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O-RING INSPECTION AND ACCEPTANCE CRITERIA IN FACTORY ACCEPTANCE TESTS

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A B S T R A C T

Factory Acceptance Tests (FAT) are commonly performed to verify the conformity and functional performance of equipment before delivery and installation at the customer's site. Although functional tests can demonstrate the performance of assembled equipment, they do not necessarily provide evidence of the conformity of critical physical components involved in its operation. This issue is particularly relevant for sealing systems, in which O-rings may directly influence equipment tightness and reliability. Existing FAT approaches generally emphasize equipment-level functional verification, while O-ring studies predominantly address component characteristics, failure mechanisms, and inspection methods. This study proposes a risk-based framework that integrates O-ring component conformity verification into the equipment-level FAT acceptance process, establishing explicit links between operational context, component criticality, verification requirements, conformity evidence, installation condition, and equipment performance. The framework distinguishes three complementary levels of evidence: component conformity, installation conformity, and equipment performance. Its application is demonstrated using a commercial Parker E1549-70 O-ring under three clearly defined FAT scenarios with different operational contexts and consequences of sealing failure. The results demonstrate that the same O-ring may require different levels of verification depending on its function and criticality within the equipment. The framework also establishes a logical relationship between earlier detection of component nonconformities and potential impacts on leakage failures, rework, downtime, and quality-related costs. The proposed approach does not establish universal acceptance limits for O-rings; instead, it provides a risk-proportionate structure for integrating component-level evidence into equipment acceptance and complements, rather than replaces, conventional functional FAT testing.

1. INTRODUCTION

Factory Acceptance Tests (FAT) constitute an important stage in the equipment verification and acceptance process, allowing its compliance with previously established technical, functional, and performance requirements to be assessed while still at the manufacturer's facilities. Conducting the tests before equipment installation enables the early identification of nonconformities and can help reduce problems, rework, and delays during subsequent transportation, installation, commissioning, and field acceptance stages. To adequately fulfill this function, FATs should be systematically planned, with clear definitions of the requirements to be verified, test methods, acceptance

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criteria, and records required to demonstrate the results obtained.

The procedures performed during a FAT depend on the characteristics and requirements of the equipment being evaluated. In systems where leak tightness is a relevant condition for reliability, sealing elements become important components for achieving the expected performance. O-rings are sealing components widely used in equipment and systems subject to different pressure and temperature conditions and exposure to fluids. Although they have a relatively simple geometry, their performance depends on characteristics such as dimensions, material, physical properties, surface condition, and assembly conditions. Defects or nonconformities in these characteristics may compromise sealing capability and consequently affect the performance of the equipment in which the component is installed. Therefore, inspection and verification of O-ring conformity may constitute a relevant complementary step in assessing equipment quality.

From an equipment acceptance perspective, however, two distinct forms of evidence must be considered. O-ring conformity can be demonstrated through dimensional and visual inspections, material documentation, identification and traceability records, assembly records, or other applicable verification methods. Equipment performance, in turn, can be evaluated through functional tests such as pressure and leak-tightness tests. The challenge is therefore not simply to inspect the O-ring, but to establish how component-level evidence should be incorporated into the equipment-level acceptance decision.

Existing FAT approaches provide structured methods for planning, executing, evaluating, and documenting equipment tests, but predominantly focus on system functions, parameters, and overall performance. Conversely, studies on O-rings primarily address sealing mechanisms, material behavior, defects, dimensional inspection, and component quality. Although these bodies of knowledge provide complementary foundations, the relationship between the conformity of a critical physical sealing component and the acceptance of the equipment in which it is installed remains insufficiently structured.

To address this gap, this study proposes a risk-based framework for integrating O-ring verification into FAT activities. The original contribution lies in establishing a structured link between the operational context and criticality of the O-ring, the requirements applicable to the component, the corresponding verification methods and conformity evidence, the installation condition, and the equipment-level functional or leak-tightness tests. Rather than introducing an alternative to conventional FAT, the framework adds a component-level verification layer whose rigor is proportionate to the potential consequences of O-ring failure.

The proposed framework is further demonstrated through three clearly defined FAT scenarios using the same commercial O-ring under different operational contexts. This application illustrates how component criticality and verification requirements may change when the function performed by the O-ring and the consequences of sealing failure change, while the component itself remains unchanged.

2. LITERATURE REVIEW

2.1 Factory Acceptance Tests

The purpose of the FAT is to assess the conformity of the equipment with the established technical and functional requirements, allowing the identification of nonconformities before the installation and commissioning stages. Hoernicke and Greifeneder (2012) highlight that conducting tests at the factory allows verifications to be performed in advance that, if carried out at a later stage, could require greater effort during commissioning. Their work also discusses the use of automation and virtual environments to reduce the effort associated with FAT preparation, execution, and documentation.

FAT planning should establish in advance the scope of the tests, the execution procedures, and the criteria used to evaluate the results. Kopcek et al. (2014) propose a systematic approach encompassing the planning, execution, evaluation, and documentation stages of the FAT, emphasizing structured test definition and traceability between requirements and test activities. In an industry-oriented perspective, DXP Enterprises (2026) similarly describes FAT as a structured process involving planning, technical documentation, inspections, testing, calibration records, and the recording of results. These approaches indicate that FAT extends beyond functional testing and may incorporate different forms of evidence to demonstrate equipment conformity.

