Design of Rolling bearings for their use in Potentially Explosive Atmospheres – A Systematic Review

There is currently no single guideline for the design of rolling bearings for use in potentially explosive atmospheres. Although one section of the ISO 80079-37 standard refers specifically to rolling bearings in the context of design in accordance with the principle of design safety, this section mainly refers to other standards and manufacturers' specifications. This work is intended to identify and summarize current standards, guidelines, technical rules and other research results on the subject of the design of rolling bearings within the framework of a systematic review and thereby create a basis for a guideline for the design of rolling bearings. In addition, further research approaches are to be derived from the current state of the art.

Keywords: *roller bearing, non-electrical explosion protection, explosive atmospheres, ATEX*

Introduction

In all industrial and private applications requiring work with flammable gases or dusts, an explosion must be expected in the worst case. This danger can be countered with suitable actions from the field of explosion protection. The primary aim of explosion protection measures is to prevent the creation or ignition of an explosive atmosphere. Here, applications from electrical or non-electrical explosion protection are used accordingly. If this is not possible, the propagation of the explosion should be kept to a minimum.

The handling of explosion protection is regulated by law in most industrialized countries. In Europe, these regulations are set out in EU Directive 2014/34/EU. At the German level, the EU directive is implemented by corresponding standards.

For development reasons, non-electrical explosion protection is comparatively little represented in standardization. Explosion protection originated underground, where attempts were made then, as now, to prevent the occurrence of electrical ignition sources by means of suitable protective measures. The development began in 1909 with the first flame-proof pit lamp for the mining industry (Eaton´s Crouse-Hinds Business, 2013). Electrical ignition sources have long been the focus of explosion protection. Only over time have non-electrical ignition sources been considered in more detail as part of the standardization process. However, this is how non-electrical explosion protection plays a major role in reality. According to Bartknecht, non-electrical ignition sources cause about 30% of industrial deflagrations and explosions (Bartknecht & Zwahlen, 2013). A common ignition source is the hot surface of a machine element. This ignition source is often caused by the friction of parts in relative motion.

This phenomenon can also be observed in rolling bearings. The heating that occurs here is not critical in normal operation if the bearings are designed correctly, maintained appropriately and mounted correctly. It is always necessary to take a close look at the prevailing operating conditions, record any temperature limit values and include them in the bearing design. If the assumed parameters deviate from their nominal values due to incorrect design, mounting or maintenance, a rolling bearing can quickly become a source of ignition.

The aim of this work is to summarize the design of rolling bearings with regard to their use in potentially explosive atmospheres in accordance with current standardization and to supplement this with a systematic review of current research findings.

Basics Explosion Protection

The prevention of explosion hazards is regulated by law in most industrialized countries. In the European Union, explosion protection is regulated in the so-called ATEX Directive 2014/34/EU standardized. This includes the harmonization of the country-specific laws of the member states for equipment, protective systems and components for the intended use in potentially explosive atmospheres. The ATEX directive defines basic safety requirements and leaves the technical specification to the European standards. The IEC 60079 ff series of standards deals with electrical explosion protection, while ISO 80079 ff describes the measures for non-electrical explosion protection.

The technical concretization and specific implementation recommendations of the individual standards can be found in national technical regulations and recommendations. In Germany, these can be found in the corresponding VDI guidelines and in various technical rules for operational safety or for hazardous substances, TRBS or TRGS for short.

In addition, the ATEX Directive regulates the conformity assessment and marking of products in potentially explosive atmospheres. As a fully harmonized directive, the ATEX Directive 2014/34/EU replaces all existing divergent national and European legislation on the same subjects.

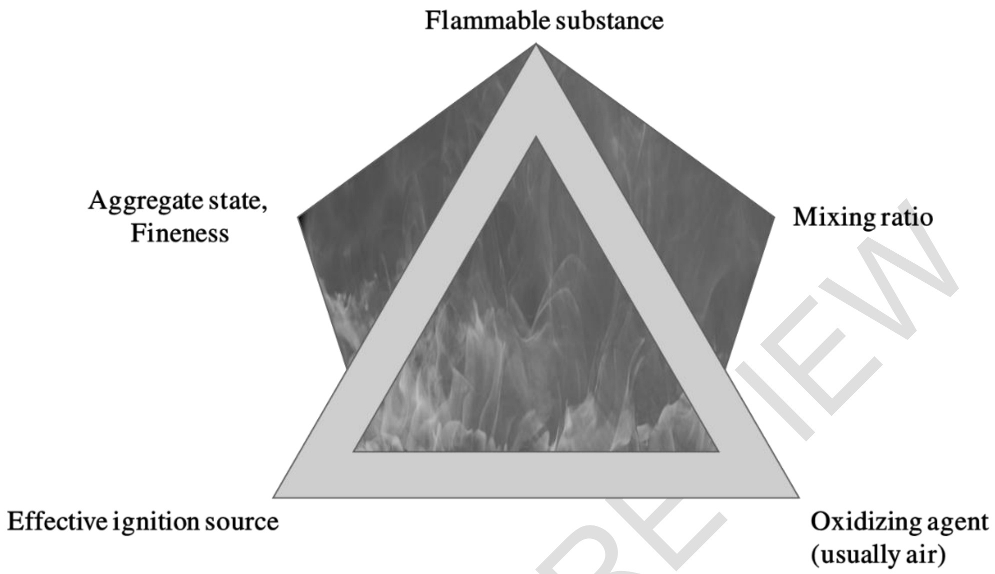
Basically, the EN 1127-1 regulates Procedures for recognizing and evaluating hazardous situations in which ignition of an explosive atmosphere can potentially occur. The standard provides guidance for risk assessment and describes suitable planning and manufacturing measures to reduce these risks and increase safety.

Furthermore, the standard deals with various parameters that must be in a defined mixing ratio spatially and temporally to each other in order to justify an explosion. These are influenced by:

- the presence of a flammable/combustible substance;
- the degree of dispersion of the flammable/combustible substance (e.g. gases, vapors, mists, dusts);
- the concentration of the flammable/combustible substance in the air within the explosion range (mixing ratio);
- the amount of explosive atmosphere sufficient to cause injury or damage in the event of ignition.

