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Parametric fuzzy study for effects analysis of age on PWR containment cooling system

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Abstract

This paper presents an alternative parametric fuzzy study to subside aging impact analysis on the performance and availability of safety industrial systems. To this sense, a fuzzy fault tree computational system analysis, named of FuzzyFTA, was adopted. FuzzyFTA is a computing system that uses fault tree and fuzzy logic to determine fault event fuzzy importance and associated fuzzy uncertainty measures. The main goal of this approach makes possible, elapsed many years of plant operation, the gray determination of the system critical components and top event occurrence probability. A typical four loops pressurized water reactor (PWR) containment cooling system (CCS) was selected to examine the feasibility of the computational system approach in a real case study. Thus, a commonly found containment spray system and a fan cooler system were modeled. Failure rates, obtained from the operation of a PWR along 20 years, were accounted in the model. The bathtub curve characteristics presents in these failure rates permit the determination of the time-dependent effects of aging degradation more important to the general uncertainty of system. Thus, the system unavailability, considering the component failure rates increase by aging, can be calculated.

Keywords: Fault tree; Fuzzy logic; Aging; Unavailability; PWR

1. Introduction

The fault tree approach has been used for the last 15 years to evaluate top event in probabilistic safety analysis studies (PSA level I & II) at nuclear power plant (NPP). Two basic problems have compromised these studies results. First, many of the systems evaluated for the PSA analysis consider components with small amount information about the operational performance of the each component. Its generates a level of uncertainty on fault tree results. Second, the population of commercial nuclear power plants has matured, resulting in component aging process.

Monte-Carlo method has been used to evaluate each component uncertainty contribution for system general uncertainty. This approach, however, may lead to large variances on top event probability and it is computationally very expensive. In recent years, artificial intelligence (AI) has yielded good solutions to old nuclear problems, such as reactor core design [1], fuel reload [2], test surveillance planing [3], preventive maintenance optimization [4,5], reduced scale experiment design [6], steam generator corrosion [7]. In our study, the FuzzyFTA computing system, which use fuzzy logic [8] and fault tree coupled [9], was able to solve the aforementioned uncertainty problem.

Another problem, however, has deserved the attention of researchers and regulators staff around the word. Today, the nuclear power plants (NPP) are account for about 20% of the electric power generated in the world. United States alone, in late 1989, had 108 reactors in commercial operation. In recent studies the future perspectives of applied nuclear energy have been analyzed under the aging process point of view [10]. These studies proved that the option by electric nuclear generation would remain in world energy matrix by at least 50 years. As mentioned, the population of commercial nuclear power plants has matured and its principal safety and

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operational components are under aging process. By the year 2014, 48 of these plants will have been operating for 40 years (design life expectance). To solve this problem, energy area researchers and engineers have developed studies to comprehend causes and effects of the aging phenomena.

Recently, was performed a study on the aging process in nuclear power plant containment cooling systems (CCS) [11]. This study was performed to assess the effects of aging on the performance and availability containment cooling system in U.S. commercial nuclear power plants. This study is part of the Nuclear Plant Aging Research (NPAR) program sponsored by the U.S. Nuclear Regulatory Commission. The main objective of this program is to provide an understanding of the aging process and how it affects plant safety so that it can be properly managed. This is one of several studies performed under the NPAR program, which provide a technical basis for the identification and evaluation of degradation caused by age. The effects of age were characterized for the containment cooling system by reviewing and analyzing failure data from national databases, as well as plant-specific data. The predominant failure causes and aging mechanisms were identified, along with the components that failed most frequently. Current inspection, surveillance, and monitoring practices were also examined. In same report, a parameter sensibility analysis was performed to examine the potential effects of aging by increasing failures rates for selected components. A commonly found containment spray system design and a commonly found fan cooler system design were modeled. Parametric failures rates for those components in each system that could be subject to aging were accounted for in the model to simulate the time-dependent effects of aging degradation, assuming no provisions are made to properly manage it. System unavailability as a function of increasing components failure rates was then calculated. This is the principal reference in our study and its was used here for comparative analysis with fuzzy parametric study proposed.

The goal of the NPAR program is to improve the operational readiness of nuclear plant systems and components that are important to safety by understanding and managing the effects of aging degradation. To accomplish this, the NPAR studies are typically performed in two phases. In phase I, the effects of aging are characterized by identifying the predominant failure modes and mechanisms, along with the components most frequently failed. The potential effects of improperly managed aging deterioration are also reviewed in terms of the impact on system availability and component importance. If aging is found to be a concern, a phase II study is performed in which methods of detecting and mitigating aging process are reviewed.

Considering the research lines aforementioned, the goal of this paper is to developed a realistic study where the safety significance and time-dependent unavailability impact, including the aging process and the uncertainty on the failure rates, are considered by the use of the a FuzzyFTA computing system. A very important nuclear safety system, a typical four loops pressurized water reactor (PWR) containment cooling system (CCS) was selected to this case study.