More recent applications reinforce this perspective. Krause et al. (2026) demonstrate the use of automated and structured FAT procedures, with predefined acceptance thresholds, systematic recording of results, and database-based traceability, enabling the early detection and correction of manufacturing defects. Coenen et al. (2022), in the specific context of power transformer FAT and SAT, emphasize that the reliability and reproducibility of the verification method are essential for obtaining consistent acceptance evidence. However, these approaches address specific domains, such as control systems, electronic equipment, and electrical measurements, and do not specifically examine how the conformity of critical physical components can be systematically incorporated into the FAT process.

Overall, the literature establishes FAT as a structured process for planning, testing, evaluating, and documenting equipment conformity, with increasing emphasis on automation, traceability, and reliability of verification evidence. Nevertheless, these approaches predominantly organize evidence at the equipment or system level and do not specifically establish how the conformity of critical physical components can be incorporated into the acceptance decision. This limitation becomes particularly relevant for sealing components whose dimensional, material, physical, and installation characteristics can affect equipment leak tightness. The present study addresses this gap by extending the FAT evidence structure to include risk-based verification of critical O-rings and by linking component conformity with installation condition and equipment-level performance.

2.2 O-Rings as Critical Sealing Components

O-rings are widely used as sealing elements in hydraulic, pneumatic, and other pressurized systems due to their simple construction and ability to maintain leak tightness under different operating conditions. Their sealing capability results from the contact established between the elastomer and the adjacent surfaces, and is influenced by the geometry, compression, material properties, and operating conditions of the sealing assembly (Wu et al., 2024).

The installation condition is particularly relevant to O-ring performance. Li (2023), through finite element analysis, showed that the compression rate applied during installation significantly affects sealing performance and influences the stresses developed in the O-ring under subsequent loading conditions. Similarly, Szabó and Váradi (2018) demonstrated that excessive initial compression can lead to cracking, while improper assembly may cause material damage and immediate leakage. Their analysis also showed that excessive operating pressure and extreme temperature conditions can promote extrusion, material damage, and loss of sealing capability.

The effects of operating conditions can also involve more complex degradation mechanisms. Wu et al. (2024) showed that changes in the clearance between mating components can reduce O-ring compression and deteriorate sealing performance, particularly under conditions involving sudden relative displacement. In a different application context, Lv et al. (2025) reviewed failure mechanisms of rubber O-rings in high-pressure hydrogen environments, identifying coupled effects such as hydrogen permeation, swelling, rapid gas decompression, and mechanical fatigue. Although these mechanisms are specific to hydrogen service, they reinforce that O-ring reliability depends on the interaction between material characteristics, assembly conditions, and the environment in which the seal operates.

Taken together, these studies demonstrate that O-ring sealing performance depends on multiple interacting factors and that component condition and installation characteristics can directly affect equipment leak tightness. However, the reviewed studies predominantly investigate the mechanisms governing O-ring performance and failure rather than how component conformity should be systematically incorporated into equipment acceptance. The distinction between understanding why an O-ring may fail and establishing how its conformity should be verified before equipment acceptance provides an important basis for the framework proposed in this study. Verification at the component level can therefore provide complementary evidence to equipment-level functional or leak-tightness tests performed during the FAT.

2.3 O-Ring Inspection and Quality Requirements

Verification of O-ring conformity may involve both dimensional characteristics and assessment of the physical condition of the component. Amrina and Firmansyah (2019), in their study of O-ring quality control, identified defects such as flow marks, tears, scratches, and contamination, demonstrating that surface condition is an important aspect of component quality. These findings indicate that visual inspection can contribute to identifying conditions that may compromise the suitability of the O-ring for its intended application.

In addition to visual inspection, dimensional measurement can be used to assess conformity with specified requirements. Yang et al. (2021) developed an optical inspection system capable of identifying surface defects and measuring component dimensions, demonstrating the feasibility of combining geometric inspection and defect detection in a systematic inspection process. The requirements against which these characteristics are evaluated should be established according to the applicable technical specifications and standards. In this regard, ISO 3601 (ISO, 2005) establishes requirements for O-ring dimensions, tolerances, designation, and related characteristics, providing a normative basis for conformity assessment.

The reviewed studies therefore provide technical and normative bases for verifying O-ring condition and dimensional conformity. However, they primarily address inspection methods and component requirements rather than the integration of these verification activities into the formal acceptance of the equipment in which the O-ring is installed. The contribution developed in the present study builds on these component-level requirements by defining how they can be translated into verification activities, acceptance evidence, and risk-proportionate controls within the FAT process.

2.4 Integration of O-Ring Verification into Factory Acceptance Tests

Kopcek et al. (2014) propose a systematic approach for FAT planning, execution, evaluation, and documentation, including the use of traceability principles to relate requirements and test activities. Their approach demonstrates the importance of defining in advance what is to be verified, how it is to be verified, and how the results are to be evaluated and documented. However, the proposed framework is primarily focused on control-system functions and parameters and does not specifically address the verification of physical sealing components as part of equipment acceptance.

Coenen et al. (2022), in the context of power transformer FAT and SAT, emphasize that acceptance evidence also depends on the reliability and reproducibility of the verification method. Their discussion of calibration, sensitivity, and measurement procedures demonstrates the importance of establishing adequate methods for obtaining reliable test results. However, their work is focused on partial discharge measurements and does not address the relationship between component-level conformity and equipment-level acceptance.

Taken together, these studies provide complementary foundations for the proposed approach. Kopcek et al. (2014) provide the systematic FAT structure, while Coenen et al. (2022) reinforce the importance of reliable verification evidence. Combined with the literature on O-ring performance and inspection, these foundations support an approach in which component requirements, verification methods, acceptance criteria, and conformity records are explicitly linked to equipment-level FAT activities. The present work applies this approach to O-ring verification, establishing a connection between component-level conformity, installation verification, and equipment-level sealing performance within the FAT process.