If the mixture described above now meets an ignition source in a suitable explosive ratio, an explosion will consequently occur (see Figure 1). This must be prevented by suitable explosion protection measures.

Figure 1. *Explosion Pentagon*



All assumptions made in the context of explosion protection must be considered in the light of the atmospheric conditions specified in EU Directive 2014/34/EU. These are generally understood to be ambient temperatures of -20 °C to +60 °C, a pressure range of 0.8 bar to 1.1 bar, and an oxygen content in the air of 21 %. (Europäische Union, 2014).

The standards IEC 60079-10-1 and IEC 60079-10-2 describe the essential principles for the classification of potentially explosive atmospheres according to the probability of the presence of an explosive atmosphere. Within the standards, a distinction is made between the zones described in Table 1 depending on the occurrence of the potentially explosive atmosphere.

In order to specify the use of the corresponding devices with regard to the permissible operating temperatures, the maximum permissible surface temperatures are divided into temperature classes from T1 to T6. The subdivision can be found in Table 2 and is based on IEC 60079-0.

The ISO 80079-36 also defines the requirements for equipment to be used in explosion-proof areas and classifies them according to an EPL (Equipment Protection Level) standard. The subdivision is compared with the zone classification from standards IEC 60079-10-1/2 in Table 3.

Table 1. *Classification of Zones*

Medium	Zone	Definition
Gas	2	Area in which an explosive gas atmosphere is not expected to occur during normal operation; if it does occur, it will only be of short duration.
	1	Area in which an explosive gas atmosphere is likely to occur periodically or occasionally during normal operation.
	0	Area in which an explosive gas atmosphere is present continuously, for a long period of time or frequently.
Dust	22	Area in which an explosive dust atmosphere in the form of a cloud of combustible dust in air is not likely to occur during normal operation; if it does occur, however, it will only be for a short period of time
	21	Place where a potentially explosive dust atmosphere in the form of a cloud of dust in air occurs occasionally during normal operation
	20	Place where an explosive dust atmosphere in the form of a cloud of dust in air is present continuously or for a long period of time or frequently

Source: Europäische Union, 2014

Table 2. *Maximum Permissible Surface Temperatures*

Temperature classes	Ignition temperature range of the mixtures	Permissible surface temperature of the devices	Example substances
T1	> 450 °C	450 °C	Hydrogen
T2	> 300 °C ... < 450 °C	300 °C	Ethylene
T3	> 200 °C ... < 300 °C	200 °C	Gasoline
T4	> 135 °C ... < 200 °C	135 °C	Ethyl ether
T5	> 100 °C ... < 135 °C	100 °C	
T6	> 85 °C ... < 100 °C	85 °C	Carbon disulfide

Source: Europäische Union, 2014

Table 3. *Comparison of zoning and EPL Level*

ATEX 2014/34/EU			IEC 60079-10-1 IEC 60079-10-2	ISO 80079-36/37			
Device category	Level of security	Zones	Group	Protection level EPL	Safe for		
					Normal operation	Expected disturbance	Rare disorder
1G	very high	0, 1, 2	II (gas)	Ga	x	x	x
2G	high	0, 1		Gb	x	x	
3G	normal	0		Gc	x		
1D	very high	20, 21, 22	III (dust)	Since	x	x	x
2D	high	20,21		Db	x	x	
3G	normal	20		Dc	x		

Source: (IEC, IEC 60079-10-1.; IEC, IEC 60079-10-2)

Research Needs and Methodology

Although, as mentioned at the beginning, non-electrical ignition sources cause around 30% of industrial deflagrations and explosions, non-electrical ignition sources are currently given little consideration in standardization. In particular, machine elements which can themselves become a source of ignition, such as belt drives, springs or rolling bearings, are not fully dealt with in standardization. For this reason, the present paper is intended to take a closer look at the current state of the art with regard to the procedure for designing rolling bearings for use in potentially explosive atmospheres. Current standards, technical rules, guidelines and other publications in the field of rolling bearing application in potentially explosive atmospheres are to form the basis of the elaboration.

The current state of the art will be based on a systematic literature review following Prielipp et al. "Conducting a Systematic Literature Review in Engineering" (Riccardo Prielipp, Carlo Emanuel, Philipp Wilsky, 2022) to be elaborated. The research and analysis of standards will follow Mangelsdorf's "Researching and Analyzing Norms and Standards" (Axel Mangelsdorf, 2019).

The specific research question is: "How should rolling bearings be designed according to the current state of the art for their use in potentially explosive atmospheres?". The aim is to comprehensively present the current state of the art according to standardization, taking into account current research results, including all references, and thus to create the basis for a guide to the design of rolling bearings for use in potentially explosive atmospheres.
For a clear definition and delimitation, this elaboration relies on a categorization of the established taxonomy for literature reviews according to Cooper (Cooper, 1988). The chosen categories of the taxonomy can be seen in Table 4.

Table 4. *Taxonomy of Literature Review*

CHARACTERISTIC	CATEGORIES			
FOCUS	Research Outcomes	Research Methods	Theories	Applications
GOAL	Synthesis	Critical view	Identification of central question	
PERSPECTIVE	Neutral reproduction		Critical position	
COVERAGE	Exhaustive	Exhaustive and Selective	Representative	Selective
ORGANIZATION	Historic	Conceptual	Methodological	
AUDIENCE	Specialized Scholars	General Scholars	Practitioners/ Politicians	General Public

The focus of the elaboration is on previous research results and the concrete application recommendations and methods of the standards, technical rules and guidelines. The aim of the work is to synthesize by combining different sources and to identify central issues. The review is intended to reflect the current state of the art as completely and neutrally as possible. The organization of the literature in the review is conceptually methodical. The paper is primarily aimed at subject matter experts and practitioners.

Standards, technical rules, guidelines and other publications in this field are taken into account. The standards analyzed must be ISO, EN or DIN standards. Technical rules or guidelines included must be recognized for their consideration in Germany.