In the next items, it will be done a summarized description of system CCS, some comments about fuzzy fault tree approach and a application using containment spray and fan cooler system. Finally, the obtained results and the pertinent conclusions are presented.

2. Containment cooling system description

The CCS (containment cooling system) has the main function of to remove heat and to control the pressure inside the containment of a reactor removing the fission products

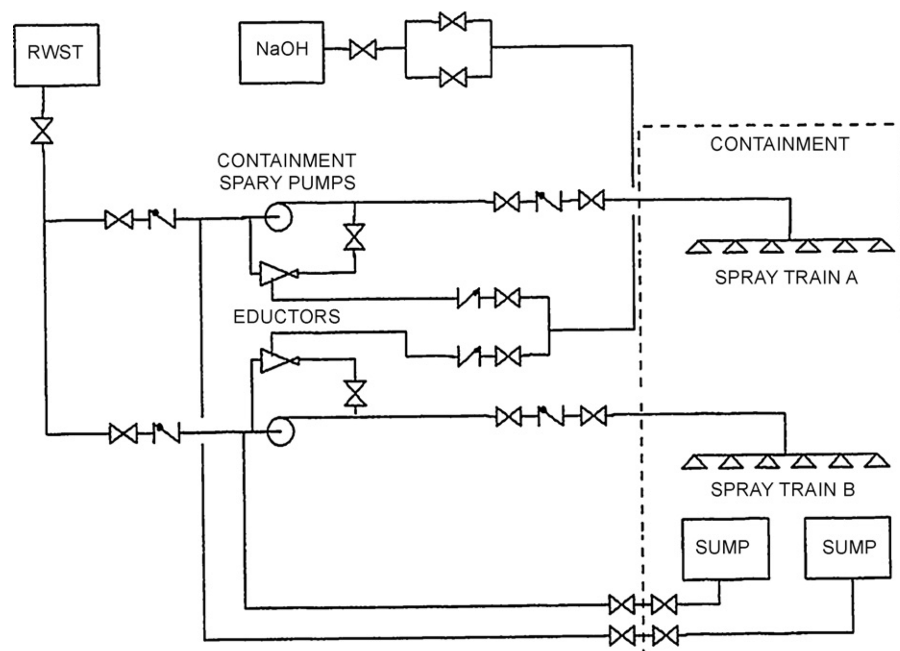

Fig. 1. Common PWR containment spray system design.

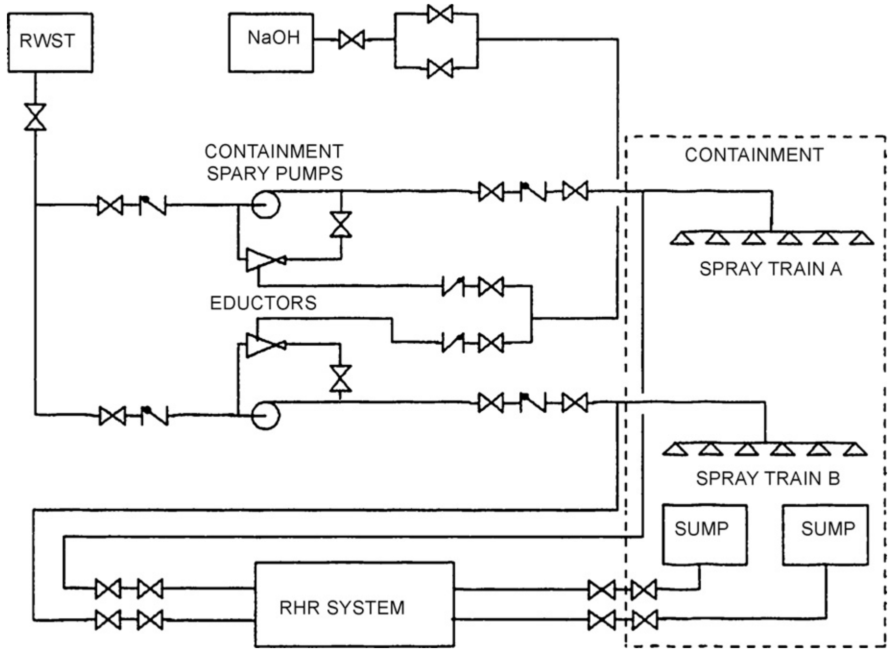

Fig. 2. Alternate PWR containment spray system design.

produced in the occurrence of an accident with release for containment. In projects of the type PWR, the CCS is constituted of spray systems and fan cooler units. The main function is the same in different systems but the projects can vary of plant for plant. The water is sprayed through nozzles located in the superior part of the containment. Its main function is to condense vapor due to a LOCA, for example, reducing the pressure and the temperature inside containment. In general, the sprayed water is used of the storage tank (RWST—refueling water storage tank) during injection phase (Fig. 1). When RWST becoming empty, or reaches a specified low level, the water now is collected of the sump of the containment. Some projects use the pumps of RHR (residual heat removal) for the re-circulation phase instead of containment pumps (Fig. 2). Chemical additive of the type hydroxide or hydrazine are adopted in the sprayed water.

