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Standard Guide for
Applying Failure Mode and Effect Analysis (FMEA) to In-Service Lubricant Testing[1]

This standard is issued under the fixed designation D7874; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide describes a methodology to select tests to be used for in-service lubricant analysis. The selection of fluid tests for monitoring failure mode progression in industrial applications applies the principles of failure mode and effect analysis (FMEA).

1.2 Although typical FMEA addresses all possible product failure modes, the focus of this guide is not intended to address failures that have a very high probability of unsafe operation as these should immediately be addressed by other means.

1.3 This guide is limited to components selected for condition-monitoring programs by providing a methodology to choose fluid tests associated with specific failure modes for the purpose of identifying their earliest developing stage and monitoring fault progression. The scope of this guide is also focused on those failure modes and their consequences that can effectively be detected and monitored by fluid analysis techniques.

1.4 This guide pertains to a process to be used to ensure an appropriate amount of condition monitoring is performed with the objective of improving equipment reliability, reducing maintenance costs, and enhancing fluid analysis monitoring of industrial machinery. This guide can also be used to select the monitoring frequencies needed to make the failure determinations and provide an assessment of the strengths and weaknesses of a current condition-monitoring program.

1.5 This guide does not eliminate the programmatic requirements for appropriate assembly, operational, and maintenance practices.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D7684 Guide for Microscopic Characterization of Particles from In-Service Lubricants

D7720 Guide for Statistically Evaluating Measurand Alarm Limits when Using Oil Analysis to Monitor Equipment and Oil for Fitness and Contamination

2.2 *IEC Standard:*

IEC 60812 Analysis Techniques for System Reliability—Procedure for Failure Mode and Effects Analysis (FMEA), 2006

3. Terminology

3.1 *Definitions:*

3.1.1 *cause(s) of failure, n*—underlying source(s) for each potential failure mode that can be identified and described by analytical testing.

3.1.2 *component incipient failure, n*—moment a component begins to deteriorate or undergo changes that will eventually lead to the loss of its design function.

3.1.2.1 *Discussion*—This moment may not be easily detectable because of sensitivity limitations of monitoring instrumentation or a lack of measurable change in performance characteristics or both.

3.1.3 *criticality number, C, n*—product of the severity (*S*) and occurrence (*O*) numbers for a given failure mode's causes and effects.

3.1.4 *design function, n*—function or task that the system or component should perform.

3.1.5 *detection ability number, D, n*—ranking number that describes the ability of a specific fluid test to successfully detect a failure mode's causes or effects. A scale is used to grade detection ability numbers; see an example in 6.4.7.

3.1.6 *effect(s) of failure, n*—potential outcome(s) of each failure mode on the system or component.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.7 *failure-developing period, FDP, n*—period from component's incipient failure to functional failure.

3.1.8 *failure mode, n*—physical description of the manner in which a failure occurs.

3.1.9 *failure mode and effect analysis, FMEA, n*—analytical approach to determine and address methodically all possible system or component failure modes and their associated causes and effects on system performance.

3.1.9.1 *Discussion*—This approach can be used to evaluate designs and track risk-reducing improvements to equipment reliability.

3.1.10 *failure modes, effects, and criticality analysis, FMECA, n*—extension to FMEA that involves ranking the risk associated with failure modes to allow prioritization and selection of an appropriate maintenance strategy.

3.1.10.1 *Discussion*—A metric-describing criticality is determined by the product of a severity number (*S*) and its occurrence number (*O*) for each given failure mode's causes and effects.

3.1.11 *functional failure, n*—inability of the component or system to perform its required design function.

3.1.12 *occurrence number, O, n*—ranking number that describes the probability of occurrence of a failure mode's causes and effects over a predetermined period of time based on past operating experience in similar applications; see an example in 6.3.2.

3.1.13 *P-F curve, n*—illustration of component failure progression (component condition versus time) from incipient failure to functional failure (*F*).

3.1.14 *P-F interval, n*—period from the point in time in which a change in performance characteristics or condition can first be detected (*P*) to the point in time in which functional failure (*F*) will occur as illustrated on a *P-F* curve.

