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A Study on Failure Rate, Reliability, and Collection Efficiency Trend of Bag Filters in a Cement Plant

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ABSTRACT

This thesis presents a comprehensive study on the failure rate, reliability, and collection efficiency trends of bag filters in a cement plant over 15 years. Bag filters are vital pollution control equipment used in various industries, including cement plants, to maintain environmental compliance. Understanding their performance and failure patterns is crucial to ensure efficient and reliable operation while adhering to stringent pollution control standards. The research findings reveal that the failure rate trend of bag filters closely follows the bathtub curve, with an initial high failure rate, a period of lower failures, and a subsequent increase in failures as the equipment nears the end of its life cycle. Reliability trends align with Madhab's Hat curve, exhibiting higher reliability during the first 10 to 12 years of operation, followed by a decline in reliability. The collection efficiency of bag filters declines as the equipment ages, with the efficiency decreasing from 99.998% in the early years to 95.05% in the 15th year. This emphasizes the importance of maintenance and retrofitting for older dust collection equipment to maintain high collection efficiency. The study concludes that the typical life span of bag filters ranges from 10 to 15 years, after which major maintenance interventions are necessary to minimize failure rates. The research provides valuable insights for maintenance engineers, design engineers, and reliability engineers, enabling them to improve the performance of pollution control equipment, such as bag filters, reverse air bag houses (RABH), and electrostatic precipitators (ESP), to meet the pollution control standards set by regulatory authorities.

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1. Introduction

The growing stringency of pollution control regulations is a daily concern, aimed at creating a healthier environment for humanity [1]. In response to certain industries not adhering to fair pollution control practices, pollution control boards have introduced online monitoring of emissions and effluent discharges from factories [2]. This poses a significant challenge for industries to maintain their pollution control equipment continuously, despite the inherent limitations, such as downtimes or failures, that are common to all machinery, including Electrostatic Precipitators (ESP), Bag filters, and cyclones. This situation is exacerbated by the fact that continuous, reliable operation is not only desirable but also mandated by statutory requirements.

While achieving year-round, failure-free operation of pollution control equipment may be impractical, every industry must make concerted efforts to minimize such failures. This study focuses on analyzing ten bag filters installed in a cement plant. Bag filters serve as the primary emission control equipment in various industries, including cement plants, [3] steel plants, sponge iron plants, and refractory plants, which is why they were selected for this study. Any failure or downtime experienced by bag filters not only compromises their reliability but can also lead to increased emissions, plant shutdowns, production losses, and higher maintenance costs, potentially resulting in non-compliance with emission standards. Therefore, it is crucial to analyze the situation and take action to prevent equipment failures and enhance reliability [4].

Failure Trend Analysis: This phase involves the analysis of failure trends using failure data analysis.

Reliability and Efficiency Trend Analysis: The second part involves evaluating trends in reliability and efficiency using equipment failure data and reliability calculations.

Reliability Improvement Techniques: The final part briefly discusses various methods for enhancing the reliability of bag filters and other pollution control equipment [5].

Failure Rate is defined as the number of failures of a system or component per unit time, usually expressed as failures per hour and denoted by the Greek letter λ (lambda). MTBF (Mean Time Between Failures) represents the average time between two failures of a system or equipment. The failure rate is essentially the reciprocal of the MTBF (1/λ).

Reliability can be defined in various ways, but in essence, it represents the probability of equipment or a system performing as designed. This means that equipment should perform according to the manufacturer's commitments within its warranty period, and ideally even after that, contributing to the manufacturer's reputation [5].

You can calculate Reliability (R) using the mathematical relationship established by Weibull, assuming a constant failure rate ($\beta = 1$):

$$R = e^{(-T/M)}$$

Where: T = Total time period, M = MTBF, λ = Failure rate

Collection Efficiency is the ratio of the total dust collected by dust collectors to the total dust load supplied with the flue gas. It can be calculated using the following formula [2, 6]:

$$\eta = 1 - (m2/m1)$$

Where m1 is the inlet dust concentration (gm/Nm3) at the bag filter's inlet side, and m2 is the outlet dust concentration (gm/Nm3) at the outlet side.