3. O-RING VERIFICATION IN FACTORY ACCEPTANCE TESTS

3.1 Verification Requirements

O-ring verification during a FAT should be based on the specific requirements established for the equipment and its sealing system. Although O-rings are relatively simple components, their performance as sealing elements depends on characteristics such as material, dimensions, installation, and operating conditions. For this reason, verification should be considered in conjunction with equipment requirements rather than as an isolated component inspection. The proposed framework additionally adopts a risk-based classification to determine the level of verification required for each O-ring according to the potential consequences and likelihood of failure in its application. Accordingly, four main aspects of O-ring verification are considered: dimensional conformity, material and traceability, surface condition, and installation condition. Storage condition may also be verified when relevant to the applicable manufacturer or technical requirements. The relevance of each aspect and the required level of verification depend on the characteristics of the equipment and the applicable technical specifications.

The criticality of an O-ring is classified according to two risk dimensions: the consequence of failure and the likelihood of occurrence. The consequence considers the potential impact of loss of sealing capability on equipment functionality, containment, safety, environmental performance, downtime, rework, or other relevant operational effects. The likelihood considers factors that may increase the probability of O-ring nonconformity or failure, including operating conditions, material compatibility, assembly sensitivity, dimensional requirements, and other application-specific characteristics. Both dimensions are rated on a three-level scale, as presented in Figure 1:

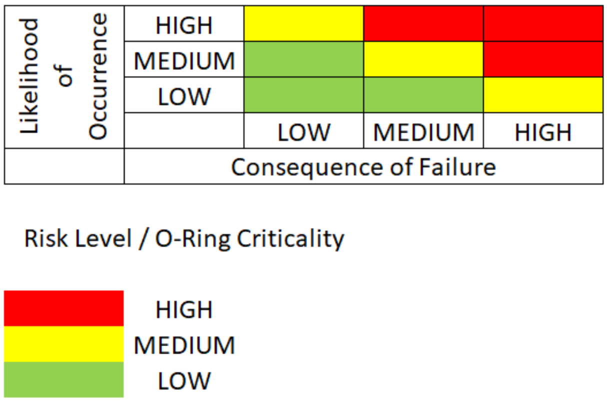

Figure 1. Risk-based classification of O-ring criticality

The resulting risk level is used to classify the O-ring as having low, medium, or high criticality. This classification does not replace the applicable technical requirements; rather, it establishes the level of rigor with which those requirements should be verified during the FAT. High-criticality O-rings therefore require more comprehensive and objective verification, whereas lower-criticality components may be verified using a more proportionate set of controls. The criticality classification is context-dependent and should not be regarded as an intrinsic characteristic of the O-ring itself. The same component may require different levels of verification when applied to equipment with different functions, operating conditions, or consequences associated with loss of sealing capability. Therefore, the proposed approach considers the operational context in which the O-ring performs its sealing function as an essential input to the risk-based classification. This principle allows the verification requirements to be proportionate to the role performed by the component and the potential consequences of its failure.

Dimensional verification aims to confirm that the O-ring complies with the specified dimensions and tolerances. Material and traceability verification provides evidence that the supplied component corresponds to the material specified for the application. Visual inspection seeks to identify surface defects or other conditions that may compromise sealing capability. When the O-ring is already installed during the FAT, its installation condition may also be verified in accordance with the equipment's design and assembly requirements. Acceptance criteria should be defined prior to FAT execution and, preferably, incorporated into the test procedure or inspection documentation. This approach prevents the acceptance decision from relying exclusively on subjective assessments made during the test and establishes a clear relationship between the technical requirement and the evidence required for its verification. Figure 2 summarizes the characteristics to be assessed during the inspection of the component:

Figure 2. Main Characteristics Considered in O-Ring Inspection

3.2 Verification Methods and Acceptance Criteria

The characteristics identified in the previous section can be associated with specific verification methods and corresponding acceptance criteria. Table 1 presents a proposed structure for organizing these requirements within the context of a FAT.

Application of these verification activities should be determined according to the criticality classification established in Section 3.1. Table 2 presents a proposed relationship between O-ring criticality and the minimum verification scope to be considered during the FAT.

Table 1. Proposed requirements for O-ring verification during FAT

Verification Aspect	Main Verification Method	Acceptance Basis	Evidence
Dimensions	Dimensional measurement	Applicable drawing/specification	Measurement record
Material	Document review	Material specification	Material certificate
Traceability	Documentary and identification verification	Applicable traceability requirements	Traceability record
Surface condition	Visual inspection	Applicable technical specification	Inspection record/photograph
Storage condition	Visual/documentary inspection	Manufacturer requirements/specification	Inspection record
Installation	Visual inspection	Design/assembly requirements	Checklist/photograph
Sealing performance	Pressure/leakage test, when applicable	FAT specification	Test report

Table 2. Verification scope according to o-ring criticality

O-Ring Criticality	Minimum Verification Scope	Expected Evidence
High	Dimensions, material, traceability, surface condition, installation condition, and sealing performance when applicable	Measurement records, material/traceability documentation, inspection records, photographs, and FAT test results
Medium	Dimensions, material/traceability, surface condition, installation condition when applicable, and sealing performance according to the FAT specification	Applicable inspection and documentary records and FAT test results
Low	Visual condition and applicable identification/documentary verification; functional verification when applicable	Inspection/documentary records and applicable FAT test results

The table does not establish universal acceptance limits for O-rings, as these depend on the application, material, dimensions, sealing configuration, and operating conditions. Instead, it presents a framework for translating technical requirements into verifiable activities during the FAT. The criticality classification determines the extent and rigor of these activities, while the specific acceptance limits remain derived from the applicable technical requirements. This distinction is important because the same type of O-ring may be subject to significantly different requirements depending on its application. Consequently, acceptance criteria should be derived from design documentation, technical specifications, and applicable standards rather than being generically defined.

