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# Fuzzy inference to risk assessment on nuclear engineering systems

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**Abstract**

This paper presents a nuclear case study, in which a fuzzy inference system (FIS) is used as alternative approach in risk analysis. The main objective of this study is to obtain an understanding of the aging process of an important nuclear power system and how it affects the overall plant safety. This approach uses the concept of a pure fuzzy logic system where the fuzzy rule base consists of a collection of fuzzy IF–THEN rules. The fuzzy inference engine uses these fuzzy IF–THEN rules to determine a mapping from fuzzy sets in the input universe of discourse to fuzzy sets in the output universe of discourse based on fuzzy logic principles. The risk priority number (RPN), a traditional analysis parameter, was calculated and compared to fuzzy risk priority number (FRPN) using scores from expert opinion to probabilities of occurrence, severity and not detection. A standard four-loop pressurized water reactor (PWR) containment cooling system (CCS) was used as example case. The results demonstrated the potential of the inference system for subsiding the failure modes and effects analysis (FMEA) in aging studies.


*Keywords:* FMEA; Fuzzy logic; Expert opinion; Risk

## 1. Introduction

Currently, the Nuclear Power Plants (NPP) provide about 18% of the electric power produced in the world. The United States only, at the end of 1989, had 108 reactors in commercial operation. In the last years, the future perspectives for nuclear energy have been analyzed under two antagonizing points of view. The positive aspect is that, in recent studies, some authors have been emphatic to support that the nuclear power plants option does not contributed to the global warming and yet, the new pressurized water reactor (PWR) generations possess important intrinsic safety characteristics [1]. These studies suggest that the option for electric nuclear generation would remain as important energy search for at least 50 year. However, the population of commercial nuclear power plants has matured and its main safety and 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, researchers and engineers of the nuclear energy area have developed studies to comprehend the causes and effects of aging phenomena. Recently, [2] performed a study about the aging process in Nuclear Power Plant containment cooling systems (CCS). Preoccupied with this

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question, the United States (US) Nuclear Regulatory Commission (NRC), a few years ago, performed an aging assessment of containment cooling systems in nuclear power plants as part of the Nuclear Plant Aging Research (NPAR) program.

The goal of aging analysis in [2] was to determine if aging degradation is a concern for the containment cooling system, and to characterize its effects. To accomplish this, a planned approach was taken. This included: (1) an extensive review of existing Final Safety Analysis Report (FSARs) to identify the different system designs, (2) identification of the operating and environmental stresses imposed on the systems, (3) an analysis of failure data from national databases covering all pressurized water reactors in the USA, (4) an analysis of plant-specific data from one PWR and (5) a system unavailability analysis on one common containment spray system design and one common fan cooler system design to evaluate the potential time-dependent effect of aging on system unavailability. The results of [2] show that aging is a concern for the containment cooling system and should be addressed in plant programs. Failure modes and aging mechanisms were identified for several of the most frequently failed components in each system.

As can be seen in aforementioned work, the traditional safety analysis, specifically the FMEA approach, has been used on aging assessment studies on the nuclear area. Beyond this, in the last years, other important knowledge field, the artificial intelligence, has appointed good solutions for old nuclear engineering problems. Such as*: reactor core design* [3], *fuel reload* [4], *test surveillance planing* [5], *preventive maintenance optimization* [6], *reduced scale experiments design* [7,8], *corrosion on steam generation* [9] and others.

Considering the research lines above mentioned, the goal of this paper is to develop a ranking FMEA using, a direct method with one expert opinion and propose a fuzzy approach to identify implicit information in a very important nuclear safety system.

Failure mode and effects analysis (FMEA) is an important technique [10] that is used to identify and eliminate known or potential failures to enhance reliability and safety of complex systems and is intended to provide information for making risk management decisions.

Fuzzy logic systems is one of the various names for the systems which have relationship with fuzzy concepts [11], like fuzzy sets, linguistic variables, etc. The most popular fuzzy logic systems in the literature may be classified into three types: pure fuzzy logic systems, Takagi and Sugeno's fuzzy system, and fuzzy logic systems with fuzzifier and defuzzifier [12]. The methodology used in this paper is the fuzzy logic systems with fuzzifier and defuzzifier [9,13–15].

The knowledge-based fuzzy systems allows for descriptive or qualitative representation of expressions such as ''remote'' or ''high'', incorporate symbolic statements that are more natural and intuitive than mathematical equations. A direct method with ''one expert'' [16] was used to aggregate opinion of an individual expert.