3.1.15 *severity number, S, n*—ranking number that describes the seriousness of the consequences of each failure mode's causes and effects on potential injury, component or equipment damage, and system availability.

3.1.15.1 *Discussion*—A scale is used to grade severity numbers. See an example in 6.3.1.

4. Summary of Guide

4.1 This guide is designed to aid the user to optimize their condition-monitoring program.

4.2 Failure mode and effect analysis (FMEA) is applied by the user of this guide to those machines selected in their condition-monitoring program based on their significance to production and safety. The user of this guide determines the possible failure modes for each machine and applies FMEA separately for each failure mode. A severity number (S) is assigned for each failure mode's causes and effects.

4.3 The user of this guide then determines how frequently the failure mode's causes or effects are likely to occur based on past operating experience under similar applications for a predetermined time period. An occurrence number (*O*) is assigned for each failure mode's causes and effects.

4.4 The severity and occurrence numbers are constant for each failure mode's specific cause or effect. Calculating the product of the severity and occurrence numbers (criticality number) for all failure modes' causes and effects allows the user to establish a ranked hierarchy of the risk associated with equipment failure. A table matrix of severity versus occurrence ranks can then be used to allow the user to determine whether a given failure mode's cause or effect is tolerable and requires periodic inspection, fluid testing, or design modification (for example, Table 1). This is used to justify the need for testing of specific failure modes' causes or effects within a predictive maintenance program.

4.5 For those failure modes' causes and effects that require fluid testing, several test methods should be considered. A detection ability number (*D*) is determined by the user for each test method based on the test's ability to detect the failure mode's causes and effects. By comparing the ranking of criticality numbers with their corresponding detection ability numbers, the user may assess the strengths and weaknesses of their fluid testing program. Cases in which the detection ability numbers are low compared to a high corresponding criticality number indicates weakness within a fluid testing program.

TABLE 1 Criticality Matrix

	Severity Number				
Occurrence Number	S-1 Insignificant	S-2 Marginal	S-3 Moderate	S-4 Critical	S-5 Catastrophic
O-1 Improbable	Tolerable	Tolerable	Periodic Inspection	Periodic Inspection	Testing
O-2 Remote	Tolerable	Periodic Inspection	Periodic Inspection	Testing	Testing
O-3 Occasional	Periodic Inspection	Periodic Inspection	Testing	Testing	Testing
O-4 Probable	Periodic Inspection	Testing	Testing	Testing	Design Modification
O-5 Frequent	Testing	Testing	Testing	Design Modification	Design Modification

4.6 An optimal sampling interval with consideration to the cost of sampling and benefits to the monitoring program can also be determined to implement a balanced testing approach.

5. Significance and Use

5.1 This guide is intended as a guideline for fluid analysis programs and serves as an initial justification for selecting fluid tests and sampling frequencies. Plant operating experience along with the review and benchmarking of similar applications is required to ensure that lessons learned are implemented.

5.2 Selection of proper fluid tests for assessing in-service component condition may have both safety and economic implications. Some failure modes may cause component disintegration, increasing the safety hazard. Thus, any fluid test that can predict such conditions should be included in the condition-monitoring program. Conversely, to maintain a sustainable and successful fluid-monitoring program, the scope of the fluid tests and their frequency should be carefully balanced between the associated risks versus expected program cost savings and benefits.

5.3 The failure modes monitored may be similar from one application to the next, but the risk and consequences of failure may differ.

5.4 This analysis can be used to determine which in-service lubricant analysis tests would be of highest value and which would be ineffective for the failure modes of interest. This information can also be used to determine the best monitoring strategy for a suite of failure modes and how often assessment is needed to manage the risk of failure.

6. Failure Mode and Effect Analysis (FMEA)

6.1 The FMEA process requires a thorough understanding of machine design requirements and equipment operating conditions. Detailed knowledge is required of the component design configuration, dimensional tolerances, load directions, design limitations, lubrication mechanisms, lubricant characteristics, metallurgy of lubricated components, and environmental conditions. System significance, equipment accessibility, and application of on-line sensors or other monitoring techniques (for example, vibration, ultrasound, and thermal images) also provide critical information in this analysis process. A committee of individuals may be assembled to ensure the listed knowledge areas are properly represented.