Regarding scientific publications, due to the poor data situation, publication of the last 20 years (from 2003-2023) are considered after the search for publications in the last 10 years (from 2013-2023) provides insufficient results. For obtaining a scientific grade, only peer-reviewed publications are considered.
The keywords used based on the research question:

- Bearing (machine element)
- Explosion protection

Table 5. *Search Terms*

Bearing		**Explosion protection**
Bearing **OR** *Rolling bearing* **OR** *Ball Bearing*	**AND**	*Explosion protection* **O**R *Atex* **OR** *Explosive atmosphere* **OR** *Hazardous areas* **OR** *NEC* **OR** *HazLoc*

The search terms derived from this are (Table 5):

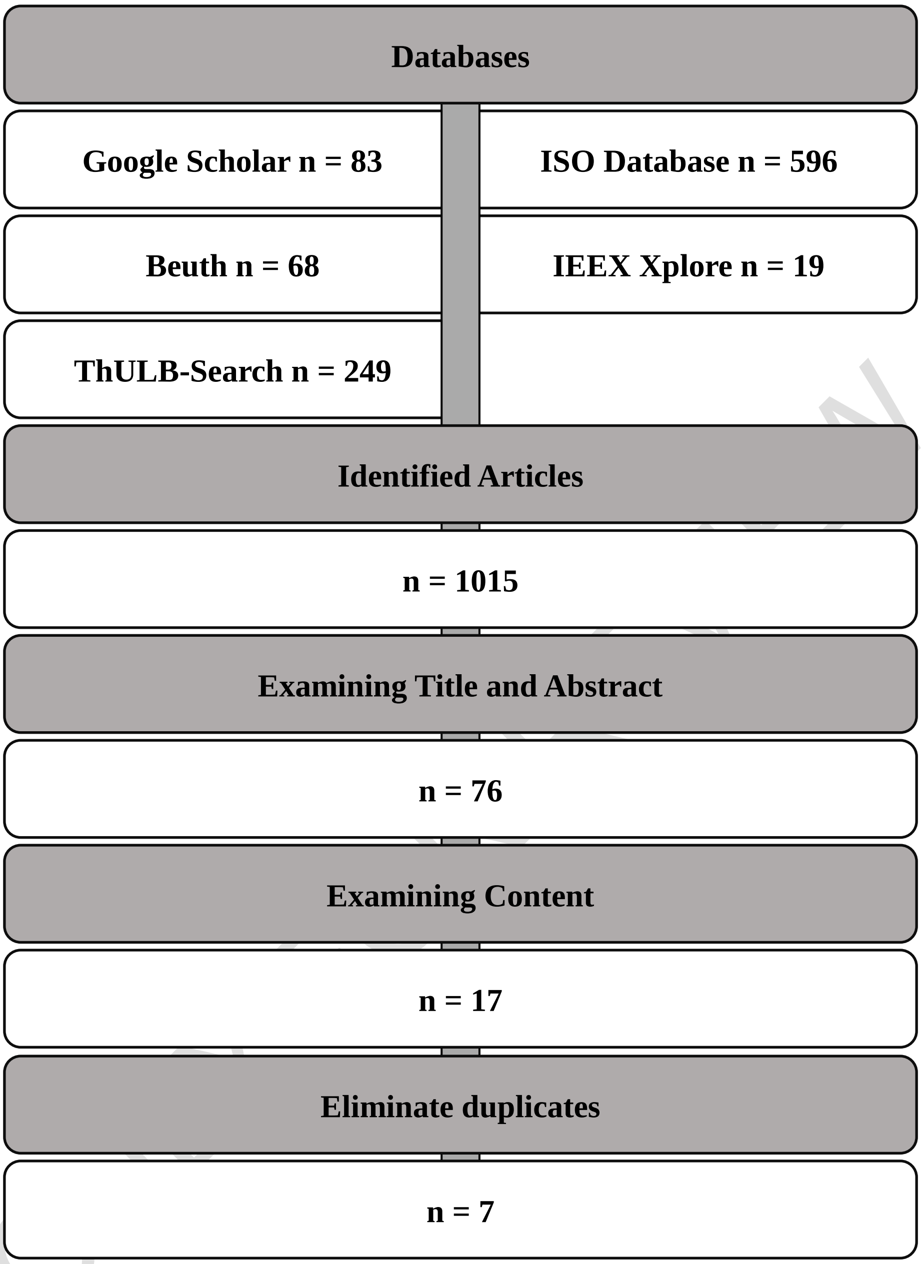
Literature searches are conducted in various databases as well as in topic-specific journals.

The databases searched are:

- Google Scholar (https://scholar.google.de/)
- ISO database (www.iso.org)
- Beuth (www.beuth.de)
- IEEE Xplore (https://ieeexplore.ieee.org/)
- ThULB search (https://www.thulb.uni-jena.de/home) incl:
    - JSTOR
    - Web of Science
    - Scopus
    - DOAJ: Directory of Open Access Journals
    - OAPEN: Online library and publication platform

The search based on the search terms resulted in 1015 hits. Taking into account the search result requirements, the removal of duplicates, and after evaluating the title, abstract, and content, the number of relevant search results is reduced from 1015 to 7 publications and articles (Table 6).

Table 6. *Databases*



The articles and publications relevant for the review are then evaluated with regard to their relevance using a point scale of 0-3 (0 = not relevant, 3 very relevant). Papers with a relevance of 0 are not considered further. Papers with no reference to the research question will be awarded 0 points. If a paper provides concrete recommendations for action or interpretation, it is given a relevance score of 3.

Table 7 shows the relevant (scale > 1) articles and publications considered in this review.

Table 7. *Sources*

Standard/Author	Relevance
DIN CEN/TR 16829	3
DIN EN 14986	2
DIN EN ISO 80079-36:2016-12	2
DIN EN ISO 80079-37:2016-12	3
VDI 2263:2018-07	1
Pieters and Perbal (2011)	2
Slavko et al. (2010)	3

Results

In the following, the contents of the identified literature will be summarized. In order to obtain a holistic overview of the design of rolling bearings for use in potentially explosive atmospheres, any references (such as in ISO 80079-37 reference to manufacturer's specifications) are included in the results.

