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Abstract

This presentation follows the ideas presented in the blog post “Testing Emergency Stop Systems” [7], from the Machinery Safety 101 blog. The presentation covers the basics of emergency stop functions, explores the fundamentals of risk and functional safety as it relates to the application of emergency stop systems, finally looking at the testing requirements in ISO 13849-1 [19] and ISO 14119 [21].

Keywords

Emergency stop, test, complementary protective measures, risk, functional safety.


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POLL 1: HOW MANY HAVE NEEDED TO TEST?
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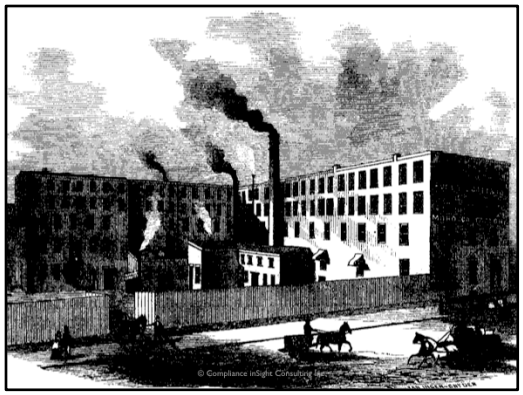

Let's talk about what Emergency Stop actually means. If we look at the definitions in ISO 12100 we find:

> ***emergency stop***
> ***emergency stop function***
> *function which is intended to avert arising or reduce existing hazards to persons, damage to machinery or to work in progress, and be initiated by a single human action*
>
> *NOTE ISO 13850 gives detailed provisions.*
>
> *[1, 3.40]*

The word "emergency" comes from the root "emerge", meaning:

> a serious, unexpected, and often dangerous situation requiring immediate action: *your quick response in an emergency could be a lifesaver* | *times of emergency*.
> - [as modifier] arising from or needed or used in an emergency: *an emergency exit*.
> - a person with a medical condition requiring immediate treatment.
>
> ORIGIN mid 17th cent.: from medieval Latin ***emergentia***, from Latin ***emergere 'arise, bring to light'***.
> [2]

Emergency stop systems are therefore designed to deal with serious, **unexpected**, and often dangerous situations **requiring immediate action**. They help to **avert arising or reduce existing hazards** to persons, damage to machinery or to work in progress, and **are initiated by a single human action**.

Complementary Protective Measures

Definitions

Protective measures which are neither inherently safe design measures, nor safeguarding (implementation of guards and/or protective devices), nor information for use, could have to be implemented as required by the intended use and the reasonably foreseeable misuse of the machine. [1, 6.3.5.1]

Protective measures that are neither inherently safe design measures, nor safeguarding (implementation of guards and/or protective devices), nor information for use may have to be implemented as required by the intended use and the reasonably foreseeable misuse of the machine. Such measures shall include, but not be limited to,

(a) emergency stop;
(b) means of rescue of trapped persons; and
(c) means of energy isolation and dissipation.
[5, 6.2.3.5.3]

Following the Hierarchy of Controls, hazards must be eliminated, or hazardous materials substituted in processes, then design controls, i.e., guards, safeguarding devices, and complementary protective measures implemented, before warnings and administrative controls can be applied. Complementary Protective Measures (CPM) are called “complementary” because they complement the primary safeguards: physical guards and safeguarding devices. CPM are the back-up to primary safeguards in case of failure, or for situations not foreseen by the manufacturer or designer. They are not primary safeguards.

Primary safeguards are designed to prevent injury automatically. They fulfill this function by preventing access to hazards, or by changing the characteristics of the hazard so that no harm is possible, i.e., removing electrical power from bare components inside an electrical enclosure before the door can be opened, or prevent approach beyond a safe distance.

CPM are intended to help avoid or limit harm in situations where the primary safeguards are ineffective for any reason. Remember that a problem, or an “emergent situation”, is already in

Emergency Stop Function

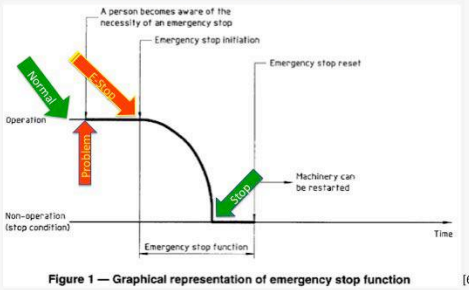

Figure 1 — Graphical representation of emergency stop function [6]

Why Test?