Verification methods may also involve different levels of complexity. Dimensional and visual inspections can generally be performed prior to functional testing, while sealing performance can be evaluated through the functional or pressure tests specified for the equipment. Thus, evidence obtained at both the component level and the system level can be considered jointly during the acceptance process. The proposed risk-based approach allows the verification effort to be proportionate to the potential consequences of O-ring failure, while maintaining the equipment-level FAT as the final basis for evaluating functional performance.

3.3 Integration with FAT Activities

Integration of the proposed O-ring verification into FAT activities should begin by identifying the function performed by each relevant O-ring and its operational context. The component can then be classified according to the risk-based approach presented in Section 3.1, considering the potential consequences and likelihood of failure in its specific application. The resulting criticality level determines the appropriate verification scope, methods, acceptance criteria, and evidence requirements. In this way, O-ring verification is incorporated into the existing FAT process rather than treated as an independent inspection procedure. The resulting workflow can be summarized as follows: identification of the O-ring → definition of its function and operational context → risk-based criticality classification → definition of applicable requirements → selection of verification methods → definition of acceptance criteria → inspection and recording of evidence → functional or pressure/leakage testing → evaluation of results → FAT acceptance or nonconformity.

Prior to conducting the functional tests, documentary, dimensional, and visual inspections may be performed to establish the conformity of the components in advance. Subsequently, functional and leak-tightness tests can provide evidence of the behavior of the assembled sealing system under the conditions established for the FAT. This distinction between component conformity and functional performance is particularly relevant. A functional test may demonstrate that the equipment performs satisfactorily under the tested conditions, but it does not necessarily provide evidence that each critical O-ring complies with the specified material, dimensional, or traceability requirements. Conversely, the individual conformity of an O-ring does not, by itself, demonstrate the proper performance of the sealing system, since this also depends on the housing geometry, assembly conditions, pressure, temperature, and other system characteristics.

Therefore, the proposed approach considers O-ring verification and FAT functional tests as complementary activities. The former provides evidence related to the conformity of the sealing component, while the latter evaluates system behavior after assembly. By incorporating risk-based criticality into this process, the proposed framework establishes a systematic link between the potential consequences of O-ring failure and the level of verification required before equipment acceptance. Figure 3 illustrates the correlation between component verification and FAT activities:

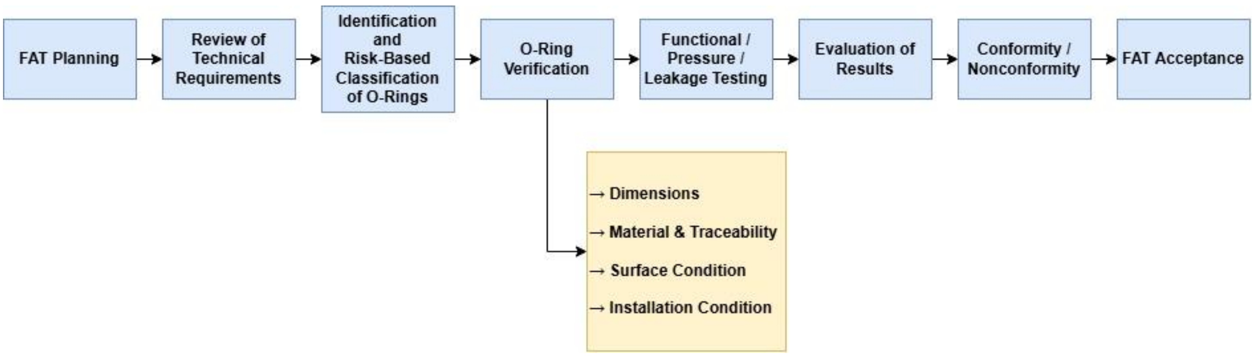

Figure 3. Integration of O-Ring Verification into the FAT Process

4. APPLICATION OF THE PROPOSED APPROACH

4.1 Application Case: Parker E1549-70 O-Ring

To demonstrate the application of the proposed approach, the Parker E1549-70 O-ring was selected as a reference. This is an ethylene-propylene-based elastomeric compound (EPDM), with a nominal hardness of 70 Shore A, intended for sealing applications involving water and steam. The manufacturer specifies the material for hot- and cold-water applications and highlights its resistance to products used in water treatment, as well as certifications associated with potable water applications, including NSF 61 and FDA (Parker, 2017; Parker, 2026). The selection of this product is not intended to evaluate the manufacturer's commercial performance or compare different sealing materials. The E1549-70 was used as an application case because it has sufficiently detailed technical documentation to demonstrate how information from a commercial component can be incorporated into the FAT process. Thus, the data presented in this study are derived from documentation provided by the manufacturer and are used as a reference for applying the proposed methodology; they do not constitute experimental results obtained by the authors.