Classification of rolling bearings for use in potentially explosive atmospheres according to ISO 80079-36 and -37

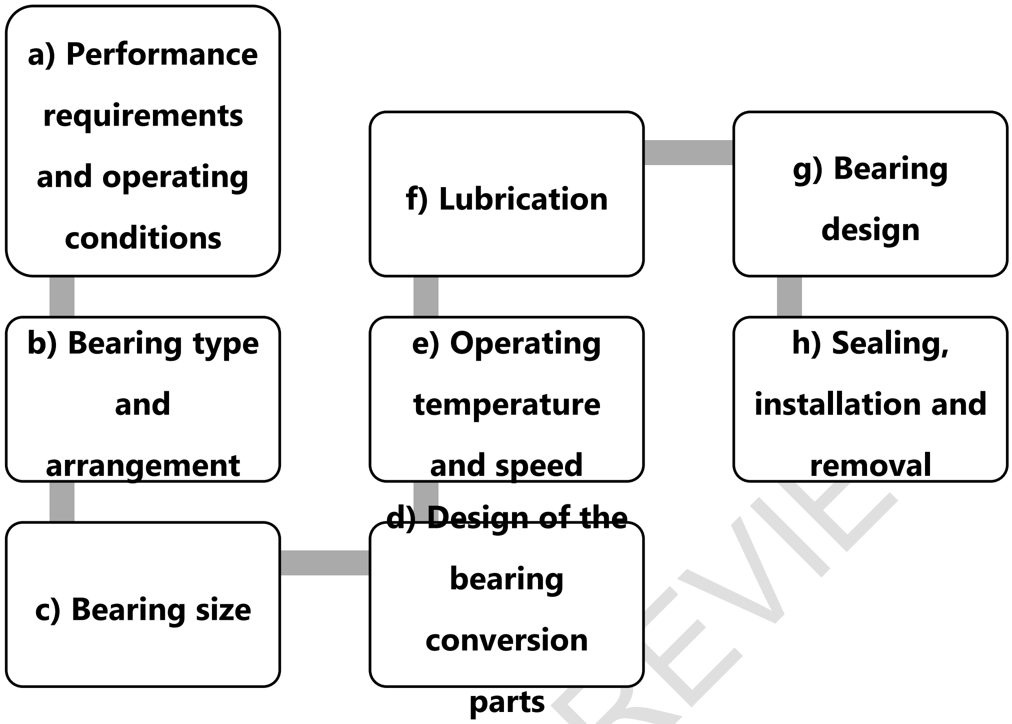
The ISO 80079-36 and -37 standards generally address the basic requirements and protection concepts for mechanical explosion-proof equipment. Specifically, ISO 80079-36 and-37 establish the "procedures for and requirements for the design, construction, testing and marking of non-electrical explosion-proof equipment, explosion-proof components, protective systems, devices and assemblies of these products which have their own potential sources of ignition and are intended for use in potentially explosive atmospheres" (ISO 80079-36).

Rolling bearings are to be understood as Ex components. Although there is no more precise definition of Ex components in the standardization, this can be derived from existing definitions. Thus, a non-electrical device can be defined as: "Device that can mechanically fulfill its intended function" (ISO 80079-36). This means that an Ex component is a component that "can mechanically fulfill its intended function" and is intended for use in an explosion-protected area.

The ISO 80079-37 considers the design of non-electrical equipment for use in potentially explosive atmospheres. One chapter is devoted to the requirements for rolling bearings.

Derived from the general requirements for devices of the "constructive safety" type of protection according to ISO 80079-37, rolling bearings must be designed for use in potentially explosive atmospheres in accordance with the applicable safety requirements of the applicable industry standards. All operating parameters specified by the manufacturer must be taken into account, including the mechanical and thermal loads to which they are to be subjected. Bearing design requirements by manufacturer using SKF as an example (Figure 2). (SKF) are as follows:

Figure 2. *Bearing Design Process*



Rolling bearing design requirements according to SKF

a) First of all, according to the manufacturer, the various operating parameters that influence the selection of the bearing arrangement must be determined. The most important operating parameters are ("Leistungsanforderungen und Betriebsbedingungen | SKF", 2023g):
   - Load,
   - Operating speed,
   - Ambient temperature,
   - Lubricant and lubricant purity.

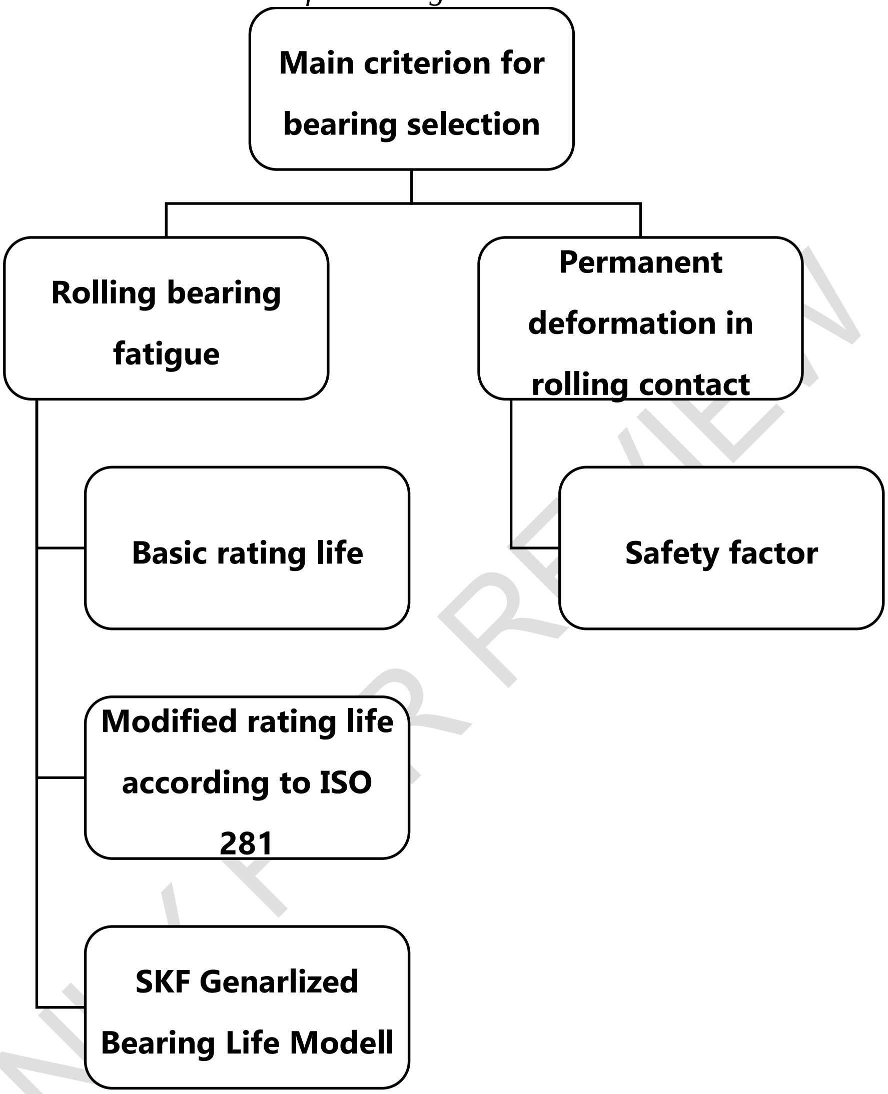
   Depending on the application, the following factors must also be taken into account in the bearing design. ("Leistungsanforderungen und Betriebsbedingungen | SKF", 2023g):
   - Bearing life,
   - Speed stability and suitability for acceleration,
   - Accuracy of radial and axial position of the shaft and
   - Resistance to low or high temperatures and temperature gradients.