Emergency stop systems are manually triggered, and usually infrequently used. The lack of use means that functional testing of the system doesn't happen in the normal course of operation of the machinery. Some types of faults may occur and remain undetected until the system is actually used, i.e., contact blocks falling off the back of the operator device. Failure at that point may be catastrophic, since by implication the primary safeguards have already failed, and thus the failure of the backup eliminates the possibility of avoiding or limiting harm. [7]

Keep in mind that there are many ways to test, including some basic ones mentioned in “Checking Emergency Stop Systems” [8], and more formal verification methods discussed in standards like ISO 13849-1 [9], ISO 13849-2 [10], IEC 62061 [11], and IEC 61508 [12].

Is Emergency Stop Required?

The general answer to this question is “NO”, however, there are some reasons that lead people to think otherwise.

1) Most machines have emergency stop devices, even if there is no ‘formal’ reason why.
2) Legislation in a few jurisdictions require an emergency stop system on every machine.
3) An error in CSA Z432 leads people to believe that the standard requires all manual control stations to have an emergency stop device. This is incorrect.

Modern machinery safety standards, like ISO 12100, require designers to decide if an emergency stop system will be useful for avoiding or limiting harm to workers using the machinery, or to the machine itself. Risk assessment is used as the tool to determine this requirement. If an emergency stop device cannot reduce the severity of injury to people, or damage to the machine itself, it has no function and is not required.


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POLL2 : DO YOU USE RISK ASSESSMENT?
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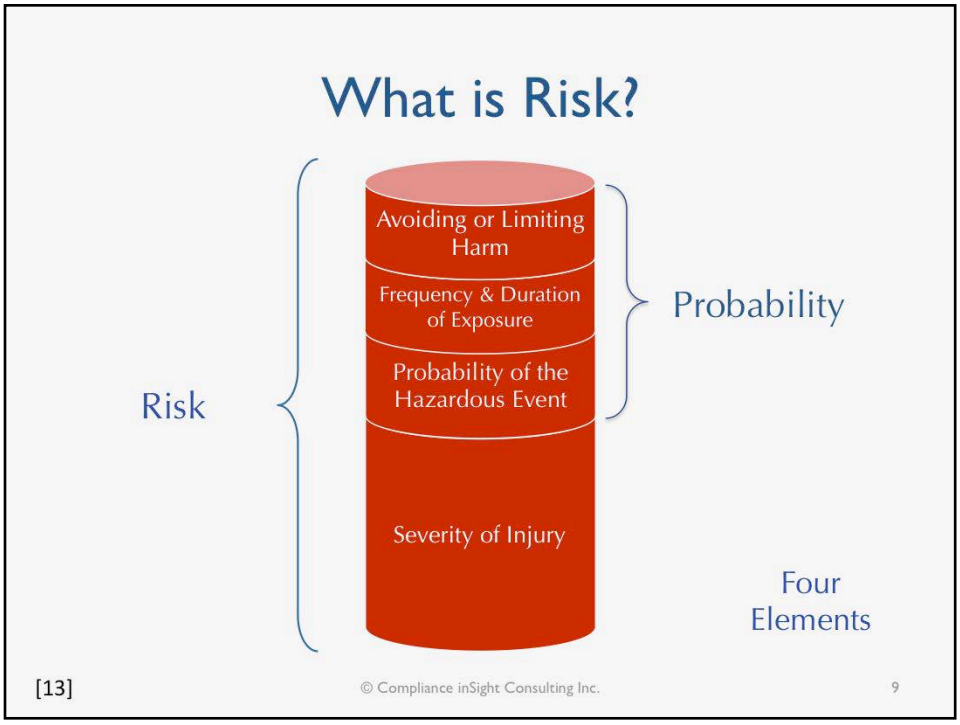