Also, fans units (Fig. 3) are integral parts of the CCS system, and they are used during the normal operation to maintain the

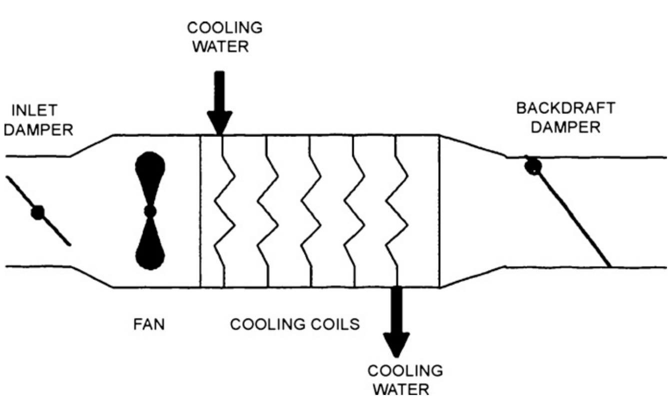

Fig. 3. Fan cooler unit schematic.

atmosphere of the containment cooled. In general, for PWRs, the fans are used also in cases of occurrence of accidents reducing the pressure and the temperature after a LOCA (loss of coolant accident). Three or more units are located inside containment, with one or two fans for unit.

Depending on the temperature and pressure inside containment in normal conditions the operator determines the number of units running.

Additional design information on PWR containment spray system (CCS) can be found in Ref. [11].

3. Fuzzy uncertainty importance measure

3.1. Probabilistic considerations

In fault tree analysis, the system failure probability can be expressed using minimal cut sets of the components. The unreliability function of a system can be written as the sum of partial products of the unreliability of components. Thus the system failure probability is

$$Q = f(q_1, q_2, \ldots q_i, \ldots, q_n) \tag{1}$$

where q_i is the unreliability or failure probability of component i and n is the total number of components.

3.2. Fuzzy considerations for uncertainty analysis

When the unreliability of each component has a point estimate, the top event unreliability will also be a point estimate. In this work, the component failure probabilities are considered as triangular fuzzy sets to incorporate the uncertainties of each relevant parameter.

The membership function of a triangular fuzzy set is defined as

$$\mu_X(x) = \begin{cases} \max\left[0, 1 - \left|\dfrac{x - x_1}{x_2 - x_1}\right|\right], & x_1 \le x \le x_2, \\ 1 & x = x_2, \\ \max\left[0, 1 - \left|\dfrac{x_3 - x}{x_3 - x_2}\right|\right], & x_2 \le x \le x_3, \\ 0 & \text{otherwise}, \end{cases} \quad (2)$$

with

$$\mu_X(x_2) = 1 \quad (3)$$

$$\mu_X(x_1) = m_X(x_3) = 0, \quad (4)$$

and $[x_1, x_3]$ are lower-bound and upper-bounds of triangular fuzzy sets. For demonstration, these values may be obtained from the median point value and the error factor (EF) of the failure probability [12]. The lower-bound, middle-value and the upper-bound are defined as

$$x_1 = \frac{q_p}{\text{EF}} \quad (5)$$

$$x_2 = q_p \quad (6)$$

$$x_3 = q_p\text{EF} \quad (7)$$

where q_p is the point median value of the failure probability. The fuzzy evaluation of the failure probability of the top event in a fault tree is carried out using α-cut method. The top event can be represented by an $N \times 2$ array, where N is the number of α-cuts.

3.3. Importance measures

The identification of critical component is essential for the safety analysis of any system. Many methods are available in probabilistic approach like risk achievement worth, Birnbaum importance, Fussel Vesely importance, etc. Two different importance measures are introduced: (1) FIM – fuzzy importance measure and (2) FUIM – fuzzy uncertainty importance measure.