b) Bearing type and their arrangement must be selected in accordance with the expected operating conditions ("Lagerart und Lageranordnung | SKF | SKF", 2023d).

c) The selection of the bearing size can be determined using two different approaches (see Figure 3) ("Lagergröße | SKF | SKF", 2023f):
   - Choice of size based on service life or

- Selection of the size based on the static load (via the static safety factor s_0 for the bearing).

Figure 3. *Main selection criteria for bearing selection*



d) For reliable bearing function, a suitable concept for lubricant supply to the bearings must then be selected on the basis of the operating conditions. The relationship between lubrication and other selection criteria must be taken into account. For example, the lubrication system has a significant influence on bearing life and operating temperature. ("Schmierung | SKF | SKF", 2023h)

e) The next step in the design considers the expected operating temperature as well as the allowable speed. There is a complex relationship between temperature and component performance degradation within an application. This relationship has interactions with many other factors, such as bearing sizes, loads, and lubrication conditions. The effects on various performance characteristics within an application and its components are varied and depend on the operating condition, such as at startup or during normal operation in steady state. It is important to predict and test operating temperature and speed limits. Especially the thermal stability of lubricants plays a decisive role. ("Betriebstemperatur und Drehzahl | SKF | SKF", 2023b)

f) After selection and design of the bearing arrangements, the bearing mounting parts must then be designed correctly. Bearing fits on the shaft and in the housing as well as axial securing of the bearings have a major influence on bearing performance. Fits for shafts and housings in rolling bearings are determined using the DIN ISO 286 standard for limiting dimensions and fits. ("Gestaltung der Lagerumbauteile | SKF | SKF", 2023c)

g) Furthermore, the following storage properties must be taken into account:
   - of the operating clearance or preload,
   - of the bearing tolerances,
   - of a suitable cage, if necessary and
   - an integrated seal, if required.

   The operating clearance or preload of a bearing in particular has a considerable influence on the running behavior and temperature development during operation. ("Lagerausführung | SKF | SKF", 2023e)

h) The last design step according to SKF deals with the selection of external seals, mounting and dismounting as well as inspection and monitoring of the bearings. ("Abdichtung, Ein- und Ausbau | SKF | SKF", 2023a)

Rolling Bearing Design Requirements according to International and National Standards

The steps specified by the manufacturer for the design of rolling bearings are supported by a number of international and national (German) standards. The following standards must be taken into account in the selection and design of rolling bearings for their use in potentially explosive atmospheres.

In the following, the contents of the standards will be briefly explained.

a) With the help of the ISO 76 he basic static load rating of a rolling bearing can be determined. C_0 can be determined. This is used for the design of rolling bearings which run at very low speeds (n < 10 min^{-1}) (SKF), perform slight swiveling movements or are loaded at standstill. It is defined as a load at which a permanent total deformation of approximately 0.0001 times the rolling element diameter occurs between the points of contact between the rolling elements and the raceway. (ISO 76)

   However, it is often not necessary to calculate the basic static load rating in practice, since this bearing-specific characteristic value is provided by most bearing manufacturers.

Table 8. *Overview of standards for the design of rolling bearings*

	ISO standard	Content	DIN standard
a)	ISO 76	Rolling bearings - Static load ratings	DIN ISO 76
b)	ISO 281	Rolling bearings - Dynamic load ratings and rating life	DIN ISO 281
c)	ISO 5753-1	Rolling bearings - Internal clearance - Part 1: Radial internal clearance for radial bearings	DIN 620-4
d)	ISO 15312	Rolling bearings - Thermal speed rating - Calculation	DIN ISO 15312
e)	-	Rolling bearings - Thermally safe operating speed - Calculation and correction values	E DIN 732

b) With the help of ISO 281 it is possible to determine the basic dynamic load rating of a rolling bearing C the basic rating life and the extended rating life according to ISO.
The basic dynamic load rating is used for the design of rotating and therefore dynamically loaded bearings. The basic dynamic load rating C is the load of invariable magnitude and direction at which a sufficiently large quantity of identical bearings achieves a nominal life of one million revolutions.
However, it is often not necessary to calculate the basic dynamic load rating in practice, since this bearing-specific characteristic value is provided by most bearing manufacturers.
The basic rating life describes the percentage of an obviously identical bearing group which achieves or even exceeds a certain rating life under identical operating conditions. The probability of achieving the calculated basic rating life is 90%. The basic rating life, given in millions of revolutions L_{10} or operating hours $L_{10}h$ of a rolling bearing is calculated from the equivalent dynamic bearing load, the basic dynamic load rating and the life exponent.
The modified service life calculation L_{nm} extends the nominal service life calculation and includes further influencing factors, such as the experience factor a_1 and the service life coefficient a_{ISO} into the calculation. The service life factor a_1 can be selected according to the operational requirements and increases the statistical probability of survival, depending on the survival factor a_1 from 90% to 99.95% with a simultaneous reduction of the service life. The experience factor is indirectly proportional to the experience probability.
Due to the service life coefficient a_{ISO} the modified service life calculation takes into account L_{nm} takes into account the prevailing operating conditions. This factor takes into account lubricant contamination, the viscosity ratio of the lubricant and the fatigue limit load.

