

RISK ANALYSIS OF CORROSION DAMAGE TO STEEL COMPONENTS OF THE MANURE SCRAPER HYDRAULIC SYSTEM IN TERMS OF WORKPLACE SAFETY IN A COWSHED USING THE FMEA METHOD

Maria PILARCZYK¹

¹Częstochowa University of Technology, Częstochowa, Poland, EU, maria.pilarczyk@pcz.pl

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Abstract

The operating conditions of free-stall barns may accelerate the corrosion and degradation of steel components used in manure removal equipment, potentially reducing service life and increasing the risk of failure. This study aimed to identify and assess the risk of corrosion damage to steel components of a hydraulic manure scraper and to determine its potential implications for occupational safety. The Failure Mode and Effects Analysis (FMEA) method was applied to systematically identify and evaluate risks. The analysis included key steel components: the scraper press body, left and right scraping arms, scraper track bar, hydraulic cylinder cover, and guide rails. These elements are directly exposed to the operating environment and mechanical loading, making them particularly susceptible to progressive degradation. Other components, such as the hydraulic power unit, hydraulic cylinders, and control box, are equipped with corrosion protection; therefore, their corrosion risk was assessed as lower, though not eliminated. For each component, potential failure modes, corrosion mechanisms, and consequences for system operation and worker safety were identified, and risk levels were estimated according to FMEA criteria. The results indicate that the highest risk is associated with the scraper press body and scraping arms. Their progressive corrosion may cause structural weakening and sudden failure, posing hazards to workers through sudden structural failure, component detachment, or uncontrolled movement. Guiding elements present moderate risk, potentially leading to increased friction and indirect overloading of the hydraulic system. The results indicate that maintenance and inspection should prioritize components with the highest RPN values, particularly structural elements exposed simultaneously to corrosion and mechanical loading.

Keywords: Corrosion, hydraulic manure scraper, occupational safety, free-stall barn, FMEA

1. INTRODUCTION

Loose-housing barns have specific environmental conditions that promote accelerated wear of structural components and equipment. The combination of moisture, manure residues, and chemically aggressive substances creates conditions that may accelerate the degradation of metallic components [1–4]. Hydrogen sulfide dissolves in the moist layer present on the surfaces of concrete and metal in livestock facilities. Under such conditions, it undergoes oxidation to sulfuric acid, which consequently contributes to material degradation and corrosion [2, 3]. Steel components may also be affected by exposure to ammonia-containing atmospheres [4]. The simultaneous action of these environmental factors creates an environment that is highly aggressive to construction materials. Corrosion is a widespread phenomenon that generates significant losses across many sectors of the economy, with agriculture being particularly exposed, as operational conditions there intensify degradation processes [5].

From a technical perspective, corrosion can be regarded as a specific type of undesirable material degradation resulting from chemical, mechanical, and biological factors. The intensity of this process depends both on

material properties and environmental conditions as well as operational loads, which in agricultural environments often occur simultaneously and mutually reinforce one another [6].

These degradation mechanisms are particularly relevant to hydraulic manure removal systems, whose components are subjected to both operational loading and progressive material deterioration. As a result, corrosion-related damage may compromise the functional performance and reliability of the equipment and, in severe cases, contribute to unsafe operating conditions. Despite extensive research on corrosion in agricultural machinery [7-9] and its impact on equipment durability, the literature still lacks comprehensive analyses focused on the occupational safety of workers operating such equipment in livestock environments. Existing studies mainly concentrate on material and operational aspects, overlooking their direct implications for operator risk. This gap is particularly important because both agricultural machinery components and metal structures in agricultural buildings are exposed to corrosive conditions that can cause progressive material degradation and compromise their functional performance [6, 10]. In severe cases, such degradation may contribute to component failure and create hazardous situations during equipment operation and maintenance. Previous studies have documented injuries and fatalities associated with manure storage, handling, and transport, including incidents involving entanglement, runover, and equipment failure [11]. Research on dairy farm safety has also identified manure-handling systems as a source of occupational injuries and fatalities among farm workers [12]. However, the specific relationship between corrosion-induced degradation of manure scraper components and worker safety remains insufficiently investigated. The novelty of this study lies in applying the FMEA method specifically to corrosion-related degradation of the structural and hydraulic components of a manure scraper, while explicitly considering the consequences of potential failures for worker safety. Rather than assessing corrosion solely in terms of material degradation or equipment service life, the study links the technical failure modes with their possible occupational safety consequences.