The evaluation of the contribution of different basic event is essential to identify the critical components in the system. The top event failure probability by making the component ‘i’ unavailable ($q = 1$) is

$$Q_{q_i} = 1 = f(q_1, q_2, \ldots, q_{i-1}, 1, q_{i+1}, \ldots, q_n) \quad (8)$$

and for component ‘i’ fully available is

$$Q_{q_i} = 0 = f(q_1, q_2, \ldots, q_{i-1}, 0, q_{i+1}, \ldots, q_n) \quad (9)$$

The fuzzy importance measure (FIM) is defined as

$$\text{FIM} = \text{ED}\,[Q_{q_i=1}, Q_{q_i=0}], \quad (10)$$

where $\text{ED}\,[Q_{q_i=1}, Q_{q_i=0},]$, is the Euclidean distance between two fuzzy sets A and B is defined as

$$\text{ED}\,[\text{A}, \text{B}] = \Sigma((a_\text{L} - b_\text{L})^2 + (a_\text{U} - b_\text{U})^2)^{0.5}_{\alpha_i}, \quad \alpha_i = 1, 2, \ldots, N \quad (11)$$

where a_L, b_L and a_U, b_U being lower and upper values of fuzzy set A and B, respectively, at each α-level.

The fuzzy uncertainty importance measure is used to identify the main components which contribute to the uncertainty of the top event, and is defined as

$$\text{FUIM} = \text{ED}\,[Q, Q_i] \quad (12)$$

where Q is the top event failure probability, Q_i is the top event probability when the error factor for component ‘i’ is unity ($\text{EF}_i = 1$), i.e., the parameter of the basic event has a point value or crisp value.

4. Safety significance, time-dependent unavailability impact and sensitive analysis (adopted premises)

One of the primary reasons for understanding and managing aging of nuclear power plants is that as components and systems age, there may be an increase in failure rate due to unchecked aging degradation. If this occurs, it could result in a decrease in system availability. In general, to understand the significance of decreased containment cooling system availability on plant safety, several existing probabilistic risk assessments (PRA) must be reviewed to better define the role of this system. A system unavailability analysis generally is performed to simulate the effects of unmitigated aging on the availability of common containment spray system and fan cooler system designs.

About safety significance of the containment cooling system may be spoken that during normal operation, the majority of the heat generated in the reactor is removed by the power conversion system. The remainder is transferred to the containment atmosphere and the structures within it. One function of the containment cooling system is to remove this waste heat during normal operation and maintain the containment atmosphere within specified temperature limits. This is necessary for proper operation of the components and structures within containment, and to prolong their life.

4.1. Unavailability analysis of the containment spray system

As the basis of this analysis, an existing utility PRA was obtained which included a common design for a containment spray system, with sodium hydroxide injection. A system fault tree model was developed, and several system components that could be affected by aging were identified. A base case unavailability was calculated using the failure rates specified in the utility PRA or generic databases.

4.1.1. Results obtained from traditional study

The unavailability for the containment spray system was calculated to be 4.1E−3 per demand. The top 15 cut sets, which account for over 99% of the system unavailability, are defined. From this cut sets, the more relevant failure events that can be affected by aging are then defined.

4.1.2. Parametric study

A parametric study was then performed and the failure rate for selected components was increased by factors of 2, 5, and 10 to simulate the effect of increasing failure rates due aging. The system unavailability was recalculated for each case. This multiplier factories are used by U.S. Nuclear Regulatory Commission (NRC) in the classical study [11]. So, to propitiate a comparative analysis and, to maintain the coherence with the NRC experience, its values were adopted.

4.2. Unavailability analysis of fan cooler units

The basic events of the fan cooler fault tree are the fan motors, circuit breakers, and dampers failures. As for the

