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Road vehicles — Application of predictive maintenance to hardware with ISO 26262-5

Véhicules routiers — Application de l'entretien<u>la maintenance</u> prédictive au matériel avec ISO <u>à</u> l'aide de <u>l'ISO</u> 26262-5

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Introduction

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Hardware elements wear out or degrade with time and usage. The presence of certain faults can cause the rate of degradation to increase. If the rate of degradation exceeds critical thresholds, then a hardware element can fail during its normal expected lifespan. Addressing fault behaviours which change over time is difficult. Functional safety standards such as <u>the ISO 26262</u> series have traditionally addressed degrading faults with avoidance measures and simplified assumptions of static behaviours.

Understanding of degrading faults is improving over time. Many industries are taking proactive steps to control degrading faults using predictive maintenance. Predictive maintenance can detect degrading faults and predict remaining useful life. Safety mechanisms based on predictive maintenance are not explicitly discussed in <u>the ISO 26262:2018 series</u>.

This document provides a survey of current state of the art for degrading faults and predictive maintenance techniques. Approaches are presented to consider degrading faults and predictive maintenance techniques in an ISO 26262 safety argument. Much of the content is focused on semiconductors, but the concepts can be applied to other hardware elements.

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Road vehicles — Application of predictive maintenance to hardware with ISO 26262-5

1 Scope

This document is intended to be applied to the usage of predictive maintenance methods for the detection of degrading faults in safety related E/E hardware elements. It applies to hardware elements developed for compliance with <u>the ISO 26262^[1] series</u> in which degrading faults are shown to be relevant due to, for instance, the technology used.

Specific technical implementations of predictive maintenance solutions are not in scope of this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 26262-<u>-</u>1: 2018, Road vehicles – Functional Safety safety – Part 1: Vocabulary

ISO 26262-5: 2018 Road vehicles Functional Safety Part 5: Product development at the hardware level

43 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 26262-1:2018 and the following apply.

ISO and IEC maintain terminologicalterminology databases for use in standardization at the following addresses:

— — ISO Online browsing platform: available at https://www.iso.org/obp bd5697e-37fa-42b - a4f-f22a959e9a65/iso-

— IEC Electropedia: available at <u>https://www.electropedia.org/dtr-98</u>

<u>3.1</u>

degrading fault

fault whose characteristics are not constant and degrade over time, that can result in an error or failure when stimulated after degradation exceeds a critical threshold

Note 1 to entry: Permanent and intermittent faults can first manifest as degrading faults. Transient faults do not manifest as degrading faults.

Note 2 to entry: Degrading faults do not create errors or failures until degradation exceeds critical thresholds. The capability to generate an error or failure is related to the current state of degradation.

Note 3 to entry: Degrading faults exhibit abnormal conditions which can cause an error or failure over time. Normal degradation does not exhibit abnormal conditions which are necessary to be classified as a fault. Normal degradation can result in a loss of functionality after expected lifespan has elapsed but cannot be considered a fault as it is not abnormal.

3.2 degrading fault detection time interval -{DFDTI}timespan from the occurrence of a *degrading fault* {[3.1] to its detection

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<u>3.3</u>

degrading fault handling time interval -{DFHTI}

sum of the degrading fault detection time interval (3.2) and the degrading fault reaction time interval (3.4).

Note 1 to entry: The degrading fault handling time interval is a property of a *predictive maintenance* (3.5) related safety mechanism.

Note 2 to entry: The degrading fault handling time interval is considered in addition to the fault handling time interval. See Figure 4.

Note 3 to entry: The timespan from occurrence of a *degrading fault* ((3.1)) until it has the capability to generate an error or failure is the maximum degrading fault handling time interval that can be specified for a predictive maintenance related safety mechanism to support the functional safety concept.

Note 4 to entry: A *degrading fault* **(**[3.1] is covered in a timely manner by the corresponding safety mechanism if there is detection and reaction within the degrading fault handling time interval.