The E1549-70 documentation presents compound characteristics, application conditions, technical specifications, and test results obtained according to ASTM methods. The Material Report identifies the elastomer as EPR/EPDM and associates the compound with ASTM D2000 M3DA714, in addition to presenting requirements and results for properties such as hardness, tensile strength, elongation, compression set, fluid resistance, tear resistance, and low-temperature performance.

This documentation is particularly suitable for the proposed application because it allows two relevant categories of information for the FAT to be distinguished. The first is related to the conformity of the component itself, which can be demonstrated through identification, material specification, physical properties, applicable standards and requirements, and test records. The second is related to the performance of the equipment in which the component is installed, which must be demonstrated through the functional tests specified in the FAT. Therefore, the manufacturer's report does not replace the equipment acceptance test but may constitute complementary evidence demonstrating that the sealing element used meets the previously established requirements. Parker itself presents its material reports as documents intended to characterize the physical properties and test results of elastomeric compounds.

For the purposes of this study, three clearly defined hypothetical FAT scenarios (Table 3) are considered to demonstrate the application of the proposed risk-based framework under different operational contexts. The same Parker E1549-70 O-ring is used as the reference component in all three scenarios, while its functional role within the equipment and the consequences associated with loss of sealing capability vary between the scenarios. This approach allows the framework to be evaluated by examining whether changes in the operational context lead to proportionate changes in component criticality and verification requirements. The scenarios were intentionally defined using the same O-ring to isolate the effect of the operational context on the proposed classification. Thus, differences in criticality are not attributed to changes in material, geometry, or manufacturer, but to the function performed by the sealing component and the consequences associated with its failure within the equipment.

Table 3. Defined fat scenarios and risk-based criticality

Scenario	Operational context and O-ring function	Consequence of sealing failure	Criticality
Scenario 1 – Essential function	O-ring used in an essential pressurized system in which maintaining leak-tightness is necessary for the equipment to perform its required function.	Loss of sealing may prevent the equipment from fulfilling an essential function and may result in significant operational consequences.	**High**
Scenario 2 – Non-essential function	O-ring used in a pressurized subsystem in which loss of sealing affects equipment performance but does not prevent an essential equipment function from being performed.	Leakage may result in reduced performance, maintenance intervention, rework, or temporary unavailability, without loss of an essential function.	**Medium**
Scenario 3 – Limited-consequence function	O-ring used in a sealing application in which loss of sealing has limited consequences for equipment operation and does not affect an essential function.	Leakage has limited operational consequences and can be detected and corrected without significant impact on equipment availability.	**Low**

Table 4 presents the technical specifications of the aforementioned O-ring:

Table 4. Technical Characteristics Of The Selected O-Ring

Characteristic	Parker E1549-70
Elastomer type	EPR / EPDM
Nominal hardness	70 Shore A
Recommended temperature range	−70 °F to 250 °F
Recommended applications	Hot water and steam
Color	Black
Drinking-water certifications	NSF 61, WRAS, KTW
Additional approval	FDA
ASTM specification	D2000 M3DA714 A26 B36 EA14 F19 G11 G21 Z1 Z2 Z3

4.2 Risk-Based Component Conformity Verification

Component conformity constitutes the first stage in applying the proposed approach, following the definition of the O-ring function and operational context and its risk-based criticality classification. The three scenarios defined in Table 3 result in different criticality levels for the same Parker E1549-70 O-ring. In Scenario 1, the component is classified as high criticality because its sealing function is directly associated with an essential equipment function. In Scenario 2, the component is classified as medium criticality because loss of sealing affects equipment performance but does not compromise an essential function. In Scenario 3, the component is classified as low criticality because the consequences associated with loss of sealing are limited. This differentiation determines the level of verification required for each scenario. The high-criticality case requires the most comprehensive set of objective evidence, whereas the medium- and low-criticality cases allow a proportionate reduction in verification scope, as established by the framework presented in Section 3. For the application considered, O-ring characteristics are compared with the specified component requirements using the manufacturer's technical documentation and the corresponding material test report as the main sources of evidence.

The criticality classification considers the potential consequence of O-ring failure and its likelihood of occurrence under the assumed application conditions. The consequence of failure considers potential effects on equipment functionality, containment, safety, environmental performance, downtime, rework, and other relevant operational impacts. The likelihood is assessed based on application-specific factors that may influence the probability of component nonconformity or sealing failure, including operating conditions, material compatibility, assembly conditions, dimensional sensitivity, and other relevant service characteristics. In the present case, the high-criticality classification is used to demonstrate the application of the proposed risk-based methodology and should not be interpreted as a general classification of the Parker E1549-70 product, since the criticality of an O-ring

depends on its application and the consequences associated with its failure.
The Material Report for the E1549-70 compound presents requirements and results obtained according to different ASTM methods (Parker, 2017). The properties evaluated include hardness, tensile strength, elongation, compression set, fluid resistance, tear resistance, and low-temperature performance. The document also records the compound's compliance with requirements related to FDA and NSF 61 certification. To demonstrate how this information can be incorporated into the FAT, characteristics directly related to component identification, mechanical properties, and material suitability for service conditions were selected. Table 5 presents a comparison between the specified limits and the results recorded in the manufacturer's report.