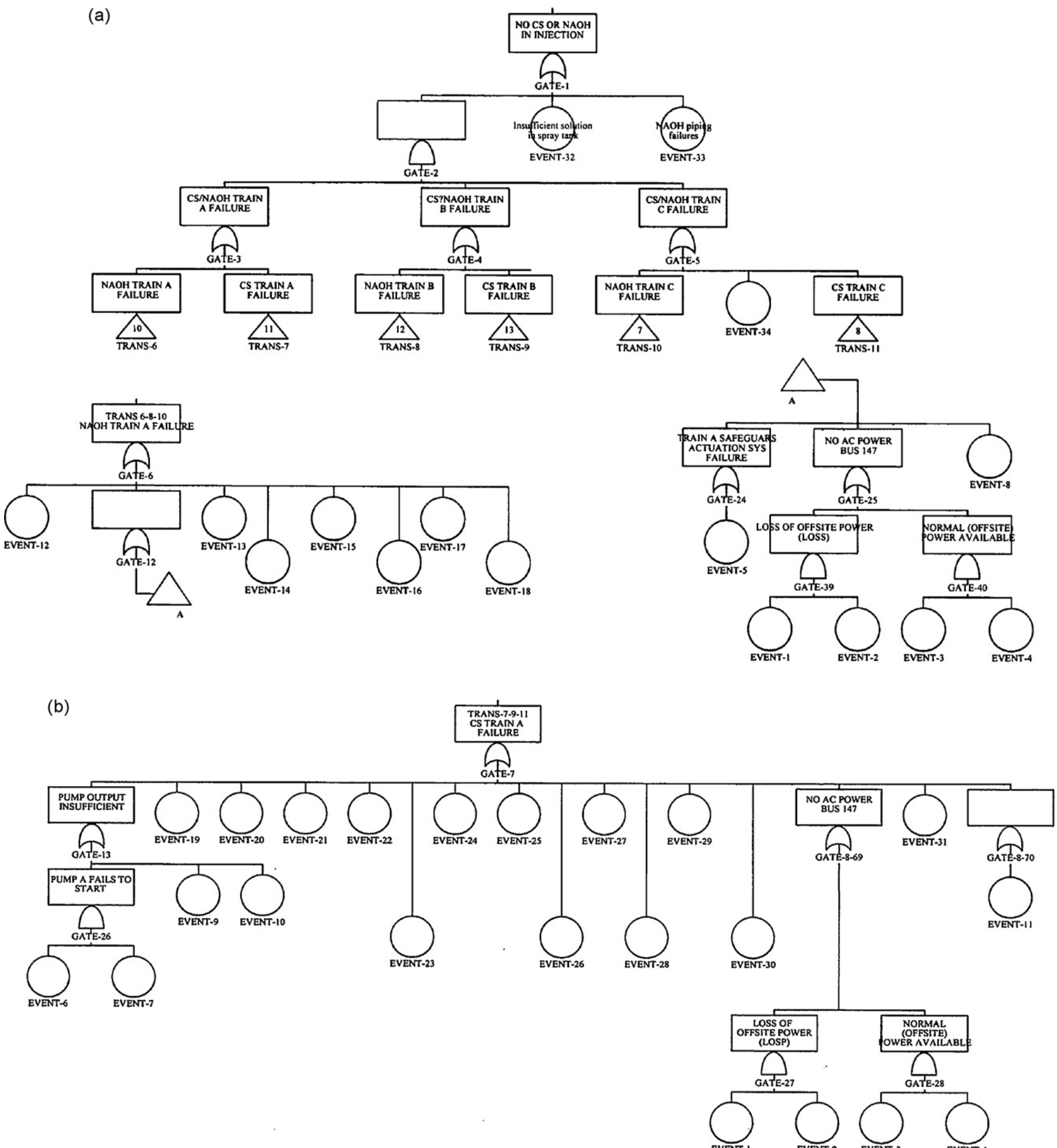

Fig. 4. (a) Fault tree of the containment spray and (b) continuation of the containment spray fault tree.

containment spray system, maintenance unavailability was also included in the model.

4.2.1. Results obtained from traditional study

Using the traditional approach the containment fan cooler system unavailability were calculated to be 5.3E−5 per demand. The top 10 cut sets are defined, and there are no dominant failure contributors. The high top cut set contributes with 11% to system unavailability.

4.2.2. Parametric study

A parametric study similar for the containment spray system was performed for the fan cooler system.

5. Fault tree qualitative analysis

In order to demonstrate the applicability of the fuzzyFTA to solve the questions commented on the introduction section, it was performed the containment spray and fan coolers system