<u>3.4</u>

degrading fault reaction time interval

-(DFRTI)

timespan from the detection of a *degrading fault* $\frac{(3.1)}{(3.1)}$ to reaching a safe state or reaching emergency operation

<u>3.5</u>

predictive maintenance

techniques that are used to detect *degrading faults* (3.1), predict *remaining useful life* (3.6), and react appropriately

Note 1 to entry: Approaches include the use of data driven methods such as machine learning applied locally or on a remote system. Guidance for developing safety related ML systems can be found in ISO/IEC TR 5469-and ISO PAS 8800 12.1.

Note 2 to entry: Prediction of *remaining useful life* <u>((3.6)</u> can be used to replace a faulty element before it can cause an error or failure.

<u>3.6</u>

2

remaining useful life

-RUL

length of time from the present time to the estimated time that the item or element is expected to no longer perform its intended function within desired specifications

[SOURCE: IEEE Std 1856-2017, modified for compliance to ISO directives]

Note 1 to entry: RUL can be estimated using *predictive maintenance* (3.5) or with other approaches.

Note 2 to entry: RUL can be estimated for expected degradation or degradation in the presence of a fault.

[SOURCE: IEEE 1856-2017^[3], modified for compliance to ISO directives]

54_Abbreviated terms

ADAS Advanced Driver Assistance System

ADS Automated Driving System

AI	Artificial Intelligence
BEoL	Back End of Line (sometimes BEOL)
BFR	Base Failure Rate
BIST	Built In Self-Test
BLM	Barrier Layer Material
CHC	Channel Hot Carrier
COTS	Commercial Off The Shelf
DC	- Diagnostic Coverage
DFDTI	Degrading Fault Detection Time Interval
DFHTI	Degrading Fault Handling Time Interval
DFRTI	Degrading Fault Reaction Time Interval
DRAM	Dynamic Random Access Memory
EM	Electromigration
ESD	Electrostatic Discharge (standards.iteh.ai)
FEoL	Front End of Line (sometimes FEOL)
FET	Field Effect Transistor ps://standards.iteh.ai/catalog/standards/sist/6bd5697e-37fa-42bc-aa4f-f22a959c9a65/iso
FDTI	Fault Detection Time Interval dtr-9839
FHTI	Fault Handling Time Interval
FTTI	Fault Tolerant Time Interval
HCI	Hot Carrier Injection
ILD	Inter Layer Dielectric
LFM	Latent Fault Metric
ML	Machine Learning
MoL	Middle of Line (sometimes MOL)
MEoL	Middle End of Line (sometimes MEOL)
MPFDTI	Multiple Point Fault Detection Time Interval
NBTI	Negative Bias Temperature Instability
NVM	Non-Volatile Memory
PCM	Phase Change Memory
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QMSQuility Management SystemRULRemaining Useful LifeStopSoft BreakdowsStopSoft BreakdowsStifeSoft Heating EffectStifeSoft Heating EffectStopSoft Heating EffectStopAdvanced Driver Assistance SystemADASAdvanced Driver Assistance SystemBEFBarcin Laguer Material <t< th=""><th>PHM</th><th>Prognostics and Health Management</th></t<>	PHM	Prognostics and Health Management
Support Support SHE Self Heating Effect SHE Self Heating Effect SHE Self Heating Effect SHE Sites Induced Leakage Current SGC System on Chip SGE System on Chip STDB Single Point Fault Metric TDD Total Indiang Dass Advanced Driver Assistance System Advanced Driver Assistance System ADS Advanced Driver Assistance System ADS Automated Driving System Advanced Driver Assistance System Soft Heating Effect ADS Automated Driving System ADS Automated Driving System BER Base Endurren Step Standard System State System BAS Automated Driving System COTS Generation Time Interval DEG Darading Eault Acartier COTS Generation Time Interval DERT Derading Eault Reaction Time Interval	QMS	Quality Management System
SHE Self Heating Effect SHE Se	RUL	Remaining Useful Life