The aim of this study was to identify and assess the risk of corrosion damage to steel components of a hydraulic manure scraper and to determine their impact on occupational safety.

The results of the conducted analysis provide a basis for developing recommendations regarding preventive and operational measures, the implementation of which may help reduce the number of failures, increase equipment reliability, and improve operator safety.

The research hypothesis assumes that corrosive conditions in livestock environments significantly influence the risk of damage to steel components of manure scrapers and that their degradation contributes to increased occupational safety hazards for operators, which can be effectively identified using the FMEA method.

2. MATERIALS AND METHODS

The subject of the analysis was a hydraulic manure scraper operating under the corrosive environmental conditions typical of loose-housing barns. To identify and assess the risk of corrosion damage, the Failure Mode and Effects Analysis (FMEA) method was applied. This method enables the systematic identification of failure modes, their causes, and their effects on system functionality and user safety. In the present study, FMEA was used to evaluate the criticality of individual components of the manure scraper. The application of the FMEA method is supported by the work of Zandi et al. [13], who confirmed its usefulness in risk management in agricultural projects and indicated that its extension with multi-criteria approaches can provide a more comprehensive risk assessment under conditions of uncertainty typical of the agricultural sector.

The assessment of operating conditions was based on the design and functional characteristics of the manure scraper, descriptions of operating conditions typical of loose-housing barns reported in the literature [1-9], and an engineering assessment of the exposure of individual components to environmental and mechanical stressors. The analysis therefore combined information from the literature, an examination of the scraper's construction and operating principle, and expert engineering judgement concerning the degradation

mechanisms of steel components. No direct measurements of ammonia or hydrogen sulfide concentrations and no statistical analysis of accident or near-miss records were performed in this study.

Based on the above criteria, the Risk Priority Number (RPN) was calculated using the classical FMEA scoring scale from 1 to 10 for the three parameters:

$$RPN = S \times O \times D \quad (1)$$

where:

- **S (Severity)** – the severity of failure effects, where 1 indicates no impact on system operation and 10 indicates a hazard to the operator's life,
- **O (Occurrence)** – the frequency of failure occurrence, where 1 indicates very rare events and 10 indicates very frequent events,
- **D (Detection)** – the detectability of a failure before it occurs, where 1 indicates easy detection and 10 indicates no possibility of early detection.

The RPN values were used to classify the relative risk level of damage to the scraper components. For the purposes of this study, the following study-specific classification was adopted: high risk: $RPN > 300$, medium risk: $RPN = 200\text{--}300$, and low risk: $RPN < 200$. The thresholds were established by the authors as a study-specific prioritization scheme and were not adopted as universal limits defined by an international standard. The boundaries were selected to distinguish failure modes requiring immediate attention ($RPN > 300$), those requiring planned corrective and preventive actions ($RPN = 200\text{--}300$), and those requiring routine monitoring ($RPN < 200$). The classification should therefore be interpreted in the context of the present study and the applied 1–10 scoring scale.

Based on the design and operational analysis, the key components of the hydraulic manure scraper were identified and subjected to FMEA evaluation. These included the scraper press body, left and right scraping arms, guide rails, scraper track bar, and cylinder cover. The hydraulic cylinder, hydraulic power unit, and control box were also included because, despite the presence of protective measures, their failure may influence the operation of the complete system and consequently affect workplace safety. For each component, potential failure modes were identified, along with their causes resulting from exposure to the corrosive environment, as well as their effects on device operation and operator safety.

The analysis was therefore treated as a structured expert-based FMEA, in which the ratings reflected the expected consequences, occurrence, and detectability of each failure mode under the analysed operating conditions. The Risk Priority Number (RPN) was calculated according to Equation (1). The results of the analysis are presented in tabular form, enabling comparison of the risk levels for individual components of the manure scraper. Additionally, the impact of the identified failure modes on operator safety was considered, which allowed the linkage of the technical reliability of the device with operational risk under real-world conditions. The values of S, O, and D were assigned using structured engineering judgement based on the expected consequences of each failure mode, its anticipated occurrence under the analysed operating conditions, and the likelihood that degradation would be detected before failure. The assessment was based on the author's engineering knowledge and consultations with three experts with experience in agricultural machinery and corrosion degradation in humid, corrosive livestock environments. Therefore, the assessment should be regarded as a structured expert-based FMEA rather than as a statistically validated estimate of failure probability.