c) ISO 5753-1 Rolling bearings - Internal clearance - Part 1: Radial internal clearance for radial bearings (ISO 5753-1) specifies the values for the radial internal clearance of various bearing types. The values given apply to bearings in unloaded, measurement force-free condition (without elastic deformation).
The bearing clearance is defined as the relative total distance by which the bearing rings (inner and outer ring) can be displaced relative to each other in the radial direction. During operation, it is important that the installed bearing has sufficient internal clearance. It should be noted that the selected fit on the shaft or in the housing may result in a reduction of the bearing clearance during mounting. Likewise, heating during normal operation due to an expansion of the bearing components leads to a further reduction in the internal clearance. These factors must be taken into account when calculating the initial internal clearance according to manufacturer (SKF) must be taken into account. According to the calculated internal clearance, a bearing of the corresponding internal clearance group can be selected in accordance with ISO 5753-1.

d) The ISO 15312 Rolling bearings - Thermal speed rating - Calculation (ISO 15312) provides a calculation basis for the determination of the thermal reference speed $n_{\vartheta r}$. According to ISO 15312 the thermal reference speed describes $n_{\vartheta r}$ describes the speed at which a bearing temperature of 70 °C is reached under reference conditions.

e) The national standard E DIN 732 Rolling bearings - Thermally safe operating speed - Calculation and correction values (DIN 732) provides a basis for calculating the thermally permissible operating speed n_{ϑ}. This calculation is based on the frictional power and the resulting heat balance in the rolling bearing. The thermally permissible operating speed n_{ϑ} is reached when the friction in the rolling bearing generates as much heat as the bearing can dissipate to the adjacent components. The complex calculation of the thermally permissible operating speed n_{ϑ} often provides results that are closer to reality than the thermal reference speed $n_{\vartheta r}$.

Further requirements according to ISO 80079-37

Certain points of the described design steps according to the manufacturer and the standard are described in ISO 80079-37 and are to be observed according to ISO 80079-37 in the ignition hazard assessment according to 80079-36 special attention must be paid to them. However, the standard only provides information on which aspects must be taken into account in the ignition hazard assessment, but does not provide any quantitative characteristic values for the design of the bearings (e.g. experience factor a_1 as a function of the desired level of protection).

According to ISO 80079-37 bearings must always be selected with regard to the task to be performed. According to the standard, the most important factors are "speed, temperature, loading and variations of speed and loading" must be taken into account. In addition, the **basic rating** life must be determined in accordance with ISO 281. The following are emphasized in ISO 80079-37 the importance of the fit selection with regard to shaft and housing as well as limit deviations, roundness and surface quality of the components surrounding the bearing. The correct alignment of the bearings is also emphasized at this point.

According to ISO 80079-37, attention must be paid to particular attention must be paid to the thermal behavior of adjacent components (shaft and housing) and the resulting additional axial and radial loads on the bearings.

The following must be considered for the ignition hazard assessment the lubrication concept to be used and the protection to prevent the ingress of liquids and solids into the bearing and the lubrication system. According to the standard, a sufficient supply of lubricant must always be ensured.

The bearing and adjacent components must be evaluated for their protection from electrical currents, including stray circulating currents.

In addition, ISO 80079-37 refers to the following refers to the inspection of the specified maintenance intervals and the scheduled replacement of bearings at the end of the recommended calculated service life or after unacceptable wear.

According to standard (ISO 80079-37) bearings must be protected against vibrations, especially in the static state, but also in the dynamic state. The use of non-metallic cages must be avoided. In addition, instructions for the preparation of the operating manual are included.

According to ISO 80079-37, a bearing failure during the period of the nominal life is considered a rare incident. Thus, in the ignition hazard assessment according to ISO 80079-36, bearings are grouped according to EPL Gb/Db without further safety precautions. To achieve EPL Ga/Da, additional ignition source monitoring, e.g. temperature sensor or vibration sensor, is necessary.

Ignition Hazards According to ISO 80079-37

Three potential ignition sources for rolling bearings can be derived from the ISO 80079-37 standard:

a) Hot surfaces,
b) Mechanically generated sparks and
c) Electrostatic discharge.

In normal operation, the ignition sources mentioned above are not to be expected, taking into account correct design, maintenance and installation. For the ignition sources to occur, at least a simple fault must exist. Under this assumption, the incorrect design, mounting or maintenance is already to be regarded as a fault. According to the definition, the bearing is no longer in normal operation. According to the Ordinance on Hazardous Substances, Annex 1, No. 1.7, this is to be understood as the condition in which the equipment is used within its design parameters. Here, the correct bearing design is the standard. If the bearing has an ignition source due to its incorrect design, this condition is not to be interpreted as normal operation. In explosion protection, depending on the intended application zone, the single or rare or double fault case must also be taken into account. This classification is based on the above classification of ignition sources.

Classification of rolling bearings for use in potentially explosive atmospheres according to DIN CEN/TR 16829

The DIN CEN/TR 16829 develops protective measures for bucket elevators used to handle flammable products that may contribute to the creation of explosive atmospheres from dust or powder inside the bucket elevator during operation of the bucket elevator. With regard to the ignition hazard assessment of rolling bearings, the standard identifies hot surfaces as a result of bearing damage as a potential direct ignition source. Regarding the initiation of an indirect ignition source, the failure of the bearing is widely considered in the standard. However, this work deals exclusively with direct ignition sources caused by bearings.

Suitable measures to reduce the risk of this ignition source becoming effective are the selection of suitable bearings and materials as well as organizational measures such as shortening maintenance intervals. Temperature monitoring can be used to further reduce the probability of occurrence of this ignition source. When using a temperature unit, over inform about the maintenance and inspection intervals of the additional safety devices in operating or maintenance manuals.

The standard also describes the information to be provided that is relevant for the user with regard to routine inspections, maintenance and cleaning. The user must be informed by means of the operating or maintenance manual that increased attention must be paid to the wear of rolling bearings. In general, the requirements for operating or maintenance manuals are already described in IEC 60079-0 ff and in ISO 80079-36 and -37, but the reference in these standards is not made explicitly to the handling of rolling bearings and their safety components.

