in the U.S. NRC report [1].

A range of factors may affect the conditional probability that for a given a fire induced cable failure a particular mode of failure might be observed. Various factors may also affect the timing of potential faults being observed as well as the timing of fault mode transitions (e.g., hot short transition to a short-to-ground). The identified factors can be roughly categorized into one of four broad groups; namely, factors associated with the cable's physical properties and configuration, factors associated with the routing of the cable, factors associated with the electrical function of the circuit, and factors associated with the fire exposure

conditions. The report [3] discusses each of the influence factors identified to date including the current evidence available regarding each of the factors from both experiments and actual experience.

The advanced cable failure analysis should be able to predict when a cable failure occurs, the relative likelihood that specific modes of cable failure would occur given failure, how long a particular failure mode is likely to persist, and the overall occurrence frequency of each cable damage state or failure mode (including fire frequency, fire severity, mitigation by detection and suppression before damage, etc.). The electrical circuit fault analysis determines how each circuit will respond to the various modes of cable failure that may be observed. The circuit fault analysis also feeds information back to the cable failure analysis task by means of specific cable failure modes that may be of particular interest to the PSA and provides occurrence frequency estimates for each of the circuit fault modes of potential interest to risk quantification.

The final task assesses the functional impact of the circuit faults on the potential for plant safe shutdown and quantifies the CDF contribution for the postulated fire scenarios. This task is in the domain of PSA plant systems modelling and event/fault tree analysis and quantification.

3. Failure mode and effect analysis

A computer aided methodology based on the principles of FMEA provided in [6] has been developed by GRS (Germany) to systematically assess the effects of cable failures caused by fire in a nuclear power plant. The main objective of the approach of the GRS is the standardization of the FMEA for similar components of affected electrical circuits. Cable FMEA (CaFEA) consists of two phases of analysis: In the first phase an analysis of generic cable failures of standardized electrical circuits of the nuclear power plant is performed (see *Figure 4*).

Based on the circuit type, the attached source and target component types and sub-types, the operating condition, and the transmitted signal the generic FMEA is performed. All possible circuit failures have to be considered, because it is not necessarily known which cable failures have to be considered while performing the specific FMEA. The experiences gained while applying the computer aided cable FMEA to all cables within one fire compartment demonstrated that about 100 generic circuit types have to be investigated for a whole nuclear power plant.

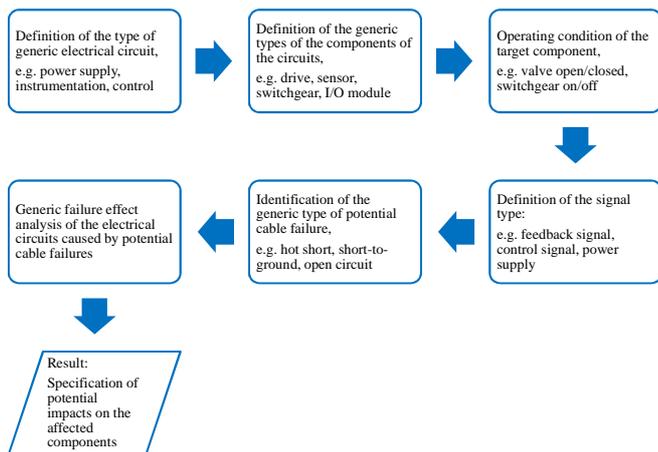


Figure 4. Generic phase of CaFEA

In a first step, the FMEA expert has to screen the list of safety related components typically provided by a Level 1 PSA for full power operational plant states and to define the generic circuit types to be investigated. Examples of circuit types may be power supply circuits, instrumentation circuits or control circuits.

In the next step, for each circuit type “source” and “target” component types have to be specified. Typical source component types are switchgear, electronic board, and relay. Examples of target component types are pump, valve, motor drive, and measurement sensor.

For both, the source and the target components a sub-type or signalling type has to be additionally specified. The sub-type is used to distinguish between different circuit types connected to one component (type). A valve might be attached to the circuit type “power supply” as well as to the circuit type “feedback signal”. For the circuit type “power supply” the source component sub-type might be “power supply” and the target component sub-type “motor”. For the circuit type “feedback signal” the source component sub-type might be “drive control module” and the target component sub-type “control head”.

The possible effects on the attached component depend on the operating condition of the target component type. Therefore, the generic FMEA has to be performed for all operating conditions of the generic circuit type. The effects also depend on the type of signal transmitted by the cable. Valid signal types could be e.g. feedback signal of a valve or control signal for a motor.

Table I shows an example of the generic FMEA for different combinations of source and target (sub-) types.

In the second phase, those generic failure modes are identified for each cable which could affect safety related components (see Figure 5). Based on the information on the cable type, the attached components and their types, as well as on their operational mode, all the possible cable failures have to be identified by the FMEA expert. The probable cable failures are a sub-set of the failure modes found in the generic FMEA. The specific effects identified in the second phase of the FMEA are mapped to basic events used as initiating events and/or component failures in the Fire PSA.