This work investigates the potential application of knowledge-based fuzzy systems in a case study. The containment cooling system information was used for this study and system description details can be found in [2].

## 2. Short description of fuzzy inference system approach

The ''pure fuzzy logic system'' is the system where the fuzzy rule base consists of a collection of fuzzy IF–THEN rules, and the fuzzy inference engine uses these fuzzy IF–THEN rules to determine a mapping from fuzzy sets in the input universe of discourse $U \subset R^n$ to fuzzy sets in the output universe of discourse $V \subset R$ based on fuzzy logic principles. The fuzzy IF–THEN rules are of the following form:

$$R^{(l)}: \text{IF } x_1 \text{ is } F_1^l \text{ and} \ldots x_n \text{ is } F_n^l, \quad \text{THEN } y \text{ is } G^l \tag{1}$$

where $F_i^l$ and $G^l$ are fuzzy sets, $\underline{x} = (x_1, \ldots, x_n)^T \in U$ and $y \in V$ are input and output linguistic variables, respectively, and $l = 1, 2, \ldots, M$. Practice has shown that these fuzzy IF–THEN rules provide a convenient framework to incorporate human experts' knowledge. Each fuzzy IF–THEN rule of Eq. (1) defines a fuzzy set $F_1^l x \ldots x F_n^l \Rightarrow G^l$ in the product space $U \times V$. The most commonly used fuzzy logic principle in the fuzzy inference engine is the so-called *sup-star composition,* described in detail in [12]. The *mini-inference* rule and *product-inference* rule are choiced as good from an axiomatic strength point of view, and also because these inferences rules are computationally simple [12]. In our application, we will use the *mini-inference* type of inferences rules in our adaptive fuzzy system application.

In order to use the ''pure fuzzy logic system'' in engineering systems where inputs and outputs are real-valued variables, the most straightforward way is to add a fuzzifier to the input and a defuzzifier to the output of the pure fuzzy logic system. The fuzzifier maps crisp points in $U$ to fuzzy sets in $U$, and the defuzzifier maps fuzzy sets in $V$ to crisp points in $V$. The *fuzzy rule base* and *fuzzy inference engine* are the same as those in the pure fuzzy logic system. In the literature, this fuzzy logic system is often called the fuzzy logic controller since it has been mainly used as a controller. It was first proposed by [13], and has been successfully applied to a variety of industrial process and consumer products. A detailed description of this fuzzy logic system can be found in [12].

The Mamdani fuzzy logic system has many attractive features. First, it is suitable for engineering systems because its inputs and outputs are real-valued variables. Second, it provides a natural framework to incorporate fuzzy IF–THEN rules from human experts. Third, there is much freedom in the choices of fuzzifier, fuzzy inference engine, and defuzzifier, so that we may obtain the most suitable fuzzy logic system for a particular problem [12].

## 3. Application of the proposed approach to CCS

The containment cooling was selected as example system to permit a comparison with the [2] results. Its function is performed by several different systems, depending on the type and design of the plant. The two systems focused on in that study and also here are the *containment spray system* and the *fan cooler system*. These systems were selected since they are the primary means of removing containment heat during accident conditions.

To start the proposed study, an ''expert'' with knowledge domain on the analyzed system was adopted. The selected specialist belongs to the reliability engineering and can participate in other domains. A traditional FMEA using the RPN ranking system is carried out in the first moment. Mathematically represented, it will give:

$$\mathrm{RPN} = O \times S \times D \qquad (2)$$

where $O$ represents the *probability of occurrence*, $S$ the *severity* and $D$ represents the *not detection* probability. The values for $O$, $S$ and $D$ are obtained by using the scaled values presented in Table 1 [14,15]. The expert in the FMEA analysis was the same in the proposed fuzzy approach. In Table 1, we can see five scales and scores of 1–10 that are used traditionally in FMEA, measuring the probability of *occurrence*, *severity* and the probability of *not detection*.

A failure modes and effects analysis was performed to determine the effects of failure over the major system components. The FMEA analysis for containment cooling system is summarized in Appendices A and B. In [2], the FMEA analysis is presented in detail and the values for $O$, $S$ and $D$ were evaluated by an expert. For example, considering the PWR operation experience, the CCS seal of valve presents a considerable aging process, consequently, the fail of a seal valve is a relatively common event. So, the occurrence probability to this event is high. However, its consequences to reactor safety and its relative importance to system is moderate (severity index is moderate). Finally, the detection of this event is easily possible with surveillance test performance. So, the non-detection probability is low.