Numerous studies have previously examined pollution control equipment failures and suggested preventive and corrective actions. For instance, hybrid electrostatic precipitators with different filter bags have demonstrated significant advantages over conventional bag filters in terms of dust removal performance, cycle life, and energy consumption [7, 8]. Some studies indicate that bag filters coated with a mixture of acrylic binder and nano-clay offer improved durability compared to normal bags [9]. Additionally, an operational parameter study found that the pressure drop across the fabric and the accumulated dust layer increased exponentially with increased dust loading on the filter [10]. Studies have also focused on factors such as filter pore size, fiber diameter, and filtration efficiency [11], optimization of filtration performance using multi-fiber filter bags [12], and the reasons for filter bag failures and methods to improve their lifespan [13].

The research has revealed that hybrid electrostatic bag-house systems exhibit better functional and collection efficiency than conventional bag filters and ESP [14]. Other studies have delved into how the efficiency of dust collection systems depends on ultrafine particle exposure and composition [15], as well as the effectiveness of high-efficiency filter media in aerosol sampling [16]. The nature of fibers in bag filters can impact dust dislodgement efficiency [17]. Additionally, studies have explored the impact of pre-charging particles on the collection efficiency of dust collectors [18, 19], the enhancement of filtration performance for coal-fired fly ash [20], and the pulse-jet cleaning performance of electrostatically stimulated fabric filtration [21]. Techniques such as dust pre-charging have shown promise in increasing the efficiency of dust collectors [19], while the layer structure and pleat count of filter bags significantly affect filtration efficiency [22]. In a specific case, the research analyzed the reasons for filter bag failures in an HDPE unit and proposed improvements [23]. Other studies have examined different types of fabric bag failures and suggested preventive actions for fabric failures in pulse-jet filters [24], as well as improved performance through opposing pulsed-jet cleaning using annular-slit nozzles for pleated filter cartridges [25]. Miscellaneous causes of bag filter failures, such as moisture, have also been proposed [26]. Recommendations such as the regular maintenance of various associated equipment in bag filter systems have been suggested to reduce bag filter failures [27, 28]. While numerous studies have explored failure and prevention in bag filters, this study uniquely investigates the failure patterns and reliability analysis of bag filters, comparing them to the idealized bathtub curve. The analysis of reliability trends is conducted in detail.

2. Materials and Method

To conduct this experiment, a dataset is gathered consisting of 10 bag filters that had completed their entire life cycle within the factory. The primary objective of this study was to validate and establish the failure trend characteristics and reliability of these bag filters. Consequently, we selected this specific equipment set to discern the relative failure rate of the entire population of equipment over time and to assess its overall reliability. The number of failures is recorded that occurred in each year for all the equipment sets. The reliability of these bag filters was computed using a predefined formula. Subsequently, we conducted a comprehensive analysis of the failure trend and compared it to the bathtub curve, a recognized ideal failure curve. This analysis allowed us to evaluate the reliability trend, and conclusions were drawn accordingly.

3. Observation and Discussion

3.1. Failure Trend Analysis

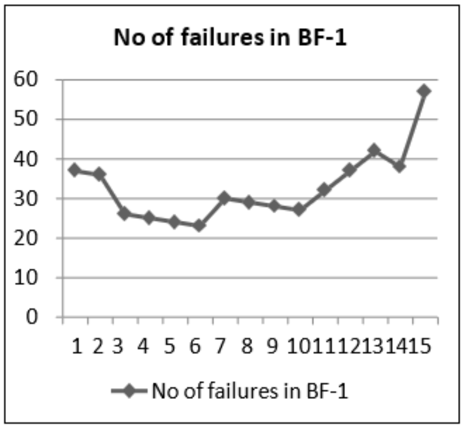
As previously mentioned, a dataset was collected to document the failure rates of the equipment over the years, and this data is presented in Table **1**. Fig. (**1**), derived from this study, exhibits a characteristic pattern resembling a bathtub curve [29]. The failure rates range from 11 failures per year to 57 failures per year.