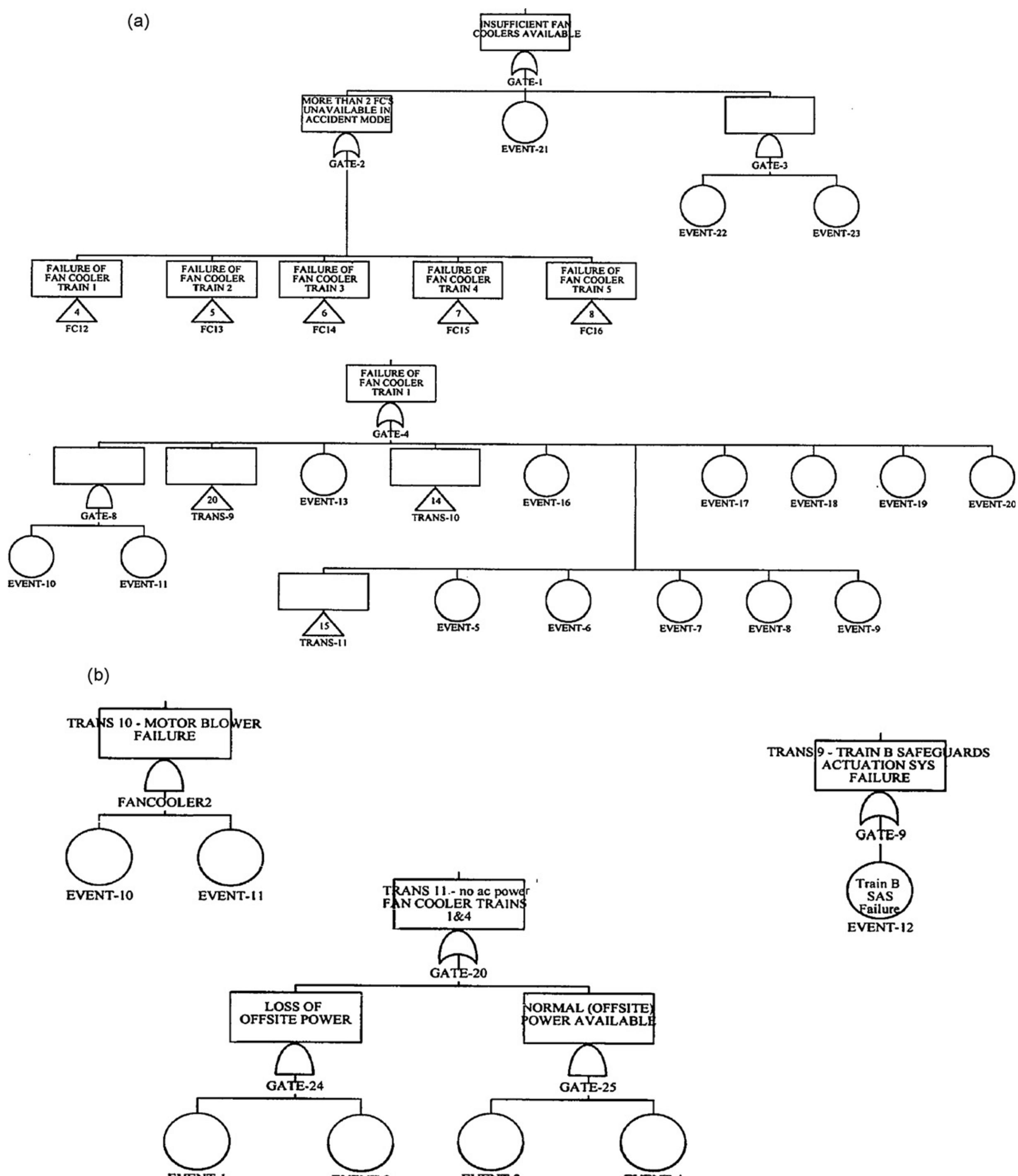

Fig. 5. (a) Containment fan cooler fault tree and (b) continuation of containment fan cooler.

Table 1
Failure probability and the ranks for spray system components

Event no.	Failure probability	Error factor	FIM ranking MCS	FUIM ranking MCS
1	6.48E−7	10	29	29
2	8E−5	10	29	29
3	8E−5	10	31	33
4	6.48E−7	10	31	33
5	9E−5	10	12	13
6	3E−4	10	33	33
7	8E−4	10	33	33
8	8E−4	10	1	3
9	3E−4	10	10	10
10	3E−4	10	10	5
11	9E−5	10	13	12
12	6E−5	10	17	16
13	6E−5	10	17	17
14	3E−5	10	22	21
15	3E−5	10	25	25
16	8E−5	10	15	14
17	8E−4	10	3	2
18	8E−5	10	15	15
19	8E−4	10	3	1
20	2E−5	10	27	26
21	2E−5	10	27	27
22	3E−4	10	10	9
23	3E−5	10	22	20
24	3E−4	10	10	8
25	3E−5	10	22	24
26	2E−4	10	11	11
27	4E−5	10	19	19
28	3E−5	10	24	22
29	3E−5	10	24	23
30	3E−4	10	10	7
31	3E−4	10	10	6
32	6E−4	10	4	4
33	5E−5	10	18	18
34	6.48E−7	10	34	34

unavailability analysis. A common operational scheme for containment cooling system with sodium hydroxide injection was made and a system fault tree model developed. Several system components that could be affected by aging were identified. In theses cases studies, the system unavailability was calculated using an hypothetical PWR 20 year operation failure rates database. Subsequently, in order to investigate extreme situations and to test the sensibility of the fuzzyFTA, a parametric study was performed. Were selected the five events that more contributed to the general uncertainty of system in regular study. In according to NRC study, in this sensitivity analysis, the probabilities were multiplied by 2, 5 and 10. This study is suitable to simulate and help the understanding of the system global effect of a hypothetical severity increase of the failure rates due to aging process. The system unavailability was recalculated for each one of these cases.

The containment spray system consists of two trains, so the success criterion for the containment spray system is at least one of two trains available to inject water into the containment, when signalled, only the injection phase of containment spray was modeled.

The other system that was chosen as basis for this analysis is the PWR fan cooler five units.

Figs. 4a and b, and 5a and b presents the fault tree to the containment spray and fan coolers system, respectively.

6. Quantitative analysis (methodology application and results)

The unavailability for the containment spray system was calculated to be 5.77E−3 per demand and for containment fan coolers was 1.35E−5. Comparatively to Ref. [11] where the base case values were 4.1E−3 and 5.3E−5, respectively, the results obtained with fuzzyFTA approach were satisfactory. This distance can be explained by use, in this work, of the rate failures in the same great order of the real conditions of a single nuclear unit. In Ref. [11] were used failure rates from global data store.