Table 5. Selected Conformity Data For Parker E1549-70 Compound

Characteristic	Test method	Specified limit	Reported result	Conformity
Hardness, Shore A	ASTM D2240	70 ± 5	70	Conforming
Tensile strength	ASTM D412	≥ 2031 psi	2161 psi	Conforming
Ultimate elongation	ASTM D412	≥ 200%	336%	Conforming
Compression set, 22 h at 150 °C	ASTM D395, Method B	≤ 25%	22%	Conforming
Hardness change after heat aging	ASTM D573	≤ +10 points	+3 points	Conforming
Tensile strength change after heat aging	ASTM D573	≥ −20%	+2%	Conforming
Ultimate elongation change after heat aging	ASTM D573	≥ −20%	−10%	Conforming
Volume change after water immersion	ASTM D471	−5% to +5%	+2%	Conforming
TR-10 temperature	ASTM D1329	≤ −40 °C	−42 °C	Conforming

Source: adapted from Parker E1549-70 Material Report.

The results presented in Table 5 demonstrate an important characteristic of the proposed approach: the existence of material test results is not, by itself, sufficient to determine their relevance to the FAT. Each property must be related to the requirement being verified and to the equipment's operating conditions. For example, compound hardness may constitute a specified characteristic of the O-ring, whereas compression set may be particularly relevant when the ability to maintain sealing performance over time constitutes a design requirement.
The same rationale can be applied to properties obtained after exposure to elevated temperature or water. In the report analyzed, the compound exhibited a hardness change of −2 points, a tensile strength change of +2%, an elongation change of 0%, and a volume change of +2% after exposure to water at 100 °C for 70 hours, remaining within the specified limits. These results constitute evidence of the conformity of the component material but should not be interpreted as demonstrating the leak tightness of the equipment in which the O-ring will be installed.
This distinction is fundamental to the application of the proposed approach. Material documentation may demonstrate that the supplied component has characteristics compatible with the specification, but it does not, by itself, allow the conclusion that the assembled system will achieve the required leak tightness. Equipment acceptance also depends on factors related to housing geometry, assembly, compression, operating conditions, and the interaction between the O-ring and the other components of the sealing system. Therefore, within the context of the FAT, the results presented in the manufacturer's documentation should be treated as evidence of component conformity, whereas tests performed on the equipment constitute evidence of the functional performance of the assembly. The integration of these two categories of evidence will be discussed in the following subsection.

4.3 Verification of O-Ring Material and Documentation

The second stage consists of verifying the documentary conformity of the O-ring used in the equipment. This verification aims to confirm whether the supplied component corresponds to the characteristics specified for the application, using manufacturer documentation as evidence of conformity. Table 6 provides an example of this documentary check.

Table 6. Example Of O-Ring Documentation Verification

Verification Item	Example Evidence	Acceptance Criteria
Manufacturer	Parker	As specified
Part Number	E1549-70	As specified
Elastomer Type	EPR / EPDM	As specified
Hardness	70 Shore A	70 ± 5 Shore A
Material Specification	ASTM D2000 M3DA714...	Applicable specification
Material Test Report	Available	Required
Temperature Range	−70 °F to 250 °F	Compatible with application
Fluid Compatibility	Water and steam	Compatible with service fluid

Source: Adapted from Parker (2017, 2026).

In the example analyzed, the Parker E1549-70 is specified as an EPR/EPDM O-ring, with a nominal hardness of 70 Shore A and a recommended temperature range of −70 °F to 250 °F (Parker, 2026). The manufacturer's Material Report additionally provides test results related to physical properties, thermal resistance, fluid resistance, compression set, and low-temperature performance. This information can be compared with the requirements defined for the equipment.
Documentary verification therefore constitutes evidence of component conformity but does not replace the functional tests performed on the equipment. In the proposed framework, this evidence is subsequently correlated with the results of pressure and leak-tightness tests, allowing the conformity of the O-ring and the performance of the assembly to be evaluated jointly.

4.4 FAT Acceptance Criteria

The final stage consists of consolidating the evidence obtained from the previous verifications and the functional tests performed on the equipment. Acceptance should not depend exclusively on the outcome of the leak-tightness test but should consider the documentary and physical conformity of the O-ring together with the performance demonstrated by the equipment during the FAT.

Table 7. Proposed acceptance structure for o-ring related fat verification

Verification Level	Main Evidence	Acceptance Condition	Relation to Criticality
Component conformity	Identification, material, dimensions and documentation	Requirements satisfied	Required for all criticality levels, with verification scope proportional to criticality
Installation conformity	Visual inspection and assembly verification	No identified nonconformity	Required when installation can affect sealing performance; greater rigor for higher criticality
Equipment performance	Pressure and leakage tests	Test criteria satisfied	Required when leak-tightness is a relevant functional requirement, particularly for high-criticality applications

T Thus, for equipment whose leak tightness depends on O-rings, the acceptance criteria can be organized into three levels: (i) component conformity, related to identification, material, dimensions, and documentation; (ii) installation conformity, related to the condition and assembly of the O-ring; and (iii) assembly performance, verified through the functional tests defined in the FAT. Table 7 summarizes this subdivision into different levels: he combined use of this evidence makes it possible to distinguish a potential failure related to the component from a failure observed during equipment operation. Thus, the FAT records not only the final test result but also the elements used to demonstrate the conformity of the sealing system. The proposed framework does not establish universal values for acceptance criteria, as these should be defined according to the technical requirements, operating conditions, and specific characteristics of each piece of equipment. The purpose of the framework is therefore to establish which evidence should be correlated and in what sequence it should be verified, allowing its adaptation to different applications. The risk-based classification further establishes the level of verification required for the component, ensuring that the verification effort is proportionate to the potential consequences of O-ring failure.