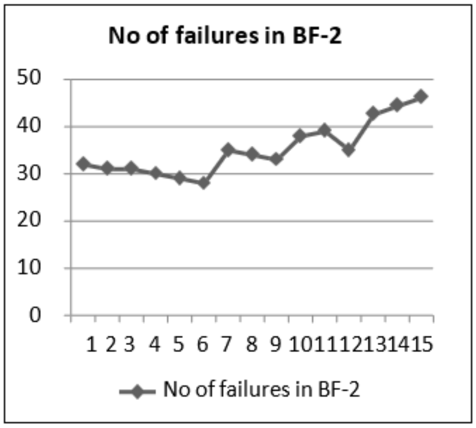
Upon analyzing this data, it becomes evident that the average failure rate for the first three years is 29.4. For the subsequent three years, spanning from the 4th to the 6th year, the average failure rate decreases to 24.7. In the following three-year period, from the 7th to the 9th year, the average failure rate was 28.63. However, the trend shifts significantly in the next three years, from the 10th to the 12th year, with an average failure rate of 35.26. In the last three years, from the 13th to the 15th year, the average failure rate has surged to 39.6 failures per year.

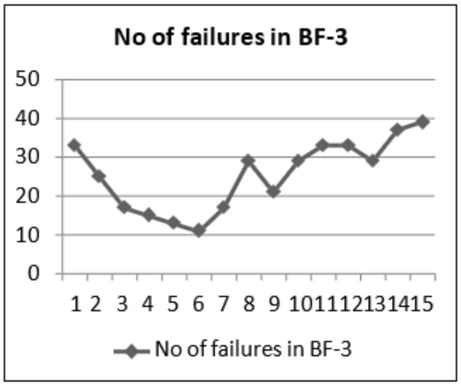
This clear depiction of the failure trend following the bathtub curve underscores the importance for industries to plan their activities with this trend in mind. This proactive approach is necessary to maintain system operations with fewer failures and higher availability, especially considering the sudden increase in the failure rate during the later stages of the equipment's life cycle.

Table 1: Failure rate of bag filters.

Year	No of Failures in BF-1	No of Failures In BF-2	No of Failures in BF-3	No of Failures in BF-4	No of Failures in BF-5	No of Failures in BF-6	No of Failures in BF-7	No of Failures-in BF 8	No of Failures in BF-9	No of Failures in BF-10
1st	37	32	33	27	39	35	34	29	31	25
2nd	36	31	25	31	29	37	33	21	29	29
3rd	26	31	17	20	39	47	28	16	19	18
4th	25	30	15	19	41	49	27	15	17	17
5th	24	29	13	17	43	51	26	13	15	15
6th	23	28	11	16	45	53	25	12	13	14
7th	30	35	17	23	31	39	32	13	27	21
8th	29	34	29	25	33	41	31	27	25	23
9th	28	33	21	27	35	42	30	26	27	25
10th	27	38	29	33	37	45	38	26	29	31
11th	32	39	33	36	39	47	37	29	29	34
12th	37	35	33	40	41	49	41	29	30	35
13th	42	43	29	34	37	41	43	29	31	37
14th	38	44	37	41	45	53	31	25	19	39
15th	57	46	39	52	47	55	48	30	32	37