The failure conditions for the cables were specified on the basis of the results of fire tests carried out at Braunschweig University of Technology Institute for Building Materials, Concrete Construction and Fire Protection (iBMB) (see [4] and [8]). In these fire tests, among other things, the fire induced functional failures of the cables were examined for both, energized as well as non-energized cables.

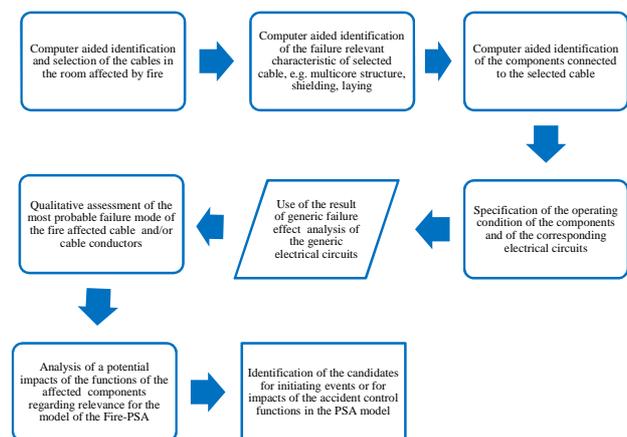


Figure 5. Room specific phase of CaFEA

Based on the test results of the iBMB study, the following different types of cable failure modes were specified and are used in the cable FMEA:

- Short-to-ground via insulation material of the cable jacket or an earthed conductor inside or outside a cable or via earthed structures, e.g. a cable tray;
- Hot short to an energized conductor inside or outside a cable (e.g. high-voltage propagation, impacts of electric arcs);
- Short circuit fault to a de-energized conductor inside or outside a cable (high or low impedance failure);
- Interruption of the cable conductor (open circuit failure mode).

Table 1. Examples of a generic FMEA

Description of the electrical circuit							Generic FMEA		
Source of signal (power) of process, electric or electronic components		Target of signal (power) of process, electric or electronic components		Description of the signal			Failure mode	Failure effect	Identification
Type	Subtype	Type	Subtype	State	Type	function			
I&C cabinet (Data acquisition sub-system)	Analog input module SAA (TXS)	Level transmitter	Differential pressure transmitter (4 lead / 0-20mA Loop)	Normal value	Level measurement	Power supply	Intrerruption of the circuit (broken conductor)	Interruption of the power supply of the transmitter	output Signal of transmitter I=0mA (Message: signal is out of the range)
I&C cabinet (Data acquisition sub-system)	Analog input module SAA (TXS)	Level transmitter	Differential Pressure Transmitter (4 lead / 0-20mA Loop)	Normal value	Level measurement	Power supply	Ground fault of the circuit	Interruption of the power supply of the transmitter	Message: signal is out of the range (output Signal of transmitter I=0mA)
I&C cabinet (Data acquisition sub-system)	Analog input module SAA (TXS)	Level transmitter	Differential pressure transmitter (4 lead / 0-20mA Loop)	Normal value	Level measurement	Measurement loop	Intrerruption of the circuit (broken conductor)	Signal is out of the range	Open circuit monitoring
I&C cabinet (Data acquisition sub-system)	Analog input module SAA (TXS)	Level transmitter	Differential pressure transmitter (4 lead / 0-20mA Loop)	Normal value	Level measurement	Measurement loop	Ground fault of the circuit	False value (higher or lower) of the output signal of transmitter	Signal range monitoring / redundant signal comparator
I&C cabinet (Data acquisition sub-system)	Analog input module SAA (TXS)	Level transmitter	Differential pressure transmitter (4 lead / 0-20mA Loop)	Normal value	Level measurement	Measurement loop	Hot-short fault of the circuit	False value (higher or lower) of the output signal of transmitter	Signal range monitoring / redundant signal comparator
I&C cabinet (drive control circuits)	Analog output module XPA92, Output C18	Contact relais of the MOV	Contacts of the control circuit	open	Normally open circuit	control command CLOSE to coupling relay	Intrerruption of the circuit (broken conductor)	Loss of CLOSE function of the MOV	MOV remains in "OPEN" position by test
I&C cabinet (drive control circuits)	Analog output module XPA92, Output C18	Contact relais of the MOV	Contacts of the control circuit	open	Normally open circuit	control command CLOSE to coupling relay	Ground fault of the circuit	spurious close of the MOV	Indication of the RUN and CLOSED functions of the MOV
I&C cabinet (drive control circuits)	Analog output module XPA92, Output C18	Contact relais of the MOV	Contacts of the control circuit	open	Normally open circuit	control command CLOSE to coupling relay	Hot-short fault of the circuit	spurious close of the MOV	Indication of the RUN and CLOSED functions of the MOV
I&C cabinet (drive control circuits)	Analog output module XPA92, Output C18	Contact relais of the MOV	Contacts of the control circuit	open	Normally open circuit	control command CLOSE to coupling relay	Hot-short fault (overvoltage) of the circuit	Destroying of the analog output module XPA92	Loss of the control of the MOV
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B03	Closed loop	position indication of the MOV	CLOSED indication of the MOV	Intrerruption of the circuit (broken conductor)	Loss of the indication of the position CLOSED of the MOV	Functional test
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B03	Closed loop	position indication of the MOV	CLOSED indication of the MOV	Ground fault of the circuit	Loss of the indication of the position CLOSED of the MOV	Functional test
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B03	Closed loop	position indication of the MOV	CLOSED indication of the MOV	Hot-short (shorts to power lead)	False indication „MOV contactor CLOSED“ and „MOV run“	Inconsistency of MOV position indication (e.g. MCR, I&C cabinet, alarm system)
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B04	Closed loop	position indication of the MOV	OPEN indication of the MOV	Intrerruption of the circuit (broken conductor)	Loss of the indication of the position OPEN of the MOV	Functional test
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B04	Closed loop	position indication of the MOV	OPEN indication of the MOV	Ground fault of the circuit	Loss of the indication of the position OPEN of the MOV	Functional test
Motor-operated valve (MOV)	Contacts of the position indication	I&C cabinet (drive control circuits)	Module XKU98, Input signal B04	Closed loop	position indication of the MOV	OPEN indication of the MOV	Hot-short (shorts to power lead)	False indication „MOV contactor OPEN “ and „MOV run“	MOV position indication (e.g. MCR, I&C cabinet, alarm system)