In the analysis, that was intended to reveal which of the components would, after 20 years of operation, greatly contribute to uncertainty, the values of fuzzy importance measure (FIM) and fuzzy uncertainty importance measure (FUIM) presented similar ranks. For the containment spray system, events 19, 17, 8, 32, and 10 are the five most important for system uncertainty. For the fan cooler system, events 21, 12, 16, 18 and 17, are the five most important contributors for system unavailability.

Table 2
Failure probability and the ranks for fan coolers system components

Event no.	Failure probability	Error factor	FIM ranking MCS	FUIM ranking MCS
1	6.48E−7	10	23	23
2	1.5E−3	10	23	23
3	1.5E−3	10	23	23
4	6.48E−7	10	23	23
5	2E−7	10	12	11
6	2E−7	10	12	12
7	1.2E−7	10	16	14
8	1.2E−7	10	16	16
9	1.2E−7	10	16	15
10	1.5E−7	10	13	13
11	2E−7	10	9	9
12	6E−5	10	2	2
13	4E−7	10	17	17
14	3E−7	10	8	8
15	2E−7	10	12	10
16	5E−7	10	3	3
17	4E−7	10	5	5
18	4E−7	10	5	4
19	3E−7	10	8	7
20	3E−7	10	8	7
21	9E−6	10	1	1
22	5.2E−3	3	19	19
23	3.5E−3	3	19	19

The reference work [11] appointed the most relevant events to system unavailability. To the containment spray system were human error, pump failure to start and failure to run, MOVs failure to open, spray nozzle plugging and check valve failure to open. The fuzzy approach appointed the following events: MOVs failure to open, human error and pump failure to run as the principal failure events. Except the order, it is coherent. To the fan cooler system, the reference work identified the dampers failure to open and the fan motor failure to start among the principal failure events. It is conceptually coherent with the FIM ranking.

Departing from the above results, a parametric study was performed to determine the potential influence of aging on the system unavailability. Basic events that could be affected by aging and that would greatly contribute to general uncertainty to the system were identified and analyzed using uncertainty ranking. The probabilities for these events were multiplied by factors of 2, 5 and 10. So, hypothetical and overestimated system unavailabilities were calculated.

In Tables 1 and 2 and Figs. 6 and 7 are presented, respectively, the basic event probabilities and, graphically, the results from computing system of ranking of components based on fuzzy importance and fuzzy uncertainty importance measures approach for containment spray and fan cooler system. Using the base case model of the containment spray and fan cooler, the results of a parametric study performed to determine the potential influence of aging on the system unavailability are presented in Tables 3 and 4. The parametric study showed that an increase in failure rate of the 19th event influences, significantly, the total system unavailability. If the 19th event failure rate was to be increase by a factor of ten, the total system unavailability increases by a factor of 2. This result shows that if the component related to 19th event presents a severe aging degradation process, and its failure rates increase over time, this event failures can become an important contributor, and lead to an increase in containment spray system unavailability. If all five in the five event probabilities were to increase by a factor of 10, the total system unavailability would increase by a factor of 6.

Similar results appear in the fan cooler case study. If the 21th event probability were to increase by a factor of 10, the total

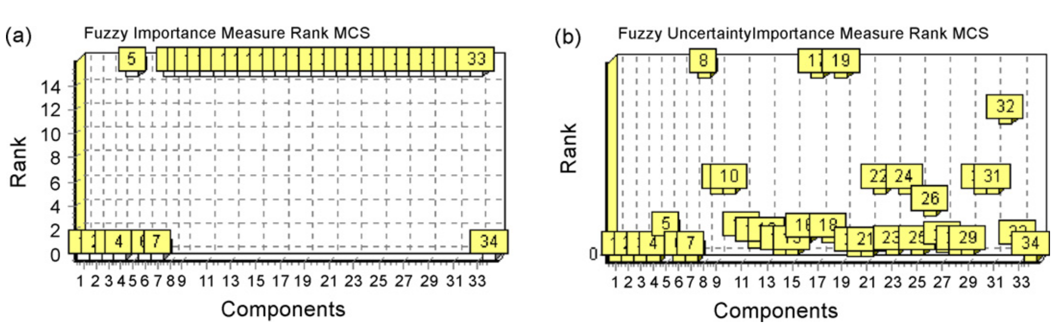

Fig. 6. Fuzzy importance (a) and fuzzy uncertainty importance (b) for the containment spray system.