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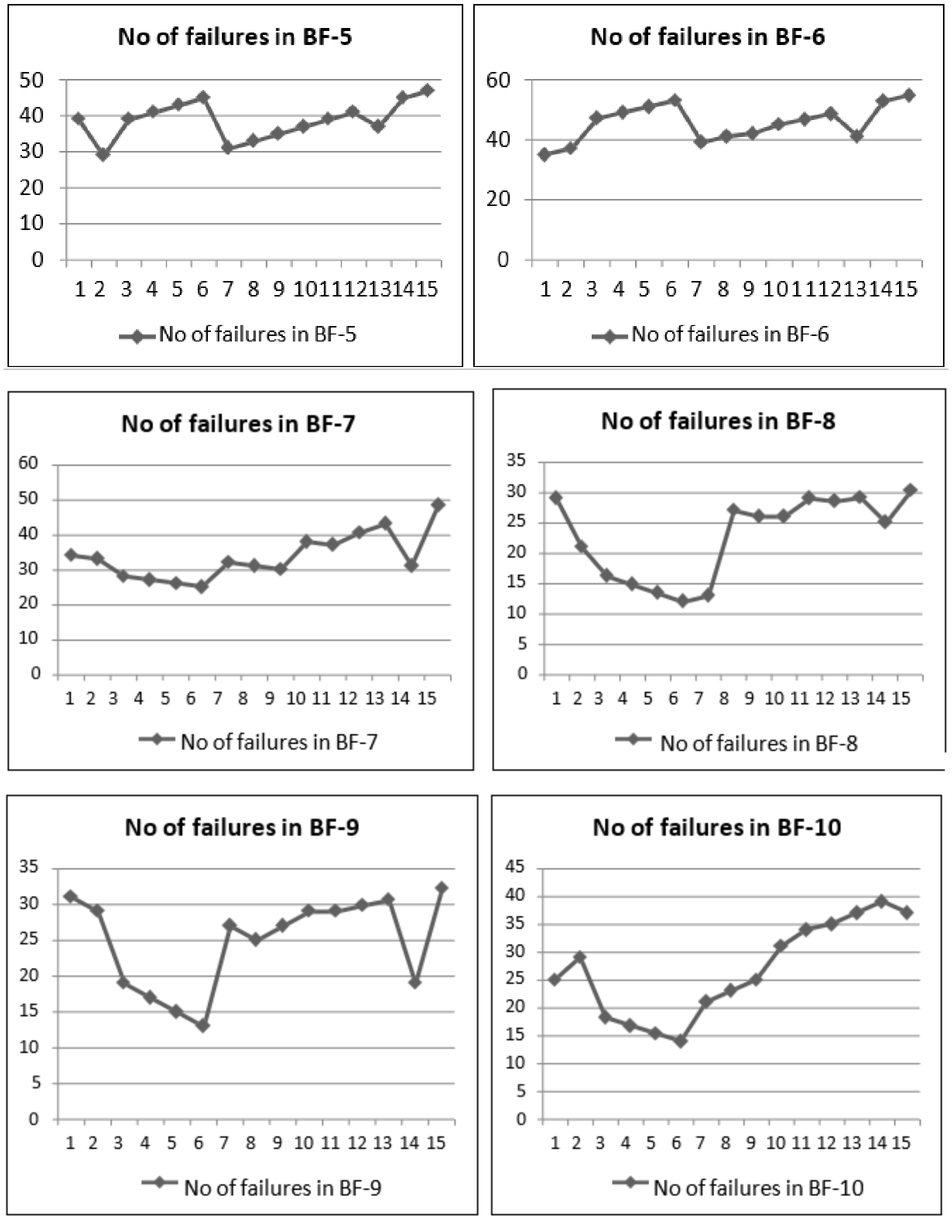


Figure 1: Failure trend of bag filters.

3.2. Reliability Trend

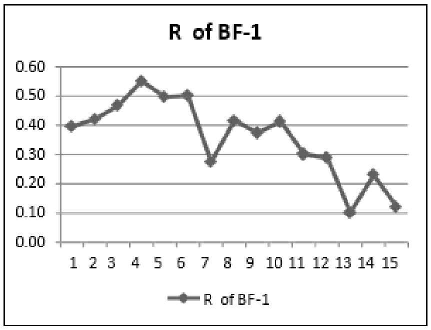
The mean Time Between Failures (MTBF) and the Reliability for each year have been calculated using the method described earlier, based on failure data [5]. The reliability data derived from these calculations for all the years are visually represented in Fig. (**2**). It's noteworthy that in most cases, the graph exhibits a pattern reminiscent of a hat curve [3, 30, 31], as previously discussed in my research on the bathtub curve and reliability curve during the first 10 to 12 years of operation.

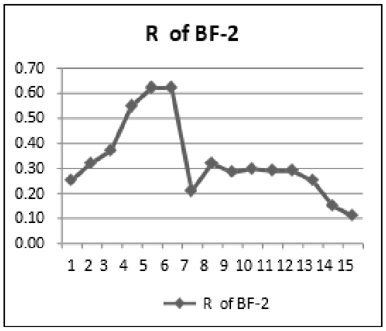
Upon closer examination of the data in Table **2**, it becomes evident that reliability varies within a range from 0.77 to 10.1. To provide further insight, the average reliability for the initial three years is 0.32. For the subsequent three years, from the 4th to the 6th year, the average reliability increases to 0.49. In the following three-year period, from the 7th to the 9th year, the average reliability remains at 0.32. However, the trend takes a significant turn in the next three years, from the 10th to the 12th year, with an average reliability of 0.27. In the last three years, from the 13th to the 15th year, the average reliability declines to 0.21.