The database application consists of a user interface frontend and a database backend. With the aid of CaFEA, the data obtained in the FMEA for fires can be systematically evaluated for cable failures. The CaFEA database comprises the data from different sources, correlates them to each other and displays the correlation results to the FMEA expert who carries out the actual failure mode and effects analysis and stores the results in the database. The database frontend can be used for data sets of different nuclear power plants. The FMEA is specific for the plant operational state stored in the database. After opening the database application the user can choose if the generic or the specific FMEA

shall be performed. For both tasks input forms are available.

If (incomplete) specific FMEA results already exist in the database the user can create template data for the generic FMEA. The input form for the generic FMEA contains questions with respect to the following data:

- Type and sub-type of source component,
- Type and sub-type of target component,
- Operating condition of target component,
- Identification of the signal type (circuit type),
- Failure of the cable occurring in the electrical circuit affected by the fire,
- Effect on the target component,

- Optional comment on the determined component effect and its relevance for the PSA.

The user interface for the component specific FMEA in the CaFEA application subdivides the different analytical steps into sub-tasks:

- After selecting a compartment and a cable function (corresponding to one signal transmitted via the cable) the first sub-task consists in providing information about the components connected to the cable (“start” and “end” component) and the target component. For the target component the operating condition has also to be provided. The last step is supported by providing information from the plant operating manual and/or safety specifications included in the database.
- In the second sub-task, the FMEA expert has to specify all possible cable failure modes for the selected cable function. For performing the FMEA information about the cable type, routing, etc. have to be considered, have to be provided by the FMEA expert and are stored in the database.
- The third sub-task consists in the determination of the effect on the component by the cable failure mode. By means of a query in the database it is checked if a generic FMEA result provided by the FMEA expert in the previous steps is applicable to the specific case. If this is the case, the FMEA expert has to decide how to apply it to the specific case.

4. First exemplary application of the cable FMEA

The analytical method and database tool CaFEA has been developed by GRS based on the available plant data (database with respect to components and compartments and cable routing in the reference nuclear power plant) and on a generic procedure for analyzing fire induced circuit failures in the cables concerned. The FMEA method was tested using data of a reference plant for a given compartment. 432 cables are routed through this compartment transmitting in total 932 signals because of some cables representing I&C cables with multiple conductors.

The qualitatively estimated probability (high, medium and low probability class) was assigned as conditional probability in case of fire to the corresponding effect on the component and the resulting PSA basic event or initiating event.

5. Conclusions and outlook

This paper describes, in addition to the U.S. approach, a second possible method to assess effects

of cable failures. The computer aided methodology of the FMEA offers a good basis for performing a systematic and traceable analysis of the effects of fire induced cable failures in the frame of a Fire PSA. In principle, the FMEA methodology developed may be also applied for investigating cable failures in the frame of analyzing the effect of other plant internal or external hazards such as flooding and or structural damage by earthquakes.

The major difference between the methodology proposed in [3] and [6] and that one developed by GRS is, that the computer aided methodology CaFEA uses a combination of generic and specific tasks of the FMEA of the cable failures. This can reduce the specific FMEA of all circuits in the fire affected compartments of the NPP significantly. The database application of generic cable FMEA can be extended with regard to consideration of all typical electrical circuits in a generic power plant.

Up to now, the results of the FMEA provide only qualitative indications for the component effects resulting in the unavailability of system functions or new initiating events in the Fire PSA. In a next step, quantification of the failure mode probabilities and the corresponding effects on the affected components shall be included in the approach. The current database architecture of CaFEA allows an easy integration of this feature in the future.

Future challenges of the CaFEA development are the consideration of failure modes of new (digital) technologies of signal transmission and processing, e.g. bus architectures of I&C systems, fiber optical cables, etc.

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