Table 1
Traditional FMEA scales for RPN

| Occurrence ($O$), Severity ($S$), Not Detection ($D$) | Rating | Possible failure rate for $O$ (operating days) | Probability of not detection |
|---|---|---|---|
| Remote | 1 | <1:20,000 | 0–5/6–15 |
| Low | 2/3 | 1:20,000/1:10,000 | 16–25/26–35 |
| Moderate | 4/5/6 | 1:2000/1:1000/1:200 | 36–45 Z46-55/56–65 |
| High | 7/8 | 1:100/1:20 | 66–75/76–85 |
| Very high | 9/10 | 1:10/1:2 | 86–100 |

To characterize the effects of aging on containment cooling system, several sources of data were analyzed. These include the Nuclear Plant Reliability Data System (NPR-DS) and Licensee Event Reports (LERs), which are national databases. In addition, plant specific data were obtained to supplement and validate the national database findings.

The results of the national database analysis and plant specific data analysis are presented in more details in [2]. Only a summary of aging characteristics will be described here.

The analysis of the national database has identified the major aging characteristics for the containment cooling system components. This information is necessary for understanding the aging process so that it can be properly monitored and managed. Appendices A and B presents the aging characteristics for the most frequently failed components in the containment spray system. The component relative failure frequency represents the relative frequency at which that component fails as compared to other components in the system. Similarly, the sub-component relative failure frequency represents the relative frequency at which that sub-component fails as compared to other sub-components in that specific component. The relative failure mode frequency represents the frequency at which that failure mode occurs when that component fails as compared to other possible failure modes for that sub-component. The frequency ratings of low, medium and high are based on the percentage of total occurrences found in the data analyzed. A frequency was judged to be high if it accounted for 50% or more of the total number of occurrences. A frequency was judged to be medium if it accounted for 25–50% of the total number of occurrences, and low if it represented less than 25% of the total. It should be noted that these ratings may not be representative of any specific plant since there are many factors which can influence these results. These findings should be considered industry averages, which can be used as a baseline for reviewing existing aging management techniques.

As an example of the interpretation of the Appendices A and B, the first entry is for valves in the containment spray system. Their relative failure frequency is medium, which indicates that if a failure occurs in the containment spray system there is a good chance it will involve a valve. Further, if the failure does involve a valve, there is a good chance that failure will involve the valve packing, and a very good chance this packing problem will manifest itself in the form of external leakage. The predominant aging mechanism leading to this type of failure is wear of the packing, and it can be detected by visual inspection. The Appendices A and B also show that, instead of leakage, there is a chance that the valve packing problem will manifest itself by causing the valve not to open or close, however, the probability of this failure mode is low. This could be caused by binding or distortion of the packing, and can be detected by a valve stroke test. Entries for other component can be interpreted in the same manner.

### 3.1. Fuzzy membership function

Making use of the fuzzy logic toolbox simulator of MatLab [17], the expert was invited to define each membership function and the values in the universe of discourse using the interpretations of the linguistic terms described in Table 2 [14]. The expert chose the triangular membership function defined by fuzzy number ($a$, $b$, $c$) expressing the proposition ‘‘close to $b$’’ [16]. After that, the following question may be answered by the expert: ‘‘Which elements $x$ ($a$, $b$, $c$) have the degree of membership $\alpha_a$ = zero, $\alpha_b$ = one and $\alpha_c$ = zero’’. Direct methods with one expert [16] were used. The linguistic terms describing the input are Remote (R), Low (L), Moderate (M), High (H) and Very High (VH), and for output are Unnecessary (U), minor (mi), very-low (vl), low (l), moderate (mod), high (h), M-high (Mh), V-high (Vh), n and A-n. After receiving the feedback from the expert, the membership function of the five linguistic terms, are generated. Fig. 1, show occurrence (identical for severity and not detection) and the membership function for the linguistic variable for risk is determined and graphically represented in Fig. 2.

