Introduction to safety engineering

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January 12, 2017
Outline

1. What is safety?
2. System safety
3. Standards
4. Example
5. Achieving safety
   - Generic safety process
   - Safety case
   - Safety integrity
   - Miscellaneous
What is safety?

Outline

1. What is safety?
2. System safety
3. Standards
4. Example
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   - Generic safety process
   - Safety case
   - Safety integrity
   - Miscellaneous
What is safety?

Classical definition
Freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.

Alternative definition
Safety = Managing complexity without going crazy and ensuring completeness and consistency.
What is safety?

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### Classical definition

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### Alternative definition

Safety = Managing complexity without going crazy and ensuring completeness and consistency.
What is safety?

Safety vs. security

- Safety = protection of environment from the system.
- Security = protection of the system from the environment.

Source: TU Wien
What is safety?

Safety vs. security

- Safety = protection of environment from the system.
- Security = protection of the system from the environment.
- But, environment is a system as well. So both safety and security represent a protection of one system from another...
What is safety?

What kind of system we have in mind?

- In general any system that can cause death, injury, . . .
- In this course we deal mainly with software systems and also with electric/electronic systems.
- But safety is much broader term – you will see later.
So you want to develop safe systems?
How to start with that?

- Hard to say
- Safety is not a set of facts
- It is a wide range of knowledge that needs to be related
- This relation happens at multiple (all) levels
- Everybody starts with naive concepts of safety
Outline

1 What is safety?

2 System safety

3 Standards

4 Example

5 Achieving safety
   ▪ Generic safety process
   ▪ Safety case
   ▪ Safety integrity
   ▪ Miscellaneous
System safety

The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]
The application of **engineering and management** principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]

Why management? Because experience has shown that many failures are not due to systems being built the wrong way but actually the **wrong systems having been built**. With other words management is there to make sure that engineering actually is doing the right thing (in all aspects).
The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]

- Safety is not checklist
- It is necessary to interpret the principles
The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]

- What is acceptable risk?
- 100% guarantee is never achieved!
The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, *within the constraints* of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]

- Perfect technical solution is not always possible.
The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]

- When we are done with system safety?
- When it went through all life-cycles stages:
  - Initial requirements
  - Design
  - Implementation
  - Service
  - Decommissioning
  - Disposal
The application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle. [DOD MIL-STD 882D Clause 3.2.13]
What is a system?

**DOD MIL-STD 882D Clause 3.2.12:**
An integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective.

**ECSS-P-001A Rev A 1997 Clause 3.144:**
System: Set of interdependent elements constituted to achieve a given objective by performing a specified function (IEC 50:1992).

**NOTE:** The system is considered to be separated from the environment and other external systems by an imaginary surface which cuts the links between them and the considered system. Through these links, the system is affected by the environment, is acted upon by external systems, or acts itself on the environment or the external systems.
What is a system?

**IEC 61508-1 3.3.1:**
Set of elements which interact according to a design, where an element of a system can be another system, called a subsystem, which may be a controlling system or a controlled system and may include hardware, software and human interaction.

**MOD 00-58 Clause 4.1.23:**
A bounded physical entity that achieves in its environment a defined objective through interactions of its part.

**NASA SP 6105 Rev1 2007:**
A construct or collection of different elements that together produce results not obtainable by the elements alone.
What is a system?

**RTCA DO 178C Annex B:**
A collection of hardware and software components organized to accomplish a specific function or set of functions.

**SAE ARP 4754a RevA 2010:**
A combination of inter-related items arranged to perform a specific function(s)
Is terminology important?

- Safety is about communication at all levels.
  - engineers, managers, computer networks
- Goal: Establish common understanding of concepts.
- Implementation = transformation of concepts to actions
- If concepts differ but actions are coupled $\Rightarrow$ problems
- Terminology is not about finding the “true meaning”
- It teaches us to be sensitive to imprecision when communicating abstract concepts
- Systems safety is about mitigation of problems arising from application of non-matching concepts
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If you don’t understand anything in this lecture, just ask me!
Part of the overall safety [...] that depends on the correct functioning of the electrical and/or electronic and/or programmable electronic safety-related systems and other risk reduction measures.