4.5 Impact on Industrial Performance Indicators

Beyond establishing conformity evidence for equipment acceptance, the proposed framework is intended to support the earlier detection of O-ring nonconformities that may affect industrial performance. Failures of sealing components may generate consequences beyond the replacement of the component itself, including additional maintenance activities, rework, production losses, equipment damage, and unplanned downtime (Orbit Fluid Solution LLP, 2026). The potential industrial impact of the framework can therefore be examined through four relevant performance indicators: leakage failures, rework, downtime, and quality-related costs.
The first indicator is leakage failure. By verifying the conformity of critical O-rings before or in conjunction with equipment functional testing, the proposed approach can identify nonconformities related to material, dimensions, surface condition, traceability, or installation before they result in a sealing failure during subsequent operation. Component-level verification does not replace pressure or leakage testing, since conformity of the individual O-ring cannot by itself demonstrate the performance of the assembled sealing system. Instead, it provides complementary evidence and may reduce the likelihood that a nonconforming sealing component remains undetected until the equipment-level test or subsequent operation. The second indicator is rework. When an O-ring nonconformity is identified during the earlier stages of the FAT, corrective action can be performed before the equipment progresses to subsequent acceptance activities. In contrast, detection during a functional or leakage test may require disassembly, component replacement, reassembly, and repetition of the test. The proposed framework therefore shifts the verification of relevant component characteristics toward an earlier stage, with the potential to reduce rework associated with late detection of O-ring nonconformities.

Downtime is also influenced by the timing and consequences of failure detection. In high-criticality applications, an O-ring failure that compromises an essential equipment function may result in unplanned unavailability and additional maintenance activities. The risk-based approach addresses this issue by assigning greater verification rigor to components whose failure has more significant operational consequences. Consequently, the framework may contribute to reducing the probability that critical sealing failures remain undetected until equipment operation or later stages of the acceptance process.

Quality-related costs represent a broader consequence of the same mechanisms. Such costs may include additional inspection and testing, labor associated with corrective actions, component replacement, repeated FAT activities, emergency interventions, and other resources required to address nonconformities. The proposed framework does not provide a direct monetary estimate of these costs; rather, it establishes a preventive verification structure intended to identify relevant nonconformities before their correction requires greater resources.

Figure 4 illustrates the relationship between the timing of O-ring nonconformity detection and its potential industrial consequences. Earlier detection during component verification allows corrective actions to be performed before the equipment progresses to subsequent acceptance stages, whereas later detection may require additional testing, rework, or operational intervention. Table 8 summarizes the expected relationship between the risk-based verification approach and the four industrial performance indicators considered in this study.

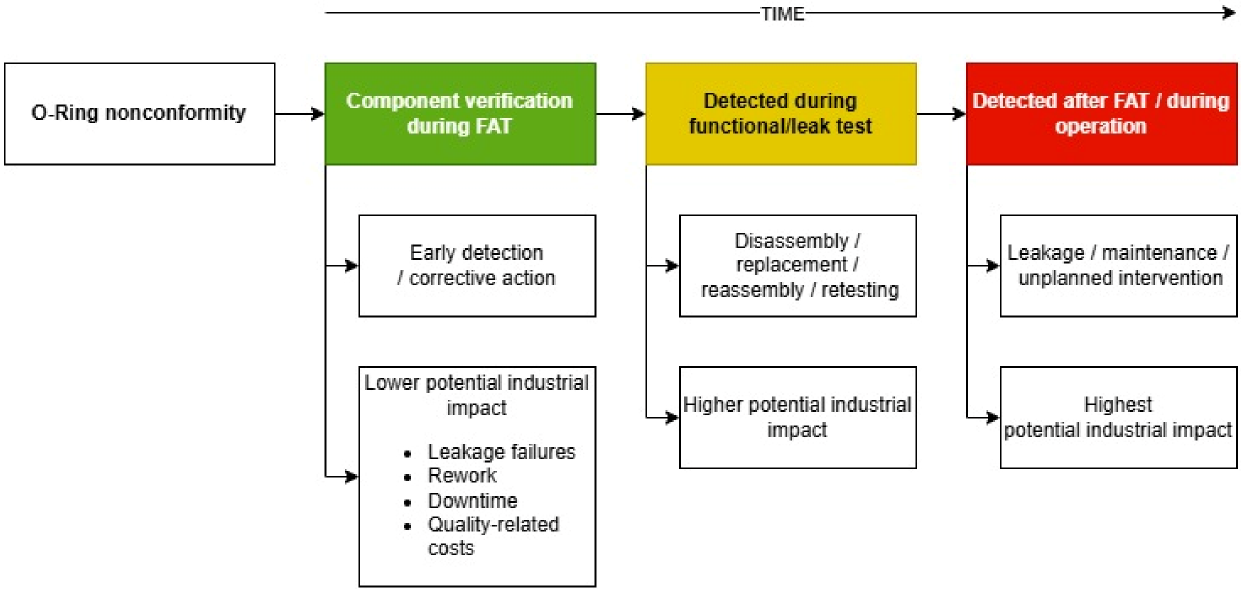

Figure 4. Relationship between O-ring Nonconformity Detection and Potential Industrial Impact

Table 8. Expected impact of the proposed framework on industrial performance indicators

Industrial Performance Indicator	Mechanism of Impact	Expected Effect of the Framework
Leakage failures	Early identification of nonconforming O-rings and verification of installation before or together with equipment-level sealing tests	Lower likelihood of O-ring-related leakage reaching subsequent stages
Rework	Detection of component or installation nonconformities before completion of functional testing	Potential reduction in disassembly, replacement, reassembly, and repeated testing
Downtime	Prevention or earlier detection of failures affecting equipment operation, particularly in high-criticality applications	Potential reduction in unplanned unavailability associated with O-ring failures
Quality-related costs	Reduction of corrective activities, repeated testing, emergency interventions, and other consequences of late detection	Potential reduction in costs associated with O-ring-related nonconformities