### 3.2. Fuzzy rule base application

The membership function derived from the expert is used to generate the fuzzy rule base. The total number of rules, equal to 125, in the fuzzy rule base, is reduced when these rules are combined. The Rule Viewer of the MatLab that opens during the simulation can be used to access the ‘‘Membership Function

Table 2
Interpretations of the linguistic terms for developing the fuzzy rule system

| Linguistic term | Probability of occurrence | Severity | Detection |
|---|---|---|---|
| Remote | It would be very unlikely for these failures to be observed even once | A failure that has no effect on the system performance, the operator probably will not notice | Defect remains undetected until the system performance degrades to the extent that the task will not be completed |
| Low | Likely to occur once, but unlikely to occur more frequently | A failure that would cause slight annoyance to the operator, but that cause no deterioration to the system | Defect remains undetected until system performance is severely reduced |
| Moderate | Likely to occur more than once | A failure that would cause a high degree of operator dissatisfaction or that causes noticeable but slight deterioration in system performance | Defect remains undetected until system performance is affected |
| High | Near certain to occur at least once | A failure that causes significant deterioration in system performance and/or leads to minor injuries | Defect remains undetected until inspection or test is carried out |
| Very high | Near certain to occur several times | A failure that would seriously affect the ability to complete The task or cause damage, serious injury or death | Failure remains undetected, such a defect would almost certainly be detected during inspection or test |

Editor'' and the ''Rule Editor''. Through ''*Simulator*'' many results can be evaluated and rules can be removed. For example, consider these three rules:

Rule 1: if *Occurrence* is M and *Severity* is H and *not Detection* is M then *Risk* is M–h.

Rule 2: if *Occurrence* is H and *Severity* is M and *not Detection* is H then *Risk* is M–h.

Rule 3: if *Occurrence* is H and *Severity* is H and *not Detection* is M then *Risk* is M–h.

Rules 1, 2 and 3, can be combined to produce: ''if *Occurrence* is M and *Severity* is H and *not Detection* is M then *Risk* is M–h'' or any combination of the three linguistic terms assigned to these variables, then Risk is M–h.

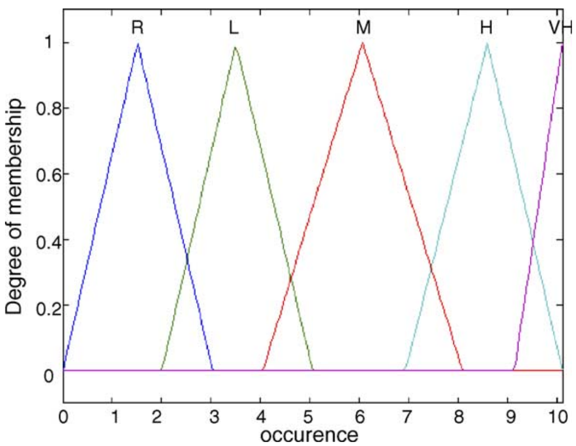


Fig. 1. Membership function generated by the expert for occurrence (identical for severity and not detection).

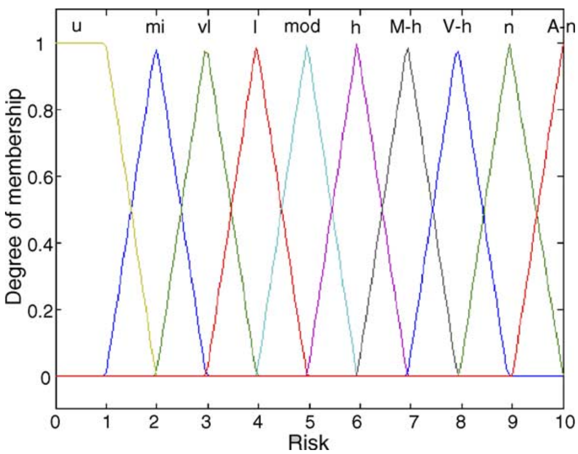


Fig. 2. Membership function for the Risk generated by expert.

This type of reduction consider that the probability of *Occurrence, Severity and not Detection* have the same importance.Fuzzy inference functions, such as the defuzzification method, used in this application are:

name: 'FMEA_CCS'
type: 'Mamdani'
andMethod: 'min'
orMethod: 'max'
defuzzMethod: 'centroid'
impMethod: 'min'
aggMethod: 'max'
input: [1 × 3 struct]
output: [1 × 1 struct]
rule: [1 × 15 struct]

## 4. Results

"RPN" and "FRPN" are the risk numbers by the FMEA. *Ranking_RPN* and *Ranking_Fuzzy* are the ranking of RPN and fuzzy methodology. The RPN is the product of $O \times S \times D$ and fuzzy is the proposed approach in this paper.

Using the same data from the traditional FMEA, and expressing the three variables considered linguistically with aid of the membership function in Fig. 1 and the fuzzy rule base, gives the results of the modified FMEA. These results are then defuzzified using the centroid method to obtain the *Fuzzy* Risk results for ranking, expressed in variable *Ranking_Fuzzy,* as shown in Table 3.