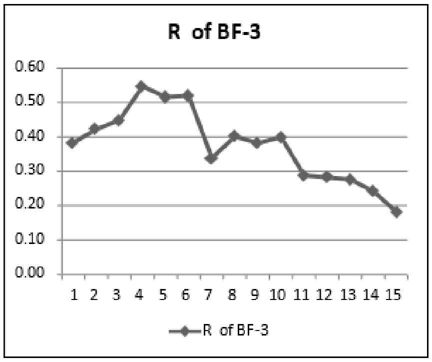
This clear depiction of the reliability trend following the hat curve underscores the importance for industries to plan their activities with this trend in mind. This proactive approach is crucial for maintaining system operations with fewer failures and higher reliability, particularly in light of the sudden decrease in reliability during the later stages of the bag filter's life cycle. It highlights the need for more focused attention on equipment health, whether through the replacement of aging equipment or retrofitting, to ensure optimal performance.

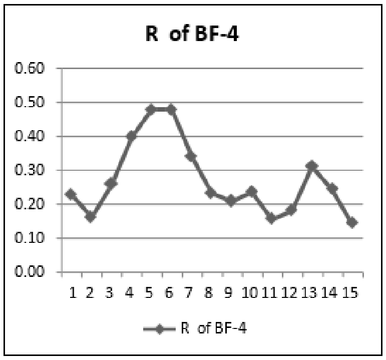
Table 2: Reliability of bag filters.

Year	R of BF-1	R of BF- 2	R of BF-3	R of BF-4	R of BF-5	R of BF-6	R of BF-7	R of BF-8	R of BF-9	R of BF-10	Mean Value of R	Total Downtime Hours
1st	0.39	0.25	0.38	0.23	0.68	0.28	0.34	0.28	0.16	0.20	0.32	210
2nd	0.42	0.32	0.42	0.16	0.48	0.17	0.24	0.22	0.14	0.15	0.27	215
3rd	0.47	0.37	0.45	0.26	0.77	0.23	0.39	0.34	0.34	0.29	0.39	208
4th	0.55	0.55	0.54	0.40	0.75	0.38	0.48	0.42	0.45	0.41	0.49	207
5th	0.50	0.62	0.51	0.48	0.48	0.50	0.48	0.41	0.42	0.46	0.49	204
6th	0.50	0.62	0.52	0.48	0.49	0.50	0.48	0.41	0.42	0.46	0.49	203
7th	0.27	0.21	0.34	0.34	0.43	0.32	0.36	0.27	0.39	0.36	0.33	201
8th	0.42	0.32	0.40	0.23	0.70	0.22	0.35	0.30	0.26	0.24	0.34	199
9th	0.37	0.28	0.38	0.21	0.62	0.20	0.31	0.27	0.23	0.22	0.31	193
10th	0.41	0.30	0.40	0.24	0.71	0.25	0.35	0.29	0.19	0.22	0.34	195
11th	0.30	0.29	0.29	0.16	0.47	0.16	0.23	0.21	0.15	0.15	0.24	212
12th	0.29	0.29	0.28	0.18	0.44	0.13	0.22	0.21	0.12	0.13	0.23	228
13th	0.10	0.25	0.28	0.31	0.42	0.21	0.12	0.26	0.15	0.32	0.24	256
14th	0.23	0.15	0.24	0.24	0.31	0.23	0.26	0.19	0.28	0.26	0.24	276
15th	0.12	0.11	0.18	0.14	0.29	0.13	0.18	0.14	0.18	0.16	0.16	298