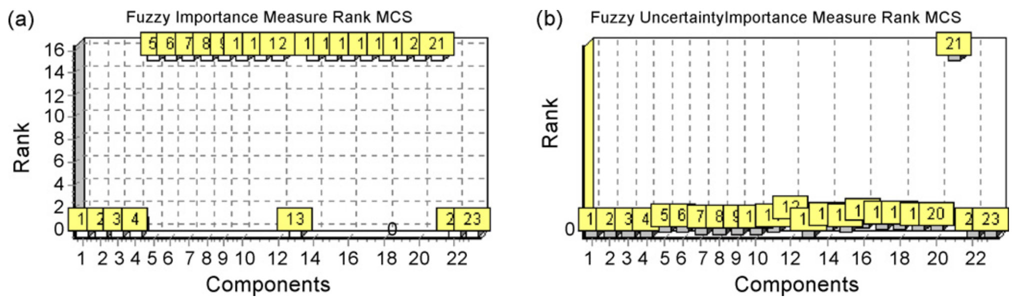

Fig. 7. Fuzzy importance (a) and fuzzy uncertainty importance (b) for the containment fan cooler.

Table 3
Parametric study of containment spray system uncertainty

Basic event description	Basic event failure rate	System uncertainty			
		Basic event failure rate multiplication factor			
		Base case	×2	×5	×10
1 Event 19	9 E−6	5.77E−3	6.57E−3	8.97E−3	1.30E−2
2 Event 17	6 E−7	5.77E−3	6.57E−3	8.97E−3	1.30E−2
3 Event 8	5 E−7	5.77E−3	6.57E−3	8.97E−3	1.30E−2
4 Event 32	4 E−7	5.77E−3	6.37E−3	8.17E−3	1.12E−2
5 Event 10	4 E−7	5.77E−3	6.07E−3	6.97E−3	8.47E−3
All of the above	–	5.77E−3	9.07E−3	1.90E−2	3.55E−2

Table 4
Parametric study of containment fan cooler system uncertainty

Basic event description	Basic event failure rate	System uncertainty			
		Basic event failure rate multiplication factor			
		Base case	×2	×5	×10
1 Event 21	9E−6	1.35E−5	2.25E−5	4.95E−5	9.45E−5
2 Event 12	6E−7	1.35E−5	1.41E−5	1.59E−5	1.89E−5
3 Event 16	5E−7	1.35E−5	1.40E−5	1.55E−5	1.80E−5
4 Event 18	4E−7	1.35E−5	1.39E−5	1.51E−5	1.71E−5
5 Event 19	4E−7	1.35E−5	1.35E−5	1.47E−5	1.62E−5
All of the above	–	1.35E−5	2.97E−5	5.67E−5	1.11E−4

system unavailability increases by a factor of 7. This result shows that if aging degradation process in this component is not properly controlled, and its failure rates increase over time, this event can become a more important greater contributor, and lead to a significant enlargement in the containment fan cooler system unavailability. If all five components were to increase by a factor of 10, the total system unavailability increases by a factor of 8. This means that in a case of fan cooler, the 21th event is the most important contributor for system unavailability of considering the five more important contributors for system general uncertainty.

7. Conclusions

In the reference study [11] was used the traditional fault tree and several existing probabilistic risk assessments (PRA) must be reviewed to better define the role of this system approach to determinate the PWR containment spray system unavailability. This study was followed by a parametric study to determine the potential influence of aging on the system unavailability. Basic events that could be affected by aging were identified and analyzed. The failure rates for these events were multiplied by factors of 2, 5 and 10, and possible degraded system unavailabilities were projected.

In this paper a similar study was performed using a alternative methodology to identify the most important component to system unavailability. This methodology use a hybrid approach where fuzzy logic and fault tree are combined to define two important variables named fuzzy important measure (FIM) and fuzzy uncertainty important measure (FUIM). Using this variables, events are ranked and then used to establish a parametric study increasing the probability of the five most relevant to the system unavailability.

However, is very important remember that in some traditional studies, the fault tree evaluation considers components with small amount information about the operational performance of the each component. Its generates a high level of uncertainty on fault tree results. In many cases, as in the reference work, only a crisp result was determinate. Monte-Carlo method has been used to evaluate each component uncertainty contribution for system general uncertainty. This approach, however, may lead to large variances on top event probability and it is computationally very expensive. So, the FuzzyFTA capability to consider the probabilities basic events uncertainty and to propagate it until to top event, is a goal of this approach.

The results of this study have helped in the understanding of the aging process in containment cooling systems and how it can be optimal management. The predominant aging mechanisms and failure modes have been determined, and the components most frequently affected by aging degradation and that most contribute to system general uncertainty have been identified. In addition, trends for increasing failure rates with age and their potential affect on system unavailability have been examined.

In future works, a more detailed look at the monitoring and maintenance practices could be performed to determine which practices are the most effective for detecting and mitigating aging degradation. Some new algorithms will be implemented in the computational system for increasing system performance through new PWR components case studies.

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