The most critically debated disadvantage of the traditional FMEA is that various sets of Occurrence ($O$), Severity ($S$) and not Detection ($D$) may produce an identical value of RPN, however, the risk implication may be totally different. For example, consider two different events having values of 3, 1, 6 and 1, 9, 2, for $O$, $S$ and $D$, respectively. Both these events will have a total of RPN of 18 ($RPN_1 = 3 \times 1 \times 6 = 18$ and $RPN_2 = 1 \times 9 \times 2 = 18$), however, the risk implication of these two events may not necessarily be the same.

Table 3
Ranking comparison

| ID | RPN | Fuzzy | Ranking RPN | Ranking Fuzzy |
|---|---|---|---|---|
| 1 | 135 | 2.9705 | 24 | 24 |
| 2 | 252 | 7.8406 | 14 | 10 |
| 3 | 210 | 7.7627 | 19 | 11 |
| 4 | 168 | 3.9597 | 22 | 23 |
| 5 | 252 | 7.8406 | 14 | 10 |
| 6 | 60 | 0.8530 | 29 | 27 |
| 7 | 343 | 7.9320 | 5 | 7 |
| 8 | 294 | 7.9221 | 10 | 8 |
| 9 | 378 | 8.0071 | 4 | 5 |
| 10 | 252 | 7.8406 | 14 | 10 |
| 11 | 252 | 7.8406 | 14 | 10 |
| 12 | 252 | 7.8406 | 14 | 10 |
| 13 | 196 | 4.9504 | 20 | 22 |
| 14 | 196 | 4.9504 | 20 | 22 |
| 15 | 168 | 4.9504 | 22 | 22 |
| 16 | 288 | 6.9915 | 11 | 18 |
| 17 | 288 | 6.9915 | 11 | 18 |
| 18 | 343 | 7.9320 | 5 | 7 |
| 19 | 294 | 7.9221 | 10 | 8 |
| 20 | 420 | 8.9651 | 2 | 2 |
| 21 | 420 | 8.9651 | 2 | 2 |
| 22 | 294 | 7.9221 | 10 | 8 |
| 23 | 210 | 7.6683 | 19 | 13 |
| 24 | 216 | 4.9504 | 18 | 22 |
| 25 | 175 | 7.5027 | 21 | 16 |
| 26 | 243 | 4.9504 | 16 | 22 |
| 27 | 70 | 1.9813 | 28 | 26 |
| 28 | 392 | 8.7839 | 3 | 3 |
| 29 | 150 | 7.5027 | 23 | 16 |
| 30 | 105 | 2.8039 | 26 | 25 |
| 31 | 245 | 7.5489 | 15 | 15 |
| 32 | 175 | 7.5027 | 21 | 16 |
| 33 | 294 | 7.9221 | 10 | 8 |
| 34 | 252 | 7.8406 | 14 | 10 |
| 35 | 315 | 7.7735 | 9 | 11 |
| 36 | 163 | 4.9504 | 22 | 22 |
| 37 | 224 | 4.9504 | 17 | 22 |
| 38 | 120 | 4.9504 | 25 | 22 |
| 39 | 270 | 6.9306 | 13 | 20 |
| 40 | 320 | 6.9664 | 8 | 19 |
| 41 | 324 | 7.9194 | 7 | 9 |
| 42 | 75 | 2.8039 | 27 | 25 |
| 43 | 294 | 7.9221 | 10 | 8 |
| 44 | 294 | 7.9221 | 10 | 8 |
| 45 | 294 | 7.9221 | 10 | 8 |
| 46 | 336 | 7.1226 | 6 | 17 |
| 47 | 288 | 6.9915 | 11 | 18 |
| 48 | 288 | 6.9915 | 11 | 18 |
| 49 | 336 | 7.1226 | 6 | 17 |
| 50 | 294 | 7.9221 | 10 | 8 |
| 51 | 432 | 9.4291 | 1 | 1 |
| 52 | 320 | 8.3659 | 8 | 4 |
| 53 | 320 | 8.3659 | 8 | 4 |
| 54 | 280 | 6.8459 | 12 | 21 |
| 55 | 336 | 7.9353 | 6 | 5 |
| 56 | 245 | 7.5489 | 15 | 15 |
| 57 | 280 | 7.5609 | 12 | 14 |

Other disadvantage of the RPN ranking method is that it neglects the relative importance among *O*, *S* and *D*.