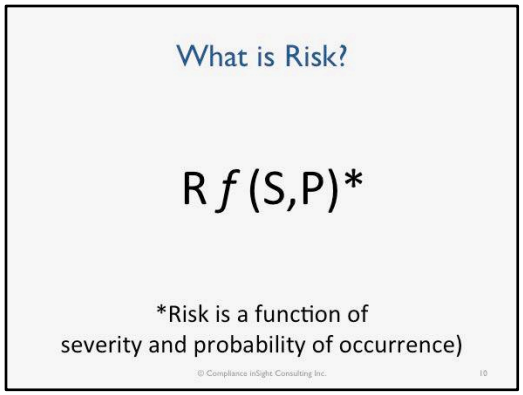
What is Risk?
R f (S,P)*
*Risk is a function of
severity and probability of occurrence)
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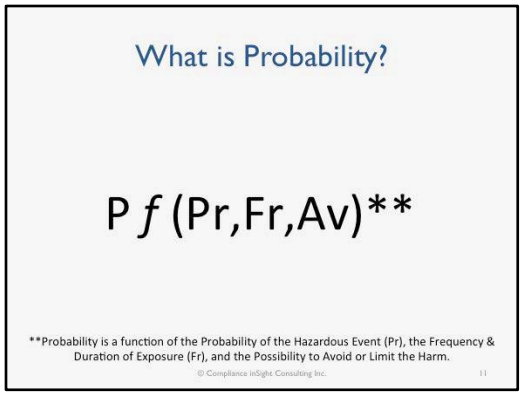
What is Probability?
P ƒ (Pr,Fr,Av)**
**Probability is a function of the Probability of the Hazardous Event (Pr), the Frequency & Duration of Exposure (Fr), and the Possibility to Avoid or Limit the Harm.
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Matrix Scoring Tool

	Probability of Injury Class [Pr x (Fr+Av)]				
Severity	3-10	11-20	21-30	31-40	41-50
4	12-40	44-80	84-120	124-160	164-200
3	9-30	33-60	63-90	93-120	123-150
2	6-20	22-40	42-60	62-80	82-100
1	3-10	11-20	21-30	31-40	41-50

Approximate Risk Ranges				
1-10	11-20	30-100	101-150	151-200
Very Low	Low	Moderate	High	Very High

[14]

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Severity of Injury (Se)

Consequences	*Severity (Se)*
Irreversible: death, losing an eye or arm	4
Irreversible: broken limb(s), losing a finger(s)	3
Reversible: requiring attention from a medical practitioner	2
Reversible: requiring first aid	1

[11]

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Probability of the Hazardous Event (Pr)

Probability of Occurrence	*Probability (Pr)*
Very high*	5
Likely	4
Possible	3
Rarely	2
Negligible	1

[11]

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Frequency & Duration of Exposure (Fr)

Frequency of Exposure	*Duration >10 min*
≤ 1 h	5
1 h to ≤ 1 day	5
> 1 day ≤ 2 weeks	4
> 2 weeks ≤ 1 year	3
> 1 year	2

[11]

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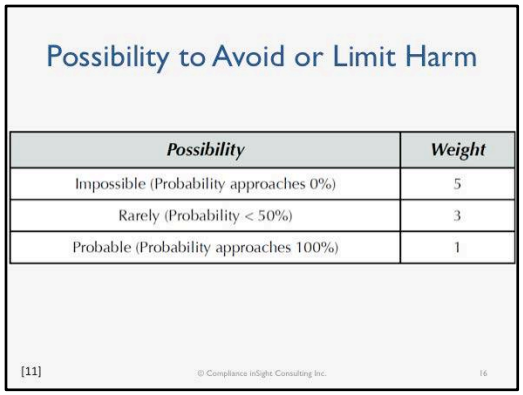

Possibility to Avoid or Limit Harm

Possibility	*Weight*
Impossible (Probability approaches 0%)	5
Rarely (Probability < 50%)	3
Probable (Probability approaches 100%)	1

[11]

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Calculating Risk Score

$$R = Se \bullet [Pr \bullet (Fr + Av)]$$

- Machine guard interlock fails – Hazard is exposed drive chain.
- Example Score
  - Se = 3 [Irreversible: broken limb(s), losing finger(s)]
  - Pr = 5 [Very high]
  - Fr = 3 [> 2 weeks ≤ 1 year]
  - Av = 5 [Impossible (Probability approaches 0%)]
- Substituting

$$R = 3 \bullet [5 \bullet (3+5)] = 120$$

 [14]