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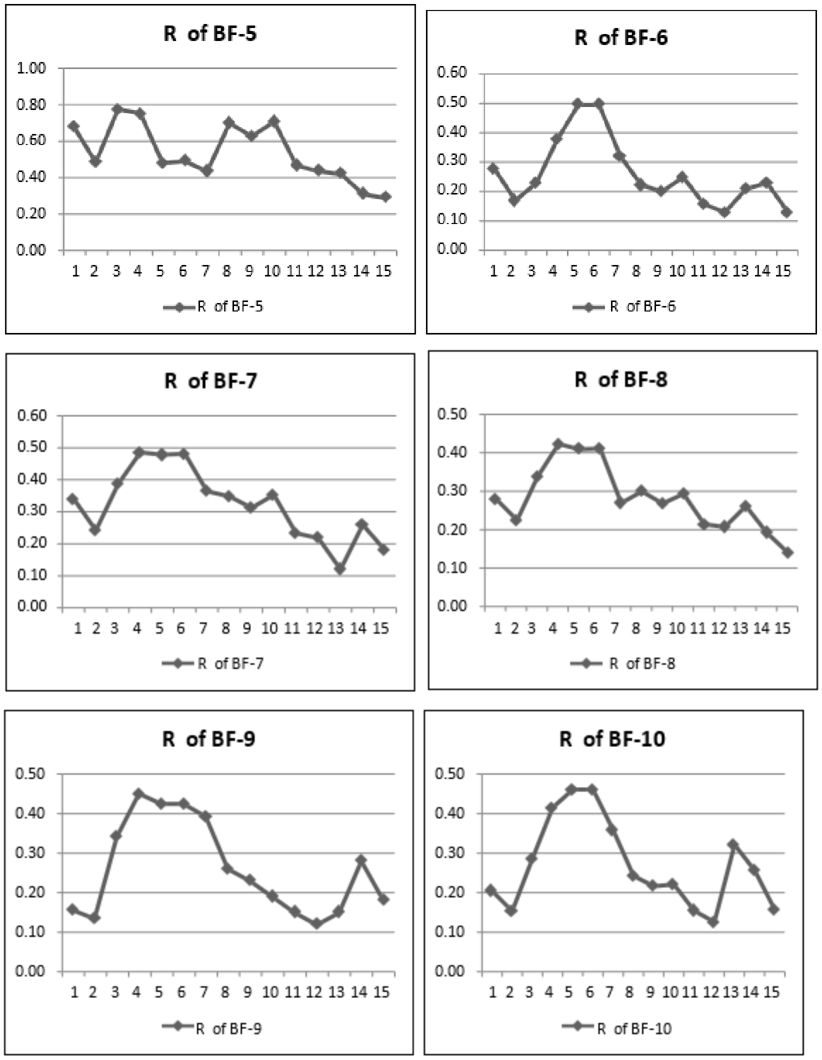

Figure 2: Reliability Trend of bag filters.

3.3. Collection Efficiency Trend Analysis

The trend in collection efficiency over the years, illustrated in Fig. (**3**), reveals a consistent pattern. In all instances, there is a decline in collection efficiency as the equipment ages. This reduction in efficiency becomes more pronounced as the equipment gets older, directly impacting the performance of the bag filters [2].

The collection efficiency is at its peak during the initial years of operation, reaching an impressive 99.998%. However, by the 15th year, the collection efficiency has decreased to 95.05%. This notable decrease underscores the necessity for increased maintenance and retrofitting as the dust collection equipment ages, to preserve and enhance the collection efficiency.

4. Different Techniques to Improve the Performance of Pollution Control Equipment

The reliability and performance of industrial equipment, such as pollution control systems, are critical to maintaining a safe and sustainable environment. Understanding the various stages of equipment failure and addressing them effectively is paramount. Let's delve deeper into these concepts:

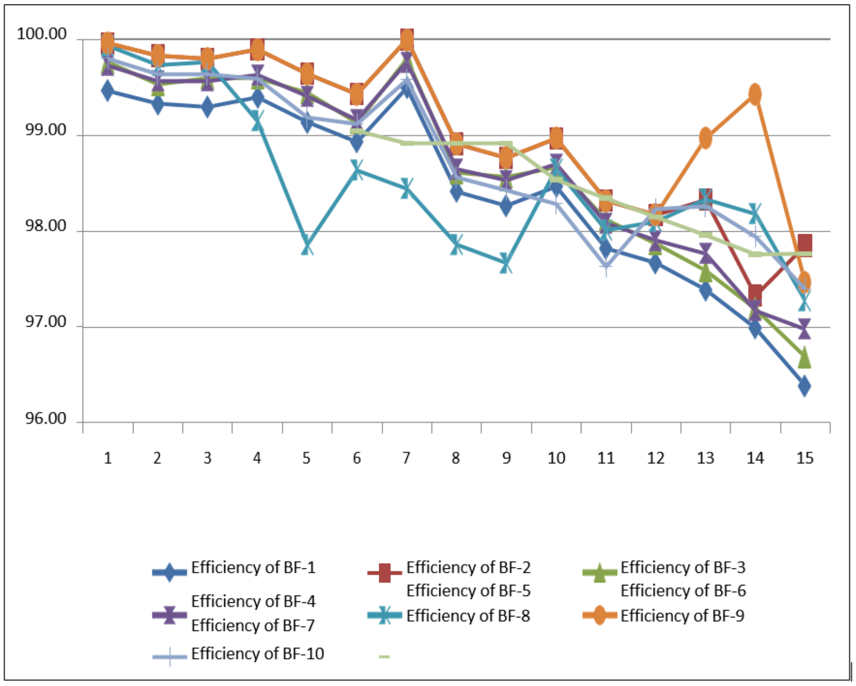

Figure 3: Collection efficiency trend of bag filters.