The three factors are assumed to have the same importance. This may not be appropriate when considering a practical application of FMEA process. An approach using fuzzy rule base is proposed to address these failures. A fuzzy rule base is used to rank the potential causes identified within the FMEA, with identical RPN values but different risk implications. The approach extends the analysis to include importance factors for *O*, *S* and *D* using defuzzified linguistic terms.

Based in comments presented before, fuzzy approach produces, for example, Ranking_Fuzzy value of 6 for event 55 and Ranking_Fuzzy value of 17 for event 49. In another case, events 13, 14 and 15, the defuzzified ranking was 4.9504. So, these three events obtained the same fuzzy priority number. In the RPN method, however, produces a result of 196, 196 and 168 for events 13, 14 and 15, respectively. This denote that event 15 has the lowest priority number. This ranking could be misleading; especially when the safety data is accompanied with a high level of uncertainty. This shows that a more accurate ranking can be achieved by the application of the fuzzy rule base to FMEA.

## 5. Conclusions

In accordance with [2], the results of Nuclear Plant Aging Research program (NPAR) study show that aging degradation exists in containment cooling systems and is a significant contributor to failures. Since these systems play an important role in *accident mitigation*, plant programs should specifically address the proper management of aging in containment cooling systems. Each of the aging mechanisms identified in this study should be addressed by at least one monitoring technique.

This article extends the use, in the nuclear area, of a capable methodology to subsidize new reactor projects through the fuzzy identification of critical systems and components and possible failure modes.

This fuzzy approach can be used for systems where safety data is unavailable or unreliable and may to combine expert knowledge and operational experience for use in an FMEA study.

Fuzzy approach have identified the priorities for the containment cooling system components and implicit information is necessary for better understanding of the aging process so that it can be properly monitored and managed in a effective NPP usefulness span extension program.

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## Appendix A. Aging characteristics for components of the containment *spray system*

| Component | Component relative failure frequency | Sub-component | Sub-component relative failure frequency | Component failure mode | Relative failure mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| Valves ID: 1–6 | Medium | Seals/packing | High | External leakage | High | Wear | Visual inspection | 9 | 5 | 3 |
| | | | | Does not open/close | Low | Binding<br>Distortion | Valve stroke test | 6 | 1 | 6 |
| | | Seats | Medium | Internal leakage | High | Wear<br>Corrosion<br>Erosion<br>Dirt/crud buildup | Valve leakage test | 7 | 5 | 6 |
| | | | | Does not open or close | Low | Binding<br>Dirt/crud buildup | Valve stroke test | 4 | 7 | 6 |
| | | Stem/linkage | Low | Does not open or close | High | Wear<br>Binding<br>Poor lubrification | Stroke test | 6 | 7 | 6 |
| | | | | External Leakage | Medium | Galling<br>Nicking | Visual inspection | 4 | 5 | 3 |

## Appendix A (*Continued*)

| Component | Component relative failure frequency | Sub-component | Sub-component relative failure frequency | Component failure mode | Relative failure mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| Valve operator ID: 7–12 | Medium | Torque switch | Medium | Does not open/close | High | Set point drift<br>Short/ground<br>Wear<br>Dirt/dust intrusion | Valve stroke test<br>Valve leakage test | 7 | 7 | 7 |
| | | Gears | Low | Does not open/close | High | Wear<br>Poor lubrification<br>Fatigue<br>Fracture/cracking | valve stroke test<br>Visual inspection | 6 | 7 | 7 |
| | | Motors | Low | Does not open/close | High | Short/burnout<br>Wear<br>Dirt/dust intrusion<br>Deterioration of insulation | Valve stroke<br>Motor current signature analysis<br>Motor insulation resistance test | 6 | 7 | 9 |
| | | Limit switch | Low | Does not open/close | High | Wear<br>Out of adjustment<br>Dirt dust intrusion<br>Short/ground | Valve stroke test | 6 | 7 | 6 |
| | | Solenoid | Low | Dots not open/close | High | Binding<br>Dirt/dust intrusion<br>Short/burnout | Valve stroke test | 6 | 7 | 6 |
| | | Diaphragms | Low | Does not open/close | High | Wear<br>Deterioration | Valve stroke test | 6 | 7 | 6 |
| Instrumentation/ Controls ID: 13–17 | Medium | Transmitter | Medium | Incorrect Signal | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Visual Inspection.<br>Functional test | 7 | 4 | 7 |
| | | Indicator/ Recorder | Medium | Incorrect signal | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Visual inspection | 7 | 4 | 7 |
| | | Computer | Medium | Incorrect signal | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Functional test | 7 | 4 | 7 |
| | | Relays/bistables/ switches | Low | Low | High | Wear<br>Deterioration<br>Dirt/dust intrusion<br>Short/ground | Functional test | 6 | 8 | 6 |
| | | Power Supply | Low | Low | High | Short/burnout<br>Wear<br>Dirt/dust intrusion<br>Deterioration | Functional test | 6 | 8 | 6 |
| Circuit breakers ID: 18–22 | Medium | Contacts | Medium | Does not open/close | High | Wear<br>Out of adjustment<br>Dirt dust intrusion<br>Binding<br>Corrosion<br>Burnout/pitting | Visual inspection<br>Functional test | 7 | 7 | 7 |
| | | Gears | Low | Does not open/close | High | Binding | Visual inspection | 6 | 7 | 7 |