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POLL 3: WHAT RISK PARAMETER CAN BE AFFECTED BY E-STOP?
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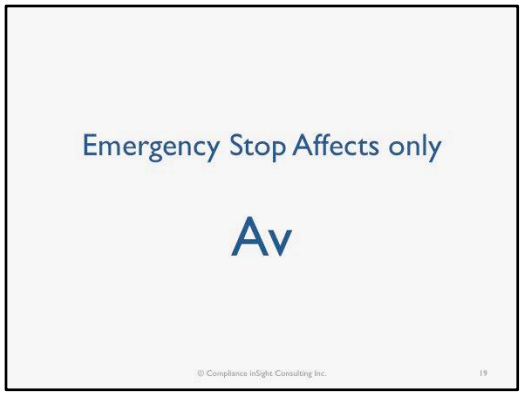
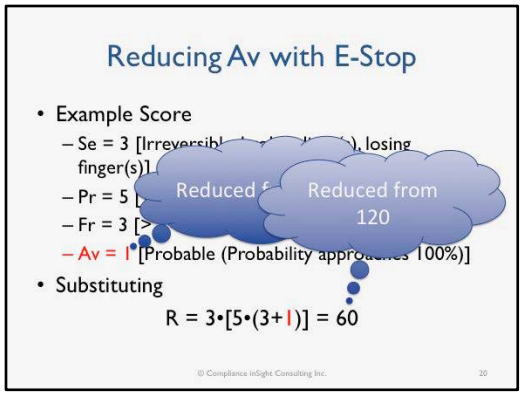


Affecting Risk using Emergency Stop

Remember that complementary protective measures are designed to "…avert arising or reduce existing hazards to persons, damage to machinery or to work in progress…"? If we consider that the reason the emergency stop has been activated is that either a) the primary safeguards have failed, or b) an unforeseen event is in progress, then we can reasonably assume the following states for the four elements of risk (Se, Pr, Fr, and Av):

Se ≥ 2 (some significant degree of injury is occurring, or damage to the machinery)
Pr = 1, since the event is in progress (human awareness of the problem is required)
Fr = doesn't matter
Av – is the only factor that can be affected

Se may or may not be affected eventually, depending on the characteristics of the hazard.


Reducing Av with E-Stop
• Example Score
– Se = 3 [Irreversib
finger(s)]
– Pr = 5 [
– Fr = 3 [>
– Av = 1 [Probable (Probability appro
• Substituting
R = 3•[5•(3+1)] = 60
Reduced f
Reduced from 120
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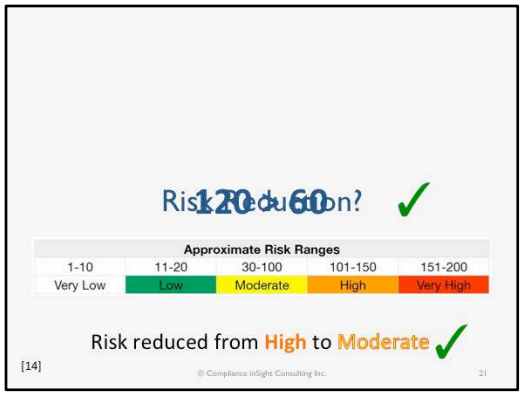
Risk reduction?
120
60
Approximate Risk Ranges
1-10
11-20
30-100
101-150
151-200
Very Low
Low
Moderate
High
Very High
Risk reduced from High to Moderate
[14]
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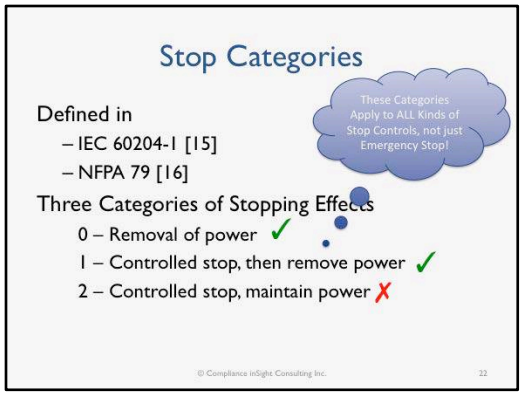
Stop Categories
These Categories Apply to ALL Kinds of Stop Controls, not just Emergency Stop!
Defined in
– IEC 60204-1 [15]
– NFPA 79 [16]
Three Categories of Stopping Effects
0 – Removal of power ✓
1 – Controlled stop, then remove power ✓
2 – Controlled stop, maintain power ✗
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REQUIREMENTS
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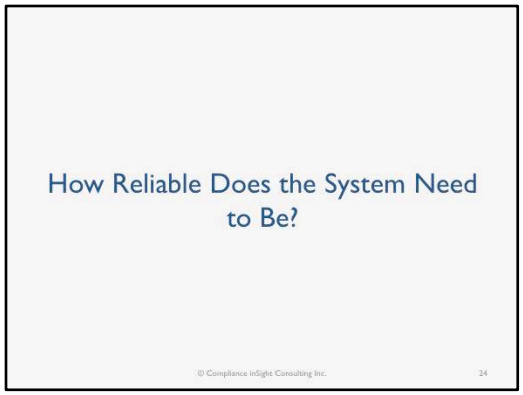