SH.C. Stress Hiduced Leakage Current SH.C. Stress Higuetion SG. System on Chip SGT System on Chip STPM Single Point Fault Metric TDDB Time Dependent Dielectric Breakdown TDDD Time Dependent Junction Degradation TD Total Ionizing Degradation TD Automated Driving System ADAS Base Failure Rate Base Failure Rate Base Failure Ra	SBD	Soft Breakdown
SM Stress Migration SoC System on Chip SPFM Single Point Fault Metric TDDB Time Dependent Dielectric Breakdown TDDD Time Dependent Junction Degradation TDD Total Ionizing Dese ADAS Advanced Driver Assistance System ADAS Advanced Driver Assistance System ADAS Advanced Driving System (Station Station Sta	SHE	Self Heating Effect
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SPFM Single Point Fault Metric FDDB The Dependent Dielectric Breakdown TDD The Dependent Dielectric Breakdown TDD The Dependent Junction Degradation TD Total Ionizing Dese ADAS Advanced Driver Assistance System ADAS Advanced Driver Assistance System ADAS Automated Driving System AI Artificial Intelligence BEAL Back End of Line (sometimes BEOL) SOYDTR 0839 BER Base Failure Rate Marrier Layer Material dri-0839 COTS Gommercial Off The Shelf DCT Degrading Fault Detectrion Time Interval DETI Degrading Fault Banding Time Interval DETI Degrading Fault Raction Time Interval DETI Degrading Fault Raction Time Interval DETI Degrading Fault Raction Time Interval DETA Bertonzigration EEA Ectromigration EFA Iectromigration TDT Degrading Fault Banding Time Interval DETI Degrading Fault Banding Time Interval EFA Iectromigration		
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TID Total lonizing Dose STANDARDPREVIEW ADAS Advanced Driver Assistance System ADS Automated Driving System ADS Automated Driving System ADS Automated Driving System ADA Artificial Intelligence Beck Back End of Line (sometimes BEOL) SPR Base Failure Rate Barrier Layer Material Antificial Intelligence ELM Barrier Layer Material ChTS Commercial Off The Shelf DCT Diagnostic Coverage DFDTI Degrading Fault Detection Time Interval DFHTI Degrading Fault Detection Time Interval DFRTI Degrading Fault Reaction Time Interval DFRTI Defrad of Line (sometimes FEOL) EEL Font End of Line (sometimes FEOL) EFL <td>TDDB</td> <td>Time Dependent Dielectric Breakdown</td>	TDDB	Time Dependent Dielectric Breakdown
ADASAvanced Driver Assistance SystemADSAuomated Driving System (Standards, site Chara)AIAutificial IntelligenceBackBack End of Line (Sometimes BEOL) (SOODTR 9839)BERBace Failure RateBATHERBarier Layer MaterialAutificial Driving SystemBarier Layer MaterialCMCDiamotel CarrierCMCCommercial Off The ShelfCMCDiamotel CoverageDFTIDigrading Fault Detection Time IntervalDFTIDigrading Fault Panel IntervalDFRTDigrading Fault Radel of Time IntervalESDEctronage RemoryESDEctronage RemoryESDDigrading Fault Radel of Time IntervalFaultDigrading Fault Radel of Time IntervalESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronage RemoryESDEctronag	TDJD	Time Dependent Junction Degradation
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BERBase Failure Rate chair of all of standards / sist / 6bd 56 97 e- 37 fa - 42 bc - a4 f- 122 a 95 90 c a 65 / iso e dimensioned and the standards / bd bc - 37 fa - 42 bc - 34 for 22 a 95 90 c a 64 for 24 for	<u>BEoL</u>	Back End of Line (sometimes BEOL)
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DFHTIDegrading Fault Handling Time IntervalDFRTIDegrading Fault Reaction Time IntervalDRAMDynamic Random Access MemoryEMElectromigrationESDElectrostatic DischargeFEoLFront End of Line (sometimes FEOL)ETBid Effect TransistorFDTIFault Detection Time Interval	<u>DC</u>	Diagnostic Coverage