6.2 An overview of the FMEA process is presented in Fig. 1.

6.3 The FMEA methodology prioritizes failures modes based on how serious the consequences of their effects are (*S*) and how frequently they are expect to occur (*O*).

6.3.1 For in-service fluid analysis applications, *S* is categorized according to a ranked-number scale. An example is provided here of a five-rank scale; however, users may modify this scale to satisfy their specific requirements.

6.3.1.1 Number S-1 indicates an insignificant condition that has little to no effect on component performance.

6.3.1.2 Number S-2 indicates a marginal condition that causes a minor effect on component performance without the need for repair.

6.3.1.3 Number S-3 indicates a moderate condition that reduces component performance and requires repair.

6.3.1.4 Number S-4 indicates a critical condition caused by the loss of component design function that makes the component inoperable.

6.3.1.5 Number S-5 indicates a catastrophic condition caused by the loss of component design function that may endanger the operator and others.

6.3.2 For in-service fluid analysis applications, *O* is categorized according to a ranked-number scale. An example is provided here of a five-rank scale. As previously mentioned, users may modify this scale to satisfy their specific requirements.

6.3.2.1 Number O-1 indicates improbable occurrence based on no identified failures in similar applications.

6.3.2.2 Number O-2 indicates remote occurrence based on a very few number of failures in similar applications for a predetermined operational period.

6.3.2.3 Number O-3 indicates occasional occurrence based on a moderate number of failures in similar applications for a predetermined operational period.

6.3.2.4 Number O-4 indicates probable occurrence based on a high number of failures in similar applications for a predetermined operational period.

6.3.2.5 Number O-5 indicates frequent occurrence based on a very high number of failures in similar applications for a predetermined operational period.

6.3.3 The predetermined operational period is selected by the user based on factors such as production schedules, outage and inspection intervals, and so forth.

6.4 Failure mode, effects, and criticality analysis (FMECA) is a part of FMEA.

6.4.1 Criticality numbers are calculated for all failure modes' causes and effects by multiplying their severity (*S*), 6.3.1, and occurrence numbers (*O*), 6.3.2.

6.4.2 Criticality numbers are then used to quantify the relative magnitude of each failure mode's causes and effects to establish a ranked hierarchy of equipment failure risk and adjust the condition-monitoring program in response.

6.4.3 To improve analysis efficiency, the list of failure mode causes and effects should be rearranged according to the hierarchy of criticality numbers.

6.4.4 The hierarchy of criticality numbers can be listed using either their actual criticality values or their numerical ranking in the hierarchy (for example, 1, 2, 3, and so forth). The list of actual criticality values may provide additional information about the difference in magnitude of risk between each rank.

6.4.5 The user should develop a criticality table matrix of severity versus occurrence ranks that can be used to determine the preferable maintenance approach for the detection of each particular failure mode's cause or effect. An example of such a criticality matrix is provided in Table 1.

6.4.6 For failure mode causes and effects that require fluid testing, users should consider a broad selection of different