In the exemplary ignition hazard assessment for rolling bearings in bucket elevators in DIN CEN/TR 16829 the following measures are introduced to prevent hot surfaces on rolling bearings from becoming effective:

- Measures to avoid arcing and stray currents: Grounding and potential equalization of all conductive elements.
- Bearings are calculated in accordance with ISO 281 for a specific service life. Under these conditions, bearing damage is basically considered a **rare failure**. The highest possible bearing temperature is determined under the most unfavorable conditions (30 °C).

The standard differentiates between internal and external categories when classifying equipment. The ignition hazard assessment carried out refers to the classification of the external device category.

To achieve internal device category 2, the standard also recommends a storage temperature monitor with alarm and emergency stop when a critical limit temperature is exceeded. To prevent an analgesic stop, the standard recommends setting a pre-alarm level.

Table 9. *Ignition Hazard Analysis for Bearings*

No.	1		2					3			4				
	ignition hazard		assessment of the frequency of occurrence without application of an additional measure					measures applied to prevent the ignition source becoming effective			frequency of occurrence incl. measures applied				
	a	b	a	b	c	d	e	a	b	c	a	b	c	d	e
	potential ignition source	description/basic cause	during normal operation	during foreseeable malfunction	during rare malfunction	not relevant	reasons for assessment	description of the measure applied	basis	technical documentation	during normal operation	during foreseeable malfunction	during rare malfunction	not relavant	nacessary restrictions
1	hot surface of a ball bearing as a result of friction	- It is assumed that the temperatures are higher than the ignition temperatures of the product under consideration. - Ingress of dust or water - Loss of lubrication - Excessive axial forces cause damage to the bearings			X		It is assumed that the temperatures are higher than the ignition temperatures of the product under consideration.	- Measures to avoid arcing and stray currents: Grounding and potential equalization of all conductive elements. - Bearings are calculated in accordance with ISO 281 for a specific service life. Under these conditions, bearing damage is basically considered a rare failure. The highest possible bearing temperature is determined under the most unfavorable conditions (30 °C).	ISO 80079-37 "c	Test report on storage temperature has shown that temperatures will not be higher than 40 °C.				X	T4

Source: DIN CEN/TR 16829

Classification of Rolling Bearings for use in Potentially Explosive Atmospheres in Accordance with DIN EN 14986

The DIN EN 14986 specifies the constructional requirements for fans of group II G (of explosion groups IIA, IIB and hydrogen) categories 1, 2 and 3 and group II D categories 2 and 3 for use in potentially explosive atmospheres. With regard to suitable bearing design, the standard refers to ISO 80079-37.

According to DIN EN 14986, performance data, including the recommended replacement interval for the bearings and seals, must be documented in the operation and maintenance manual. In addition, information on wear and tear must be highlighted. If monitoring equipment is used, e.g. for temperature or vibration monitoring of rolling bearings, these must be checked regularly.

Classification of Rolling Bearings for use in Potentially Explosive Atmospheres according to VDI 2263

The VDI 2263 applies to the assessment of hazards and to measures for the prevention of dust fires and dust explosions including, their dangerous effects. The guideline describes the hazards of different plants with regard to their ignition sources. Rolling bearings are mentioned as a potential ignition source in a large part of the described plants and machines. The general protective measure to prevent the ignition source from becoming effective according to VDI 2263 is temperature monitoring of the bearings. Further measures are not described,

Classification of rolling bearings for use in potentially explosive atmospheres in accordance with current publications

Rumbak et al. deals in "Analysis of ignition risk to ball bearings in rotating equipment in explosive atmospheres". (Slavko Rumbak, Vedran Mudronja, Nikola Šakić, Hrvoje Cajner, & Marijan Bogut, 2010) with the effects of damage to ball bearings as an indicator of mechanical ignition sources in rotating machine elements. In the study, temperatures and vibration data of damaged bearings are investigated (figure 4). The aim is to derive corresponding limit values in order to initiate appropriate countermeasures when impermissible vibrations occur or temperatures.

Figure 4. *Damage to the Outer Ring of Ball Bearing*

Source: Rumbak et al. 2010

As part of the experimental work, bearings pre-damaged by erosion on the outer ring (Fig. 5) are examined on a test rig. During the test, vibration and temperature data are recorded.

Table 10. *Time t, min required to achieve the temperature of each temperature class of ball bearing with the damage of the outer ring*

Time *t*, (min)					
T6	**T5**	**T4**	**T3**	**T2**	**T1**
85 °C	**100 °C**	**135 °C**	**200 °C**	**300 °C**	**450 °C**
2,02	2,63	3,75	5,21	6,72	8,23

Source: Rumbak et al. 2010

By analyzing the obtained data, Rumbak et al. derived the time between damage occurrence and the effectiveness of an ignition source to ignite gases and vapors according to their temperature classes (Table 9). In addition, the time between the occurrence of the bearing damage and the temperature for ignition of dust clouds and layers is derived from the data (Table 10).

Table 11. *Time t, min required to achieve the temperature of ignition of clouds and layers of combustible dust, flour and coal bearing at ball with the damage of the outer ring*

Time *t*, (min)			
Layer		**Cloud**	
Wheat flour	**Coal**	**Wheat flour**	**Coal**
230 °C	**350 °C**	**430 °C**	**580 °C**
5,73	7,3	8,06	9,18

Source: Rumbak et al. 2010

Pieters and Perbal in "QUANTATIVE "ATEX" RISK ASSESSMENT - An alternative method for (parts of) rotating equipment" deal in general with objective risk assessment methods for the use of rotating equipment using a quantitative method. There is a clear description of the boundaries between the different zones expressed in terms of the probability of the presence of an explosive atmosphere. To test the developed method, they use rolling bearings as an example.

Rotating machine elements are discussed in the work of Pieters and Perbal based on their Frequency of Dangerous failure versus the Duration of effective ignition source with regard to their suitability for use in zones 2 and 1. In the exemplary consideration, a bearing is used which, on the basis of the basic rating life calculation, achieves a running time of 40,000 hours over 20 years under given operating conditions. The relubrication interval is 2000 hours. The bearings are classified according to the "Ignition Risk Assessment" table developed in the paper as follows:

- Assuming that in the event of a failure of the lubricant supply to a bearing, the bearing temperature rises to a critical temperature range (180 °C) within a very short time (< 60 min) and the lubrication of a bearing cannot be guaranteed by suitable maintenance intervals, the failure of the bearing must be expected within one or less than one year of operation. Bearings under this assumption may, according to Pieters and Perbal bearings must not be used in potentially explosive atmospheres.
- With regular lubrication, according to Pieters and Perbal the bearing is not expected to fail within 10 years. Taking into account the unchanged duration of effective ignition source (> 60 min), the bearing can therefore be used in zone 2.