DFRTIDegrading Fault Reaction Time IntervalDFRMDynamic Random Access MemoryEMElectromigrationESDElectrostatic DischargeFEoLFront End of Line (sometimes FEOL)FETBield Effect TransistorFDTIFault Detection Time Interval	<u>DFDTI</u>	Degrading Fault Detection Time Interval
DRAMDynamic Random Access MemoryEMElectromigrationESDElectrostatic DischargeFEoLFront End of Line (sometimes FEOL)FETField Effect TransistorFDTIFault Detection Time Interval	<u>DFHTI</u>	Degrading Fault Handling Time Interval
EMElectromigrationESDElectrostatic DischargeFEoLFront End of Line (sometimes FEOL)FETField Effect TransistorFDTIFault Detection Time Interval	<u>DFRTI</u>	Degrading Fault Reaction Time Interval
ESDElectrostatic DischargeFEoLFront End of Line (sometimes FEOL)FETField Effect TransistorFDTIFault Detection Time Interval	<u>DRAM</u>	Dynamic Random Access Memory
FEoLFront End of Line (sometimes FEOL)FETField Effect TransistorFDTIFault Detection Time Interval	<u>EM</u>	Electromigration
FET Field Effect Transistor FDTI Fault Detection Time Interval	<u>ESD</u>	<u>Electrostatic Discharge</u>
FDTI Fault Detection Time Interval	<u>FEoL</u>	Front End of Line (sometimes FEOL)
	<u>FET</u>	Field Effect Transistor
FHTI Fault Handling Time Interval	<u>FDTI</u>	Fault Detection Time Interval
	<u>FHTI</u>	Fault Handling Time Interval
FTTI Fault Tolerant Time Interval	<u>FTTI</u>	Fault Tolerant Time Interval
HCI Hot Carrier Injection	<u>HCI</u>	Hot Carrier Injection
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ILD	Inter-Layer Dielectric	
<u>LFM</u>	Latent Fault Metric	
ML	Machine Learning	
<u>MoL</u>	Middle of Line (sometimes MOL)	
<u>MEoL</u>	Middle End of Line (sometimes MEOL)	
<u>MPFDTI</u>	Multiple Point Fault Detection Time Interval	
<u>NBTI</u>	Negative Bias Temperature Instability	
<u>NVM</u>	Non-Volatile Memory	
<u>PCM</u>	Phase Change Memory	
<u>PHM</u>	Prognostics and Health Management	
RUL	Remaining Useful Life	
<u>SBD</u>	<u>Soft Breakdown</u>	
<u>SHE</u>	Self-Heating Effect	
<u>SILC</u>	Stress-Induced Leakage Current	
<u>SM</u>	System on Chin Chin Chin STANDARD PREVIEW	
<u>SoC</u>	System on Chip CHI S LANDARD I REVIEW	
<u>SPFM</u>	Single Point Fault Metric	
<u>TDDB</u>	Single Point Fault Metric Time Dependent Dielectric Breakdown	
<u>TDJD</u>	Time Dependent Junction Degradation	
TID	Total Ionizing Dose ISO/DTR 9839	
65 Literature survey of degrading faults		

65 Literature survey of degrading faults

5.1 General

This technical report<u>d</u>ocument reviews many technical documents to summarize the current state of the art understanding of degrading faults in industry standards and technical publications.

+ Terminology in the referenced publications and standards is not always aligned to ISO 26262 terms NOTE and definitions of the ISO 26262 series. When referencing publications and standards, the terminology of the referenced work is used.

6.1<u>5.2</u>Degrading faults in industry standards

6.1.15.2.1 JEDEC JEP122H

The JEDEC Solid State Technology Association is a semiconductor industry trade association and standardization body. JEDEC has over 300 companies as members and publishes electronics standards on a wide variety of topics.

The-JEDEC JEP122H-standard is the latest revision on JEDEC's standard for "Failure Mechanisms and Models for Semiconductor Devices," last updated in 2016. The standard describes eighteen different failure mechanisms, classifying them as being related to the die <u>Front Endfront end</u> of <u>Lineline</u> (FEoL), die <u>Back Endback end</u> of <u>Lineline</u> (BEoL), or packaging. Models are provided for estimating the rates of degradation per failure mode. The information provided in JEP122H is validated by a team of reliability experts from the SEMATECH/ISMI Reliability Council and supported by extensive references to technical publications.