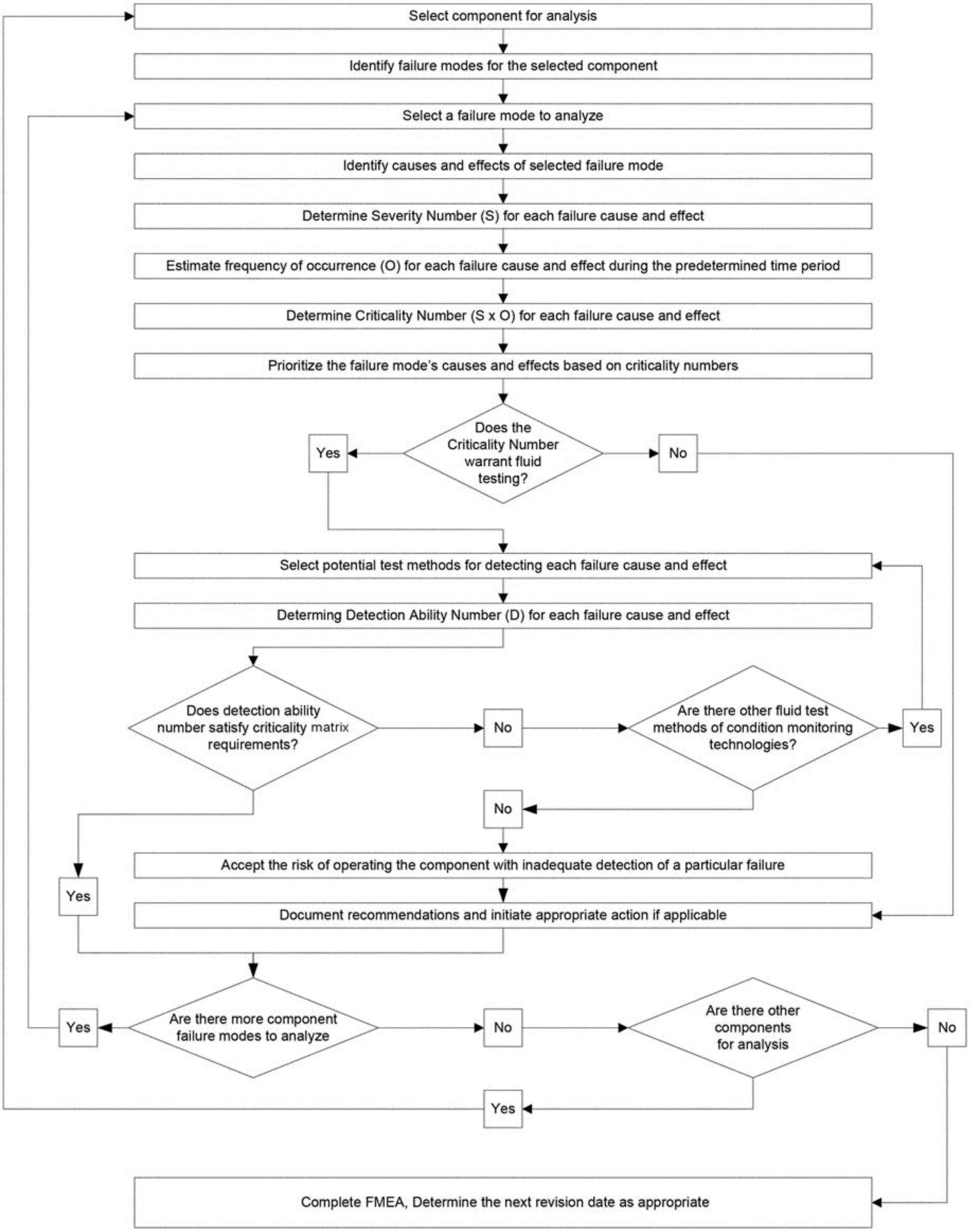

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FIG. 1 FMEA Flowchart (Modified from IEC 60812)

fluid test methods capable of detecting and monitoring the progression of the specific failure modes.

6.4.7 For each fluid test method, users should assign a detection ability number, *D*, based on how easily and reliably the failure mode's causes and effects can be detected by the test. *D* is categorized by selecting one of the following ranks for each test being reviewed. As previously mentioned, users may modify this scale to satisfy their specific requirements.

6.4.7.1 Number D-1 is assigned for a fluid analysis test that is highly unlikely to detect the failure mode's causes or effects.

6.4.7.2 Number D-2 is assigned for a fluid analysis test that has a slight chance to detect the failure mode's causes or effects.

6.4.7.3 Number D-3 is assigned for a fluid analysis test that has a moderate chance to detect the failure mode's causes or effects.

6.4.7.4 Number D-4 is assigned for a fluid analysis test that has a high chance to detect the failure mode's causes or effects.

6.4.7.5 Number D-5 is assigned for a fluid analysis test that is almost certain to detect the failure mode's causes or effects.

6.4.8 Users should consider a wide range of factors that may influence detection ability number (*D*) values, such as the location of the sampling port within the system, sampling hardware, human factors, and the environment.