- With a suitable maintenance plan and the associated replacement of the bearing before the end of the calculated service life, the probability of bearing failure can be further reduced (<1x/100yr), which means that rolling bearings can also be used in zone 1.
- Use in zone 0 is not considered.

Discussion

Existing literature provides a good overview of the potential ignition sources of rolling bearings.

However, the results of the review do not show a uniform approach to rolling bearing design for their use in potentially explosive atmospheres. Based on ISO 80079-37 "Non-electrical type of protection constructional safety "c", control of ignition sources "b", liquid immersion "k", guidance is given to the designer, but a precise description of the procedure for the design of rolling bearings is not given. The designer is primarily referred to further standards (ISO 281) and manufacturer specifications referred to. If these are followed comprehensively and applied correctly, including all the requirements specified by the manufacturer for the ambient conditions and the observance of maintenance intervals, rolling bearings are suitable for use without further safety precautions in accordance with the standards (DIN CEN/TR 16829.; ISO 80079-37) and are therefore permissible for use in zones 2/22 and 1/21. According to the standard, the occurrence of an ignition source due to rolling bearings is only to be expected in the event of a rare malfunction. (DIN CEN/TR 16829.; ISO 80079-37).

In the standard 80079-37 the determination of the service life is based on the nominal service life calculation according to ISO 281, irrespective of the intended level of equipment protection. (ISO 281). However, the current standard for rolling bearing calculation is the calculation of the modified rating life in accordance with ISO 281. The calculation of the modified rating life takes into account contemporary bearings of high quality and, under favorable operating conditions, can considerably exceed the calculated values of the basic rating life ("Tragfähigkeit und Lebensdauer | Schaeffler medias", 2023i). For example, a rolling bearing of type 6004-2RSH/VA947 (Forces Radial 1 kN; Forces Axial 0 kN; Speed 3000 r/min; Temperature Inner ring 70 °C; Temperature Outer ring 65 °C; Cleanliness High cleanliness) achieves a rating life according to the basic rating life calculation of L_{10h} 5,470 hours, the service life according to the calculation of the modified service life under favorable operating conditions amounts to L_{nm} 30,000 hours. This corresponds to a factor for life coefficient a_{iso} of 5.48.

In a comparison with the basic rating life (reduction of the modified rating life to 5,470 hours, by changing the service life coefficient a_1), this corresponds, under constant operating conditions, to an equivalent reduction in the service life coefficient a_1 from 1 to approx. 0.19, which in turn increases the lifetime probability from 90 % to 99.6 %. This significant reduction in service life results in considerable additional expense in the area of maintenance and servicing. At the same time, the service life probability increases significantly.

If, instead of the favorable operating conditions with a high cleanliness of the lubricants L_{nm} instead of the favorable operating conditions with a high cleanliness of the lubricants, the modified rating life is reduced from L_{nm} from

30,000 hours to 2,910 hours. This means that the modified rating life is now only 53% of the basic rating life L_{10h} (5,470 hours) with a service life coefficient of 1. a_{iso} of 1. Based on the service life coefficient a_{iso} of 1, the probability of survival corresponds to 90 %. From a statistical point of view, therefore, 10 out of 100 bearings fail before the calculated modified rating life is reached.

When designed in accordance with the standard and manufacturer's specifications and assuming favorable operating conditions, the failure of a bearing can nevertheless be classified as a rare malfunction (ISO 80079-36). However, a deterioration of these operating conditions leads to a significant reduction in the expected bearing service life as well as to a deterioration in the probability of experience. Thus, the simple case of failure (e.g. the failure of a seal) already has a considerable influence on the safety of rolling bearings. According to the standard, no consideration of real operating conditions is provided for in the design of rolling bearings.

For a grouping in the EPL Ga/Da are according to ISO 80079-36 further monitoring devices, such as temperature sensors for ignition source monitoring on rolling bearings, must be provided. A different approach is taken by DIN CEN/TR 16829 follows a different approach in the context of ignition hazard assessment for bearings. According to the standard, rolling bearings are classified in equipment category 1 (equivalent to EPL Ga/Da), taking into account measures to prevent sparkover and stray currents as well as bearing design in accordance with ISO 281 and a calculation of the maximum possible bearing temperature taking into account the operating conditions.

An interesting approach is provided by Rumbak et al. through his investigation of the effect of rolling bearing damage (pitting damage) on the temperature development of the bearings over time. He thus provides a good basis for the design of automatic shutdown systems. It is possible to determine from these results the time remaining after the rolling bearing damage has occurred until a critical temperature limit is reached. Future research could build on these results and investigate further rolling bearing damage.

Conclusions

The overall objective of this paper is to present the current approach to the design of rolling bearings for use in potentially explosive atmospheres. The specific research question is:

"How should rolling bearings be designed according to the current state of the art for their use in potentially explosive atmospheres?"

In addition, further research approaches will be derived from the current state of the art.

The answer to the research question is developed by means of a systematic literature review. Overall, the literature search shows that the topic described has been dealt with comparatively little in the past.

On the basis of the current standards and their references, this paper can provide an overview of the design steps required for the use of rolling bearings in potentially explosive atmospheres. The various standards are consistent with regard to the measures required for the grouping of rolling bearings with respect to EPL Gb/Db. ISO 80079-36 and DIN CEN/TR 16829 provide a different approach to the grouping of rolling bearings into an EPL Ga/Da.

The various standards all assume favorable operating conditions, which rarely occur in reality, for the design of rolling bearings. In reality, however, a deviation from these favorable conditions results in a considerable deterioration in the service life and the probability of survival. These changes in operating conditions are not considered further in standardization.

Rumbak et al. provide a promising approach for the thermal behavior of rolling bearings in the event of damage. This can be used as a starting point for further research in this field.

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