## Appendix A (*Continued*)

| Component | Component relative failure frequency | Sub-component | Sub-component relative failure frequency | Component failure mode | Relative failure mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Out of adjustment<br>Fatigue<br>Fracture/crack<br>Wear | Functional test | | | |
| | | Overload Relays | Low | Breaker trip | High | Wear<br>Deterioration<br>Fatigue<br>Dirt/dust intrusion | Visual inspection<br>Functional test | 6 | 10 | 7 |
| | | Delay timer | Low | Failure to trip when required | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion<br>Wear | Visual inspection<br>Functional test | 6 | 10 | 7 |
| | | Handle/control switch | Low | Does not open/close | High | Wear<br>Fatigue/cracking<br>Binding<br>Deterioration<br>Poor lubrification<br>Short/burnout | Visual inspection<br>Functional test | 6 | 7 | 7 |
| Pumps ID: 23–27 | Low | Shaft seals | Medium | Leakage | High | Wear<br>Dirt dust intrusion<br>Deterioration | Visual inspection<br>Functional test | 6 | 5 | 7 |
| | | | | Does not run | Low | Binding<br>Out of adjustment<br>Distortion<br>Wear | Visual inspection<br>Functional test<br>Shaft torque measurement | 3 | 9 | 8 |
| | | Gaskets | Low | Leakage | High | Wear<br>Deterioration | Visual inspection<br>Functional test | 5 | 5 | 7 |
| | | Bearings | Low | Does not run | Medium | Deterioration<br>Dirt/dust intrusion<br>Wear<br>Poor lubrification<br>Binding | Visual inspection<br>Functional test<br>Vibration measurements<br>Excessive noise<br>Lube oil analysis | 3 | 9 | 9 |
| | | | | Leakage | Low | Wear<br>Deterioration<br>Poor lubrification | Visual inspection<br>Functional test | 2 | 5 | 7 |

## Appendix B. Aging characteristics for components of the fan cooler unit

| Component | Component relative future frequency | Sub-component | Sub-component relative future frequency | Component future mode | Relative Future Mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| Valves/dampers ID: 28–32 | Low | Stem/linkage | High | Does not open/close | High | Wear<br>Binding<br>Poor lubrification | Valve stroke test<br>Visual inspection | 8 | 7 | 7 |
| | | Seals | Low | Internal leakage | High | Wear<br>Corrosion<br>Erosion<br>Dirt/crud buildup | Valve leakage test | 5 | 5 | 6 |