6.4.9 The fluid test method with the highest detection ability number (*D*) for a given failure mode cause or effect is selected.

6.5 An assessment of the condition-monitoring program can be performed by comparing the hierarchy of criticality numbers (*C*) with their corresponding detection ability number (*D*) for each failure mode's causes and effects. For the program to be effective, the failure modes with the highest criticality numbers (*C*) should have high detection ability numbers (*D*). Users should identify all cases in which the detection ability number (*D*) does not reflect the value of the criticality number (*C*) or its ranking. These cases represent weaknesses in the condition-monitoring program and should be used as justification for further enhancement.

7. Sampling and Testing Frequencies

7.1 After selecting the recommended set of fluid tests, end users should determine the fluid sampling frequency for each test. For time-dependent failure modes this is done based on the determination of the failure-developing period (FDP) that describes the period from component incipient failure to functional failure.

7.2 The *P-F* curve (Fig. 2) illustrates failure progression. A component will eventually deteriorate to the point (*P*) at which failure can be detected. If allowed to continue, functional failure will occur (*F*).

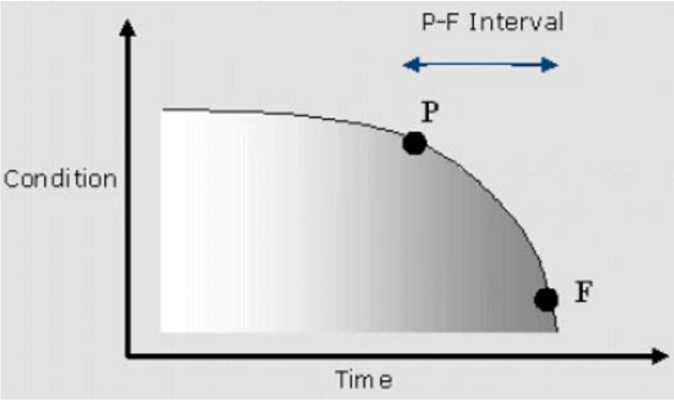

FIG. 2 *P-F* Curve and *P-F* Interval

7.3 *P-F* intervals can be estimated using the judgment and experience of the component manufacturers or end users.

7.4 The preferable approach in this analysis is to specify a degradation model that fits the observed data. The choice of degradation model may come from an understanding of how the degradation progresses over time. The next step is to collect the data and calculate the *P-F* interval by subtracting the time that the failure was first detected (*P*) from the time of functional failure (*F*). The final *P-F* interval is determined by averaging the available data.

7.5 The monitoring intervals are usually equivalent to half of the *P-F* interval. This is considered an appropriate balance between monitoring cost and the risk of not detecting failures because of inadequate monitoring frequency. In some applications, the time necessary for repairs also needs to be considered, and therefore, the monitoring frequency may be increased to a third of the average *P-F* interval. The severity of the failure may also influence the frequency of the monitoring intervals.

7.5.1 Preferred sampling intervals give advance trend indications as failure mechanisms progress from incipient to catastrophic for an indicated property or other characteristic.

7.5.2 In-service oil analysis typically generates multiple measurements reflecting wear condition for equipment, contamination condition for the lubricating system, and chemistry condition for the lubricant. Alarm limit thresholds are commonly assigned to flag at least one selected measurement within each of these three categories. Refer to Guide D7720 for guidelines to statistically evaluate alarm limits for in-service lubricants, and refer to Guide D7684 for guidelines related to use of microscopic wear particle analysis for finding evidence of failure progression evident from wear and contaminant debris transported by in-service lubricants.

7.6 Typically, the test with the shortest sampling frequency interval would determine the recommended sampling frequency for the entire fluid analysis set for a specific component. However, in cases in which there is a significant spread of sampling frequencies or cost of testing, the entire fluid analysis test program may be split by performing some tests more frequently than others. Typically, for practical considerations no more than two different frequencies are used.

8. Applications

8.1 The severity, occurrence, and detection ability numbers mentioned in 6.3.1, 6.3.2, and 6.4.7 may change for each application.