3. RESEARCH RESULTS

The FMEA analysis enabled the identification and prioritization of corrosion-related failures in the components of a hydraulic manure scraper in terms of their impact on operational reliability and safety. The highest risk level ($RPN > 300$) was identified for the scraper press body (378) and the left and right scraping arms (350

and 324, respectively) (**Table 1**). The high severity and occurrence values indicate that these are critical components whose corrosion may lead to sudden failures and pose a direct threat to workers.

Most of the remaining components were classified as medium risk (RPN 200–300), including guide rails, scraper track bars, and the hydraulic cylinder (**Table 1**). Corrosion–mechanical wear processes dominate in these elements, leading to deterioration in the interaction of moving parts. Phenomena such as guide seizure (288) and track irregularities (252) may result in overloads and disruptions in motion.

The hydraulic cylinder (RPN 240 and 225) is also significant (**Table 1**). Corrosion of the piston rod and seal wear lead to leakage and pressure drops, resulting in unstable and unpredictable system operation.

Lower RPN values (<220) were obtained for the hydraulic power unit and control box (**Table 1**); however, their failure may affect the entire system. The lowest risk (120–150) was identified for the cylinder cover (**Table 1**), which has a protective function, though its damage accelerates corrosion of other components.

The most critical failures are those leading to sudden structural damage, uncontrolled movement of components, as well as leaks and control disturbances (**Table 1**).

Table 1. Risk assessment of corrosion damage to the components of a hydraulic manure scraper using the FMEA method

Component	Failure mode	Cause / mechanism	Effect	S	O	D	RPN
Scraper press body	Pitting corrosion, perforation	Continuous exposure to moisture, NH ₃ , H ₂ S	Structural weakening, possibility of cracking	9	7	6	378
Scrapping arms (left/right)	Structural cracking	Advanced corrosion and mechanical loading	Sudden failure, risk of worker injury	10	5	7	350
	Material loss	Abrasive wear and chemical corrosion	Reduced scraping efficiency	7	8	5	280
	Deformation / fracture	Cross-sectional weakening due to corrosion	Component detachment - risk of injury	9	6	6	324
Scraper track bar (left/right)	Surface corrosion	Moisture and manure	Increased movement resistance	6	7	5	210
	Track irregularities	Non-uniform corrosion	Jamming, system overload	7	6	6	252
Guide rails	Corrosive wear	Friction and aggressive environment	Deterioration of guidance performance	6	7	5	210
	Guide seizure	Corrosion and lack of lubrication	Cylinder overload	8	6	6	288
Cylinder cover	Cover corrosion	Damage to the protective coating	Exposed cylinder	5	6	4	120
	Cover perforation	Long-term corrosion	Ingress of contaminants	6	5	5	150
Hydraulic cylinder	Piston rod corrosion	Moisture, aggressive environment	Seal damage, leakage	8	6	5	240
	Leakage	Seal wear, corrosion	Pressure drop, loss of motion	9	5	5	225
Hydraulic power unit	Oil degradation	Contaminants, moisture	Reduced system efficiency	7	6	5	210
	Pump failure	Wear, corrosion	Loss of pressure, system shutdown	9	4	5	180
Control box	Corrosion of contacts	Moisture, NH ₃ (ammonia)	Control disturbances	7	6	4	168
	Short circuit	Moisture ingress	System failure, fire risk	9	4	6	216

4. DISCUSSION

The results of the FMEA indicate that the scraper press body and scraping arms are the most critical components of the analysed machine from the perspective of occupational safety. The safety significance of corrosion depends not only on the extent of material degradation but also on the function of the affected component within the machine. This is related to the primary structural and operational functions of these components, as corrosion-related material loss, cracking, deformation or loosening may reduce the stability and load-bearing capacity of the working system and, in advanced cases, lead to unexpected machine behaviour. In this context, the high RPN values assigned to these components should be interpreted as an indication of the need for priority inspection and preventive action rather than as an absolute probability of failure. This interpretation is consistent with previous applications of FMEA in agricultural machinery and technical systems, where the method has been used to structure risk assessment, identify critical components, and support the prioritization of preventive and maintenance activities [14-17]. The significance of a component's function and the consequences of its failure for occupational safety should be considered within the broader context of agricultural machinery safety [18, 19].