Definitions

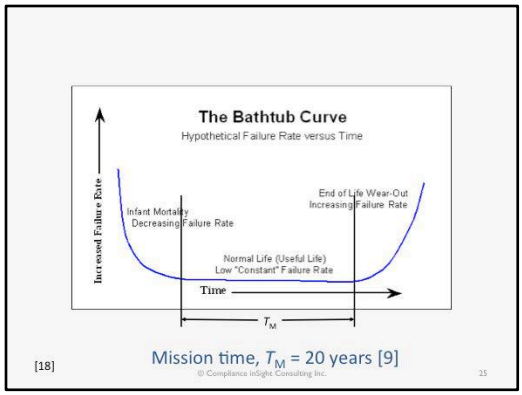
reliability
adjective
consistently good in quality or performance; able to be trusted: *a reliable source of information*.
noun
a person or thing with trustworthy qualities: *the supporting cast includes old reliables like Mitchell*.
[2]

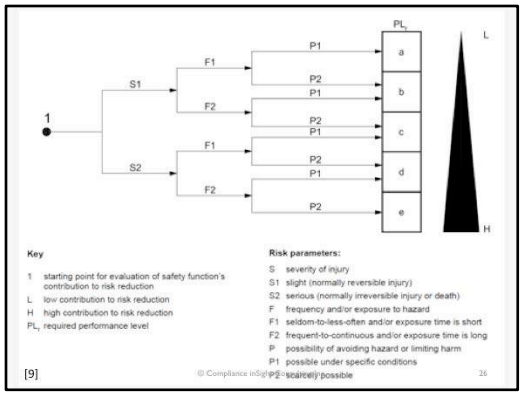
functional safety
part of the overall safety relating to the Equipment Under Control (EUC) and the EUC control system which depends on the correct functioning of the Electrical/Electronic/Programmable Electronic safety-related systems, other technology safety-related systems and external risk reduction facilities
[17. 3.1.9]

NOTE: The functional safety definition is also extended to include mechanical fluidic control systems as well as electrically based systems.

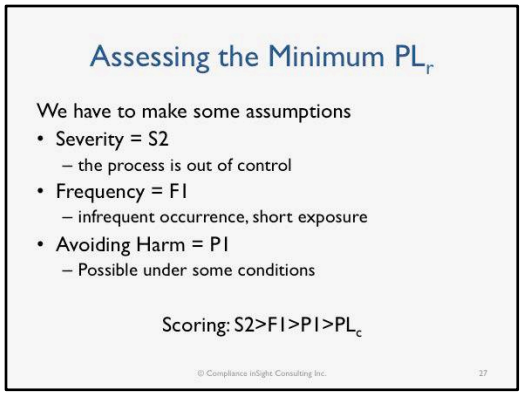
Author's Note: ISO 13850, 3rd edition, will provide guidance on the minimum Performance Level [9] required from emergency stop systems when it is published in 2016.

mission time
T_M
period of time covering the intended use of the Safety Related Parts of the Control System (SRP/CS)
[9, 3.1.28]


The Bathtub Curve
Hypothetical Failure Rate versus Time
Increased Failure Rate
Infant Mortality
Decreasing Failure Rate
End of Life Wear-Out
Increasing Failure Rate
Normal Life (Useful Life)
Low "Constant" Failure Rate
Time
T_M
Mission time, T_M = 20 years [9]
[18]


PL
1
S1
S2
F1
F2
P1
P2
a
b
c
d
e
L
H
Key
1 starting point for evaluation of safety function's contribution to risk reduction
L low contribution to risk reduction
H high contribution to risk reduction
PL, required performance level
Risk parameters:
S severity of injury
S1 slight (normally reversible injury)
S2 serious (normally irreversible injury or death)
F frequency and/or exposure to hazard
F1 seldom-to-less-often and/or exposure time is short
F2 frequent-to-continuous and/or exposure time is long
P possibility of avoiding hazard or limiting harm
P1 possible under specific conditions
P2 scarcely possible

[9]