The three scenarios defined in this study further illustrate how the expected impact varies according to component criticality. In Scenario 1, the O-ring performs an essential sealing function and is classified as high criticality. A failure in this context may directly affect equipment availability and therefore has greater potential consequences in terms of leakage failures, rework, downtime, and quality-related costs. Accordingly, the framework assigns a more comprehensive verification scope to this application. In Scenario 2, the consequences of loss of sealing capability are less severe because the affected function is not essential, resulting in a medium criticality classification and a proportionate verification scope. In Scenario 3, where the operational consequences are limited, the lower criticality permits a less extensive verification effort while maintaining the required evidence of conformity.

The proposed framework therefore establishes a proportional relationship between component criticality, verification rigor, and the potential industrial consequences of failure. Higher criticality justifies greater investment in preventive verification because the consequences of late detection may include more significant leakage failures, rework, downtime, and quality-related costs. The value of the proposed approach thus lies not only in detecting O-ring nonconformities, but also in enabling their identification at an earlier stage of the equipment acceptance process.

The present study does not quantify the absolute reduction in these indicators, since such quantification would require empirical data from repeated industrial FAT applications, historical failure records, or controlled comparative studies. The effects presented in Table 8 should therefore be interpreted as expected impacts rather than measured percentage reductions. Future industrial applications of the framework could quantify these effects using indicators such as the number of O-ring-related leakage failures, rework hours, downtime hours, repeated FAT activities, maintenance costs, and total quality-related costs.

5. DISCUSSION

The proposed framework addresses a gap between conventional equipment-level FAT verification and component-level conformity assessment of critical sealing elements. Existing FAT approaches provide structured methods for verifying equipment functions, parameters, and performance, whereas O-ring studies predominantly address component characteristics, failure mechanisms, and inspection. The present work connects these two perspectives by incorporating O-ring conformity, installation condition, and equipment-level sealing performance into a single acceptance logic. This integration is complemented by a risk-based classification that determines the level of verification according to the function performed by the O-ring, its operational context, and the potential consequences of failure.

A distinctive feature of the framework is therefore that criticality is not treated as an intrinsic property of the O-ring. The three scenarios demonstrate that the same Parker E1549-70 component may require different levels of verification when its operational function and the consequences of sealing failure change. This context-dependent classification provides a basis for allocating verification effort proportionately to risk rather than applying a uniform inspection scope to all O-rings.

The application case also demonstrates the importance of combining different forms of acceptance evidence. Manufacturer documentation can establish evidence of component conformity, while installation verification addresses conditions that may affect sealing performance and functional or leak-tightness testing provides evidence of equipment-level performance. Establishing the relationship among these evidence levels can facilitate the identification of the origin of potential nonconformities and prevent an unsatisfactory leak-tightness result from being analyzed in isolation.

Several limitations should nevertheless be recognized. The criteria presented do not constitute universal acceptance values and should be defined according to the equipment requirements, operating conditions, O-ring material, and specific application. In addition, the application uses information from a commercial product and does not represent an experimental validation of the framework across different equipment or service conditions. Accordingly, the proposal should be understood as a framework for organizing and prioritizing conformity evidence related to O-rings during FAT, rather than as a test procedure or technical specification for these components. The three scenarios demonstrate that the proposed framework does not assign a fixed criticality level to the O-ring based solely on its material, manufacturer, or physical characteristics. Instead, the criticality is determined by the function performed by the component within its operational context and by the consequences associated with loss of sealing capability. As a result, the same Parker E1549-70 O-ring can be subject to different levels of verification depending on its application. This behavior demonstrates the adaptability of the framework and supports its use for structuring risk-proportionate O-ring verification within FAT activities.

6. CONCLUSION

This study proposed a risk-based framework for integrating O-ring verification into Factory Acceptance Tests, addressing the gap between component-level conformity assessment and equipment-level functional acceptance. The framework establishes a structured relationship between the O-ring's operational context and criticality, applicable component requirements, verification methods, conformity evidence, installation condition, and equipment-level performance. Application of the framework to a commercial Parker E1549-70 O-ring demonstrated how these elements can be incorporated into the FAT acceptance process.

The proposed approach contributes to FAT practice by treating critical O-ring conformity as complementary evidence rather than relying exclusively on equipment-level functional or leak-tightness results. Component conformity, installation conformity, and equipment performance are considered as interconnected but distinct forms of evidence. The three defined FAT scenarios further demonstrated that criticality is context-dependent: the same O-ring may require different verification scopes when its function and the consequences of sealing failure change. This risk-proportionate structure provides a basis for directing greater verification effort toward components whose failure may have more significant operational consequences.

The analysis also indicates a potential relationship between earlier detection of O-ring nonconformities and industrial performance indicators such as leakage failures, rework, downtime, and quality-related costs. However, these effects were not quantitatively measured in the present study and should therefore be interpreted as expected impacts rather than demonstrated reductions.

The main limitation of the study is that the framework was not subjected to an experimental FAT campaign involving different types of equipment. Its application was demonstrated through a case based on real manufacturer data for a commercial O-ring and through three clearly defined hypothetical operational contexts. Future studies should evaluate the framework in actual FAT applications and quantify its effects using historical or comparative data on O-ring-related leakage failures, rework hours, downtime, repeated FAT activities, maintenance costs, and other quality-related costs.

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