The results obtained for the guides, scraper track strips and hydraulic cylinder indicate a different relationship between degradation and occupational safety. The deterioration of these components may initially manifest itself as impaired operating parameters, increased resistance to movement, irregular scraper movement, or leakage. Although these symptoms may initially affect mainly efficiency and reliability, they may also constitute early indicators of a developing technical condition that could subsequently lead to unsafe machine behaviour. Such symptoms may therefore provide an opportunity for early intervention before the degradation develops into a more serious safety problem. This is particularly important because a gradual deterioration in operating performance may affect the predictability of machine behaviour. Consequently, monitoring changes in movement resistance, scraper motion, hydraulic performance, and leakage can complement visual corrosion inspections. In contrast, the lower RPN values obtained for the power supply and control systems indicate a lower relative priority within the analysed risk hierarchy, but do not imply an absence of potential safety consequences. In particular, malfunction of the control system may affect the predictability of machine movement and lead to unexpected machine behaviour [20].

From the perspective of occupational safety, the main value of the FMEA conducted in this study lies in its ability to establish priorities for preventive and inspection activities at the level of individual components. This is particularly important because analyses of agricultural machinery failures have often focused primarily on technical reliability, while the potential consequences of component degradation for operator safety have received less attention [21]. Moreover, both technical failures and unfavourable operating conditions may contribute to accident events and occupational injuries in agriculture [22]. Accordingly, inspection and maintenance activities should be prioritised according to the potential safety consequences of component degradation. From a practical perspective, inspection programmes should include periodic visual examination of the scraper body and arms for pitting, section loss, cracks, deformation, and loosening. Guide rails and track bars should be monitored for irregular movement and increased resistance, while hydraulic cylinders should be inspected for piston-rod corrosion and leakage. Where coating damage is observed, corrosion protection should be renewed, while the use of corrosion-resistant materials and protective coatings should be considered as part of the preventive maintenance strategy [23–25]. This approach allows inspection resources to be directed towards the failure modes with the greatest potential consequences rather than being distributed uniformly across all components. In this respect, FMEA provides a link between the technical condition of individual components and the planning of preventive measures aimed at reducing occupational safety risks. The results should be interpreted in light of the limitations of the classical FMEA method. RPN is a relative indicator used to compare failure modes and establish component priorities, rather than an absolute probability of failure or a complete measure of occupational risk. The same RPN value may result from different combinations of Severity, Occurrence and Detection ratings, while these ratings may be partly dependent on expert judgement. These limitations have been highlighted in the literature, which has also proposed

alternative approaches to classical FMEA that account for uncertainty and dependencies between risk parameters [26,27]. Therefore, in the present study, RPN should be treated as a relative indicator for comparing components and establishing priorities within the analysed machine.

A further limitation is the lack of a comprehensive statistical database covering actual failures, accidents, and near-miss events associated with the analysed equipment. The assessment was based on engineering analysis and structured expert judgement rather than on statistically validated failure frequencies. Future research should therefore combine FMEA with field inspection data, measurements of environmental exposure, long-term monitoring of corrosion and mechanical degradation, and systematic analysis of maintenance, failure, and near-miss records. Design-of-experiments approaches and modelling methods, including neural-network-based techniques, could further support the analysis of complex relationships between operating conditions, degradation processes, and the risk of unsafe machine behaviour [28, 29].

The main contribution of this study is the identification of differences in the safety significance of degradation at the level of individual components of a hydraulic manure scraper. The results demonstrate that the same type of degradation may have different consequences depending on the function of the affected component and the potential consequences of its failure. This provides a basis for establishing inspection and preventive maintenance priorities according to the potential safety consequences of degradation, rather than treating all components uniformly.

5. CONCLUSIONS

The FMEA analysis showed that the corrosive livestock environment increases the risk of degradation and failure of hydraulic manure scraper components. The highest RPN values were obtained for the scraper press body and scraping arms, indicating the particular importance of these components for occupational safety.

The greatest hazard to workers is posed by damage that may lead to sudden structural failure, mechanism jamming, or uncontrolled movement of working parts. Reducing these risks requires the use of corrosion-resistant materials, appropriate surface protection, and regular monitoring of the technical condition of the most heavily loaded components.

The results confirm that FMEA can support the identification of components whose degradation poses the greatest risk to worker safety. The identified risk priorities can be used to plan inspections, maintenance, and preventive measures.

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