Assessing the Minimum PL_r
We have to make some assumptions
• Severity = S2
– the process is out of control
• Frequency = F1
– infrequent occurrence, short exposure
• Avoiding Harm = P1
– Possible under some conditions
Scoring: S2>F1>P1>PL_c
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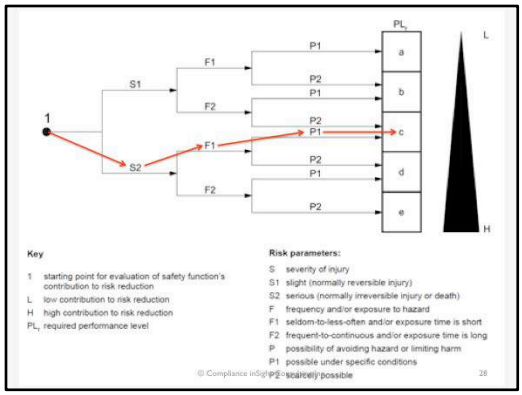
PL
1
S1
S2
F1
F2
P1
P2
a
b
c
d
e
L
H
Key
1 starting point for evaluation of safety function's contribution to risk reduction
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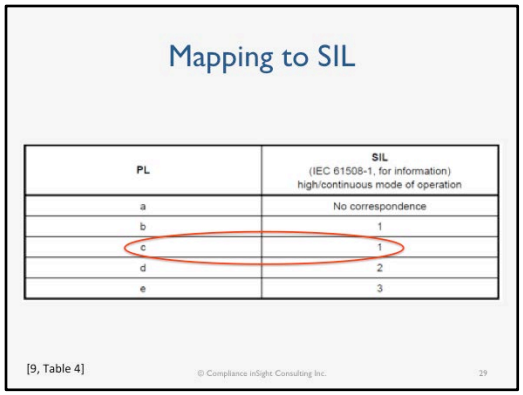
F frequency and/or exposure to hazard
F1 seldom-to-less-often and/or exposure time is short
F2 frequent-to-continuous and/or exposure time is long
P possibility of avoiding hazard or limiting harm
P1 possible under specific conditions
P2 scarcely possible
28


Mapping to SIL
PL
SIL
(IEC 61508-1, for information)
high/continuous mode of operation
a
No correspondence
b
1
c
1
d
2
e
3
[9, Table 4]
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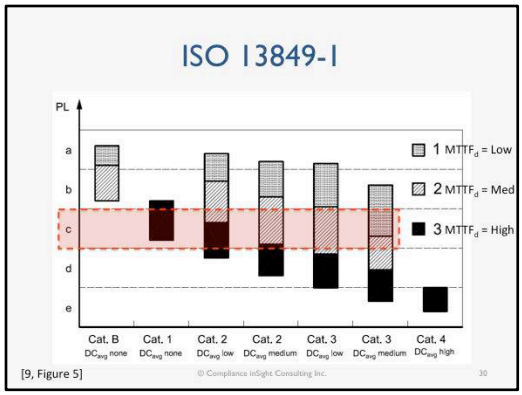


Terms

diagnostic coverage
DC
measure of the effectiveness of diagnostics, which may be determined as the ratio between the failure rate of detected dangerous failures and the failure rate of total dangerous failures

NOTE 1 Diagnostic coverage can exist for the whole or parts of a safety-related system. For example, diagnostic coverage could exist for sensors and/or logic system and/or final elements.

NOTE 2 Adapted from IEC 61508-4:1998, definition 3.8.6.
[9, 3.1.26]

performance level
PL
discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions
[9, 3.1.23]

mean time to dangerous failure
MTTFd
expectation of the mean time to dangerous failure

NOTE Adapted from IEC 62061:2005, definition 3.2.34.
[9, 3.1.2.5]

failure
termination of the ability of an item to perform a required function

NOTE 1 After a failure, the item has a fault.
NOTE 2 “Failure” is an event, as distinguished from “fault”, which is a state.
NOTE 3 The concept as defined does not apply to items consisting of software only. [IEC 60050–191:1990, 04-01]
NOTE 4 Failures which only affect the availability of the process under control are outside of the scope of this part of ISO 13849.
[9, 3.1.4]

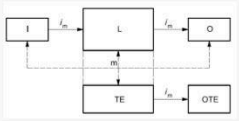
dangerous failure
failure which has the potential to put the Safety Related Parts of the Control System (SRP/CS) in a hazardous or fail-to-function state

NOTE 1 Whether or not the potential is realized can depend on the channel architecture of the system; in redundant systems a dangerous hardware failure is less likely to lead to the overall dangerous or fail-to-function state.
NOTE 2 Adapted from IEC 61508-4:1998, definition 3.6.7.
[9, 3.1.5]

Category 1 & 2 Architectures

Key

l_m interconnecting means
I input device, e.g. sensor
L logic
O output device, e.g. main contactor