8.1.1 Some fluid properties (for example, kinematic viscosity, acid number, and ASTM color) are less sensitive to sampling location and sampling methodology. Others (for example, solid particle distribution) depend significantly on the sampling location, hardware, and the applied sampling methodology.

8.2 Some fluid properties may be determined by a number of different test methods which may have significantly different detection levels and precision.

8.2.1 For example, in determination of water content for in-service lubricating fluids, the Karl Fischer titration method has significantly better detection level and precision than a crackle test method and this will impact the value of the detection ability number as well as the *P-F* interval.

8.2.2 The knowledge, experience, and qualifications of personnel performing fluid analysis tests and their capabilities to interpret the test results properly (for example, analytical ferrography) are also critical in the condition-monitoring process.

8.3 As a result, a conservative approach should be applied when selecting the severity, occurrence, and detection ability numbers.

8.4 In Table 2, a typical example of the approach used in preparing a FMEA template for fluid analysis applications is presented.

8.5 The presented methodology can also be used for upgrading the condition-based maintenance program by justifying the use of more precise fluid analysis instrumentations or specific sensors for the purpose of getting earlier indication of failure modes. This is important for cases in which the detection ability number is inadequate in relation to the criticality number requirement. Occasionally, the user may have to accept the risk of operating the equipment without adequate monitoring capabilities and instead depend on time-based maintenance.

8.6 It is important that the entire FMEA process is well documented and periodically reviewed to maintain the effectiveness of the condition-monitoring program.

9. Keywords

9.1 condition monitoring; failure modes; FMEA; lubricant analysis program

TABLE 2 Example of Application of FMEA Methodology for Fluid Analysis

Failure Mode	Test Location	Test 1		Test 2			Test m	
		Location A[A]	Location B[A]	Location A[A]	Location B[A]		Location A[A]	Location B[A]
Failure Mode 1	S	X_{1A1}	X_{1B1}	X_{1A2}	X_{1B2}	. . .	X_{1Am}	X_{1Bm}
	O	Y_{1A1}	Y_{1B1}	Y_{1A2}	Y_{1B2}	. . .	Y_{1Am}	Y_{1Bm}
	C	$X_{1A1}Y_{1A1}$	$X_{1B1}Y_{1B1}$	$X_{1A2}Y_{1A2}$	$X_{1B2}Y_{1B2}$	. . .	$X_{1Am}Y_{1Am}$	$X_{1Bm}Y_{1Bm}$
	D	Z_{1A1}	Z_{1B1}	Z_{1A2}	Z_{1B2}	. . .	Z_{1AM}	Z_{1Bm}
Failure Mode 2	S	X_{2A1}	X_{2B1}	X_{2A2}	X_{2B2}	. . .	X_{2Am}	X_{2Bm}
	O	Y_{2A1}	Y_{2B1}	Y_{2A2}	Y_{2B2}	. . .	Y_{2Am}	Y_{2Bm}
	C	$X_{2A1}Y_{2A1}$	$X_{2B1}Y_{2B1}$	$X_{2A2}Y_{2A2}$	$X_{2B2}Y_{2B2}$	. . .	$X_{2Am}Y_{2Am}$	$X_{2Bm}Y_{2Bm}$
	D	Z_{2A1}	Z_{2B1}	Z_{2A2}	Z_{2B2}	. . .	Z_{2Am}	Z_{2Bm}
	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Failure Mode n	S	X_{nA1}	X_{nB1}	X_{nA2}	X_{nB2}	. . .	X_{nAm}	X_{nBm}
	O	Y_{nA1}	Y_{nB1}	Y_{nA2}	Y_{nB2}	. . .	Y_{nAm}	Y_{nBm}
	C	$X_{nA1}Y_{nA1}$	$X_{nB1}Y_{nB1}$	$X_{nA2}Y_{nA2}$	$X_{nB2}Y_{nB2}$	. . .	$X_{nAm}Y_{nAm}$	$X_{nBm}Y_{nBm}$
	D	Z_{nA1}	Z_{nB1}	Z_{nA2}	Z_{nB2}	. . .	Z_{nAm}	Z_{nBm}

[A] Indexes after *x*, *y*, and *z* are, in order, failure mode/location/test method.

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