## Appendix B (*Continued*)

| Component | Component relative future frequency | Sub-component | Sub-component relative future frequency | Component future mode | Relative Future Mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bolts/ fasteners | Low | Does not open/close | High | Vibration<br>Fatigue<br>Fracture/cracking | Visual inspection | 5 | 7 | 3 |
| | | Louvers | Low | Does not open/close | High | Fatigue<br>Wear<br>Fracture/cracking | Visual inspection<br>Functional test | 5 | 7 | 7 |
| | | Seals | Low | External leakage | High | Wear<br>Deterioration | Visual inspection<br>Functional test | 5 | 5 | 7 |
| Valve operator ID: 33–35 | Low | Diaphragm | Medium | Does not open/close | High | Deterioration<br>Wear | Valve stroke test<br>Valve leakage test | 6 | 7 | 7 |
| | | Solenoids | Medium | Does not open/close | High | Wear<br>Deterioration<br>Short/ground | Valve stroke test | 6 | 7 | 6 |
| | | Motors | Low | Does not open/close | High | Short/burnout<br>Wear<br>Dirt/dust intrusion<br>Deterioration of insulation | Valve stroke test<br>Motor current signature analysis<br>Motor insulation resistance test | 5 | 7 | 9 |
| Instrumental ion/ controls ID: 36–39 | Low | Transmitter | Medium | Incorrect signal | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Visual inspection<br>Functional test | 6 | 4 | 7 |
| | | Indicator/ recorder | High | Incorrect signal | High | Calibration drift<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Visual inspection<br>Functional test | 8 | 4 | 7 |
| | | Integrator/ computer | Low | Incorrect signal | High | Calibration<br>Short/ground<br>Deterioration<br>Dirt/dust intrusion | Functional test | 5 | 4 | 6 |
| | | Controllers | Low | Loss of function | High | Wear<br>Deterioration<br>Dirt/dust intrusion<br>Short/ground | Functional test | 5 | 9 | 6 |
| Cooling coils ID: 40–42 | Low | Tubes | High | External leakage | High | Wear<br>Fracture/cracking | Visual inspection<br>Eddy current testing | 8 | 5 | 8 |
| | | | | Fouling/ plugging | Medium | Dirt/crud buildup | Visual inspection<br>Functional test<br>Differential pressure/temperature | 6 | 6 | 9 |
| | | Gaskets | Low | External leakage | High | Wear<br>Deterioration | Visual inspection | 5 | 5 | 3 |
| Circuit breakers ID: 43–50 | Medium | Contacts | Low | Does not open/close | High | Out of adjustment<br>Corrosion<br>Burnout/pitting | Visual inspection<br>Functional test | 6 | 7 | 7 |
| | | Gears | Low | Does not open/close | High | Binding<br>Out of adjustment<br>Fracture/crack<br>Wear | Visual inspection<br>Functional test | 6 | 7 | 7 |

## Appendix B (*Continued*)

| Component | Component relative future frequency | Sub-component | Sub-component relative future frequency | Component future mode | Relative Future Mode frequency | Aging mechanisms | Detection methods | *O* | *S* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Overload relays | Low | Breaker trip | High | Wear<br>Deterioration<br>Fatigue | Visual inspection<br>Functional test | 6 | 7 | 7 |
| | | Fuses | Low | Loss of function | High | Short/ground<br>Deterioration<br>Fatigue | Functional test | 6 | 8 | 7 |
| | | Coils | Low | Loss of function | High | Out of adjustment<br>Short/burnout<br>Deterioration | Functional test | 6 | 8 | 6 |
| | | Starters | Low | Loss of function | High | Wear<br>Short/burnout | Visual inspection<br>functional test | 6 | 8 | 6 |
| | | Springs | Low | Loss of function | High | Wear<br>Fatigue<br>Binding<br>Distortion | Visual inspection<br>Functional test | 6 | 8 | 7 |
| | | Handle/ control switch | Low | Does not open/close | High | Wear<br>Fatigue/cracking<br>Binding<br>Deterioration<br>Poor lubrification<br>Short/burnout | Visual inspection<br>Functional test | 6 | 7 | 7 |
| Blowers ID: 51–54 | Low | Bearings | Medium | Does not run | High | Deterioration<br>Dirt/dust intrusion<br>Wear<br>Poor lubrification<br>Binding | Visual inspection<br>Functional test<br>Vibration measurements<br>Excessive noise | 6 | 8 | 9 |
| | | Shaft | Low | Loss of function | High | Wear<br>Fatigue<br>Fracture/cracking | Functional test<br>Disassembly inspection | 5 | 8 | 8 |
| | | Rotors/blades | Low | Loss of function | High | Wear<br>Fatigue<br>Fracture/cracking<br>Vibration | Visual inspection<br>Functional test<br>Disassembly inspection | 5 | 8 | 8 |
| | | Belts | Low | Loss of function | High | Wear<br>Deterioration | Visual inspection<br>Functional test | 5 | 8 | 7 |
| Motors ID: 55–57 | Low | Bearings | Medium | Does not start | High | Wear<br>Dirt/dust intrusion<br>Poor lubrification | Functional test<br>Vibration measurement | 6 | 7 | 8 |
| | | Leads/connectors | Low | Does not start | High | Dirt/dust intrusion<br>Vibration | Visual inspection<br>Functional test | 5 | 7 | 7 |
| | | Insulation | Low | Does not start | High | Wear<br>Deterioration | Disassembly inspection<br>Functional test<br>Resistance measurement | 5 | 7 | 8 |

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