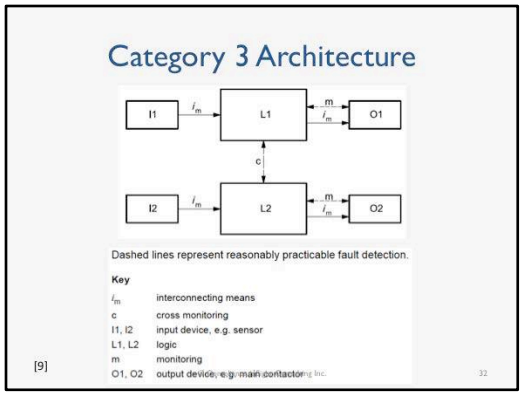


Dashed lines represent reasonably practicable fault detection.

Key

l_m interconnecting means
I input device, e.g. sensor
L logic
m monitoring
O output device, e.g. main contactor
TE test equipment
OTE output of TE

[9]



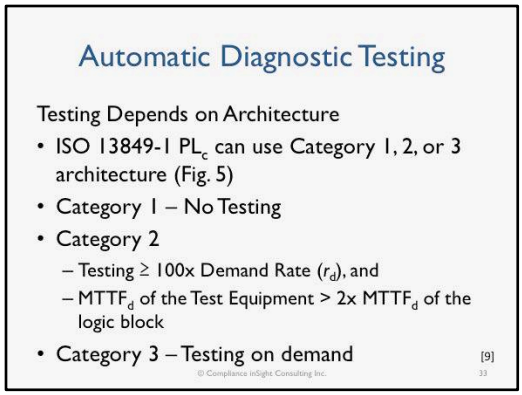
Category 1 is single channel, and does not include any diagnostics. A single fault can cause the loss of the safety function (i.e., the machine still runs even though the e-stop button is pressed). Using **Category 1**, the reliability of the design is based on the use of highly reliable components and well-tried safety principles. This approach can fail to danger.

Category 2 adds some diagnostic capability to the basic single channel configuration, and does not require the use of "well-tried" components. This approach can also fail to danger.

Category 3 architecture adds a redundant channel, and includes diagnostic coverage. Category 3 is not subject to failure due to single faults and is called "single-fault tolerant". This approach is less likely to fail to danger, but still can in the presence of multiple, undetected, faults.

A key concept in reliability is the "fault". This can be any kind of defect in hardware or software that results in unwanted behaviour or a failure. Faults are further broken down into dangerous and safe faults, meaning those that result in a dangerous outcome, and those that do not. Finally, each of these classes is broken down into detectable and undetectable faults. I'm not going to get into the mathematical treatment of these classes, but my point is this: there are undetectable dangerous faults. These are faults that cannot be detected by built-in diagnostics. As designers, we try to design the control system so that the undetectable dangerous faults are extremely rare, ideally the probability should be much less than once in the lifetime of the machine.

What is the lifetime of the machine? The standards writers have settled on a default lifetime of 20 years, thus the answer is that undetectable dangerous failures should happen much less than once in twenty years of 24/7/365 operation. So why does this matter? Each architectural category has different requirements for testing. The test rates are driven by the "Demand Rate". The Demand Rate is defined in [9].



Definition

demand rate

r_d

frequency of demands for a safety-related action of the SRP/CS

[10, 3.1.30]

Test Requirements for Category 2

Safety Related Parts of Control Systems (SRP/CS) of category 2 shall be designed so that their function(s) are checked at suitable intervals by the machine control system. The check of the safety function(s) shall be performed

- at the machine start-up, and
- prior to the initiation of any hazardous situation, e.g. start of a new cycle, start of other movements, and/or periodically during operation if the risk assessment and the kind of operation shows that it is necessary.

The initiation of this check may be automatic. Any check of the safety function(s) shall either

- allow operation if no faults have been detected, or
- generate an output which initiates appropriate control action, if a fault is detected.

For the designated architectures, the following typical assumptions are made:

- mission time, 20 years (see Clause 10);
- constant failure rates within the mission time;
- for category 2, demand rate <= 1/100 test rate;
- for category 2, $MTTF_{d,TE}$ larger than half of $MTTF_{d,L}$.

NOTE When blocks of each channel cannot be separated, the following can be applied: $MTTF_d$ of the summarized test channel (TE, OTE) larger then half $MTTF_d$ of the summarized functional channel (I, L, O).

PL_c can be accomplished using any of three architectures: Category 1, 2, or 3. If you are unsure about what these architectures represent, have a look at my series covering this topic [20].