4.1. Infant-Stage Failures

Early failures, often referred to as infant-stage failures, are highly undesirable. These typically occur during the initial period of operation and can be attributed to a range of issues, including material defects, design flaws, and manufacturing imperfections. Such failures can lead to unexpected downtime, increased maintenance costs, and potentially hazardous situations. To mitigate these issues, rigorous quality control during the manufacturing process and comprehensive testing are essential.

4.2. Normal Life Failures

Normal life failures occur randomly during the operational life of equipment. They result from stress factors exceeding the designed strength of components, often due to abnormal operating conditions or unforeseen circumstances. Addressing normal life failures requires a thorough understanding of the equipment's operational parameters and robust risk management strategies.

4.3. Wear and Tear

Wear and tear, caused by material fatigue and the depreciation of components, is an inevitable aspect of equipment life. While it may lead to gradual performance degradation, it is manageable through routine maintenance and component replacement.

4.4. End-of-Life Failures

Beyond a certain point in an equipment's lifecycle, it is expected that most components will reach the end of their operational life. At this stage, failures are considered normal and acceptable. Proper asset management planning is required to ensure that these failures do not disrupt overall operations or result in environmental harm.

4.4.1. Techniques for Ensuring Equipment Reliability

To enhance the reliability and performance of pollution control equipment, several key techniques should be consistently applied throughout its life cycle.

4.4.2. Proper Design and Selection

The initial design phase is pivotal in choosing materials and configurations that are best suited to the equipment's intended function and the environment in which it operates.

4.4.3. Proper Installation

Correct installation is essential to optimize equipment performance. Proper alignment, calibration, and adherence to manufacturer specifications are crucial during this phase.

4.4.4. Proper Operation

Adhering to manufacturer guidelines and best practices during the operational phase minimizes stress and ensures efficient performance. Regular inspections and operator training are also vital.

4.4.5. Proper Maintenance

Routine maintenance, encompassing cleaning, inspections, and repairs, is necessary to address wear and tear, extend equipment life, and prevent early failures. Retrofitting or upgrading equipment may also be required to keep pace with changing regulations or industry standards.

By applying these techniques at each stage of the equipment's life cycle, organizations can improve reliability and efficiency while maintaining their commitment to environmental sustainability. Properly maintained pollution control equipment contributes to cleaner air and a healthier environment for all.

5. Conclusion

The study reveals intriguing trends in the performance of bag filters used in various industries, with a particular focus on the cement plant. The failure rate trend of bag filters closely mirrors the well-known bathtub curve, particularly during the first ten to twelve years of their operational life. This trend indicates a higher incidence of equipment failures during the initial phase and another surge in failures as the equipment approaches the end of its life cycle. The reliability trend of bag filters exhibits a pattern that we've termed as "Madhab’s Hat curve of reliability." This curve demonstrates higher reliability during the first decade of operation, followed by a notable decrease in reliability beyond this point. This pattern highlights the importance of proactive maintenance and system enhancements to manage the increasing failure rates that occur later in the equipment's life. The study illustrates a consistent decline in collection efficiency as the bag filters age. Collection efficiency is at its peak during the early years of operation, reaching an impressive 99.998%. However, by the 15th year, it dwindles to 95.05%. This emphasizes the necessity of vigilant maintenance and retrofitting to preserve and augment collection efficiency. Based on these findings, it's reasonable to consider the typical lifespan of a bag filter to be between 10 to 15 years. Beyond this point, significant maintenance interventions are required to minimize failure rates and sustain optimal performance. This study not only provides insights for maintenance engineers but also benefits design engineers and reliability engineers. By understanding these trends, they can work towards improving pollution control equipment like bag filters, reverse air bag houses (RABH), and electrostatic precipitators (ESP) to meet the stringent pollution control standards set by governing bodies. Ultimately, this research contributes to the broader goal of maintaining a clean and environmentally responsible industrial landscape.

Conflict of Interest

The authors declare that they have no conflict of interest.

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