Category 1 has no diagnostics, so there is no guidance in [9] to help us out with these systems.

Category 3 is single fault tolerant, so as long as we don't have multiple undetected faults we can count on the system to function and to alert us when a single fault occurs; remember that the automatic tests may not be able to detect every fault. This is where the "proof test" comes in. What is a proof test? To find a definition for proof test, we have to look at IEC 61508-4 [11]:

> *3.8.5*
> ***proof test***
> *periodic test performed to detect failures in a safety-related system so that, if necessary, the system can be restored to an "as new" condition or as close as practical to this condition*
>
> *NOTE - The effectiveness of the proof test will be dependent upon how close to the "as new" condition the system is restored. For the proof test to be fully effective, it will be necessary to detect 100 % of all dangerous failures. Although in practice 100 % is not easily achieved for other than low-complexity E/E/PE safety-related systems, this should be the target. As a minimum, all the safety functions which are executed are checked according to the E/E/PES safety requirements specification. If separate channels are used, these tests are done for each channel separately.*

The 20-year life cycle assumption used in the standards also applies to proof testing. Machine controls are assumed to get at least one proof test in their life time. The proof test should be designed to detect faults that the automatic diagnostics cannot detect. Proof tests are also conducted after major rebuilds and repairs to ensure that the system operates correctly.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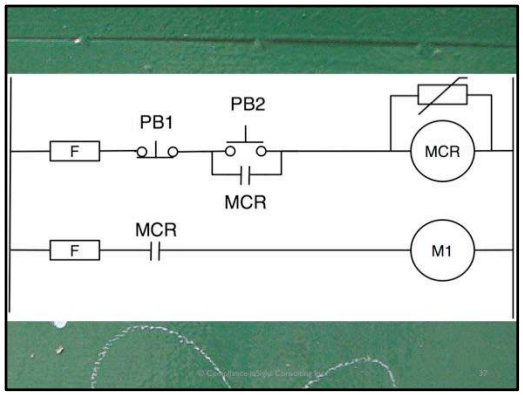
The Good News is that modern safety relays and safety PLCs look after the testing for you, so if you have one of these systems, you're already covered for the automatic diagnostic parts of the test requirements!



The Bad News

Ok, so now for the bad news: If you have a circuit that looks like this, it's a single-channel architecture. Depending on the component selections, it could be ISO 13849-1 Category B)for Basic), or Category 1. In either case, there is NO testing built in.

If the circuit meet Category 1 requirements, then it may be able to achieve PL_c. Only some functional safety calculations will tell.

Image: Bad News [19], Circuit [8]

If you know the architecture of the emergency stop control system, you can determine the test rate based on the demand rate. It would be considerably easier if the standards just gave us some minimum test rates for the various architectures.

One standard, ISO 14119 [21] on interlocks does just that. Admittedly, this standard does not include emergency stop functions within its scope, as its focus is on interlocks, but since interlocking systems are more critical than the complementary protective measures that back them up, it would be reasonable to apply these same rules. Looking at the clause on Assessment of Faults, [9, 8.2], we find this guidance:

> *For applications using interlocking devices with automatic monitoring to achieve the necessary diagnostic coverage for the required safety performance, a functional test (see IEC 60204-1:2005, 9.4.2.4) can be carried out every time the device changes its state, e.g. at every access. If, in such a case, there is only infrequent access, the interlocking device shall be used with additional measures, because between consecutive functional tests the probability of occurrence of an undetected fault is increased.*
>
> *When a manual functional test is necessary to detect a possible accumulation of faults, it shall be made within the following test intervals:*
>
> - *at least every month for PL_e with Category 3 or Category 4 (according to ISO 13849-1) or SIL 3 with HFT (hardware fault tolerance) = 1 (according to IEC 62061);*
> - *at least every 12 months for PL_d with Category 3 (according to ISO 13849-1) or SIL 2 with HFT (hardware fault tolerance) = 1 (according to IEC 62061).*
>
> *NOTE It is recommended that the control system of a machine demands these tests at the required intervals e.g. by visual display unit or signal lamp. The control system should monitor the tests and stop the machine if the test is omitted or fails.*

In the preceding, HFT=1 is equivalent to saying that the system is single-fault tolerant.
This leaves us then with recommended test frequencies for Category 2 and 3 architectures in PL_c, PL_d, and PL_e, or for SIL 2 and 3 with HFT=1. We still don't have a test frequency for PL_c, Category 1 systems. There is no explicit guidance for these systems in the standards.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