[IEC 61508-4/Ed.2, clause 3.1.12]
Functional safety

Part of the overall safety […] that depends on the correct functioning of the electrical and/or electronic and/or programmable electronic safety-related systems and other risk reduction measures.

[IEC 61508-4/Ed.2, clause 3.1.12]

- Safety-related system (element): element which has the potential to contribute to the violation of or achievement of a safety goal.
  [ISO 26262-1:2010(E), 1.113]

- Example: fire alarm in a building, seat belt in a car
Standards

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   - Miscellaneous
What are safety standards?

Standards are created because there is a need for them. By industry, governments or international bodies.

The need arises because something went wrong without the standard (incompatibility etc.).

Standards are here to help you.

They contain useful knowledge that is hard (or painful) to gain. The knowledge was gained from failures in the past.

Safety standards should not be followed without thinking.
Compliance with this Defence Standard shall not in itself relieve any person from any legal obligations imposed upon them.

This standard has been devised solely for the use of the Ministry of Defence (MOD) and its contractors in the execution of contracts for the MOD. To the extent permitted by law, the MOD hereby excludes all liability whatsoever and howsoever arising (including, but without limitation, liability resulting from negligence) for any loss or damage however caused when the standard is used for any other purpose.
Hierarchy of safety standards

Safety regulations, norms and standards

- **IEC 61800**
  - Electric-drive

- **IEC 61511**
  - Process-industry

- **RTCA DO-178B EUROCAE ED-12B (Software)**
- **RTCA DO-254 (Hardware)**
- **CAP 670**
- **EATMP**
- **ESARRs**

- **IEC 61513**
  - Nuclear power

- **ISO/DIS 26262**
  - Automotive

- **IEC 60601**
  - IEC 80001
  - Medicine

- **EN/IEC 62061**
- **EN/ISO 13849**
- **EN/ISO 14121**
- **EN/ISO 12100**

- **MIL STD 882D**
- **Def Stan 00-56**

- **CENELEC EN 50126**
- **CENELEC EN 50128**
- **CENELEC EN 50129**
- **CENELEC EN 50159**

Source: FH Campus Wien
Hierarchy of safety standards

MIL-STD-882E – high-level standard

Section 4 gives good overview of system safety! We will see this later.

IEC 61508 – generic functional safety standard

This International Standard sets out a **generic approach** for all safety lifecycle activities for systems comprised of electrical and/or electronic and/or programmable electronic (E/E/PE) elements that are used to perform safety functions. This unified approach has been adopted in order that a rational and consistent technical policy be developed for all electrically-based safety-related systems. A major **objective is to facilitate the development of application sector standards.**

... enables application sector international standards, dealing with E/E/PE safety-related systems, to be developed; the development of application sector international standards, within the framework of this standard, **should lead to a high level of consistency** (for example, of underlying principles, terminology etc.) both within application sectors and across application sectors; this will have **both safety and economic benefits**;
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Example: Ariane 5 Flight 501 Failure
4 June 1996
What happened?

- H0+36.7 seconds: Failure of the back-up Inertial Reference System followed immediately by failure of the active Inertial Reference System;
- swivelling into the extreme position of the nozzles of the two solid boosters and, slightly later, of the Vulcain engine, causing the launcher to veer abruptly;
- self-destruction of the launcher correctly triggered by rupture of the links between the solid boosters and the core stage.

- Loss: US $ 370 million

Source: http://www.di.unito.it/~damiani/ariane5rep.html
The launcher started to disintegrate at about H0 + 39 seconds because of high aerodynamic loads due to an angle of attack of more than 20 degrees that led to separation of the boosters from the main stage, in turn triggering the self-destruct system of the launcher.
Failure event chain

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- This angle of attack was caused by full nozzle deflections of the solid boosters and the Vulcain main engine.
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- This angle of attack was caused by full nozzle deflections of the solid boosters and the Vulcain main engine.

- These nozzle deflections were commanded by the On-Board Computer (OBC) software on the basis of data transmitted by the active Inertial Reference System (SRI 2). Part of these data at that time did not contain proper flight data, but showed a diagnostic bit pattern of the computer of the SRI 2, which was interpreted as flight data.
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- The reason why the active SRI 2 did not send correct attitude data was that the unit had declared a failure due to a software exception.
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The reason why the active SRI 2 did not send correct attitude data was that the unit had declared a failure due to a software exception.

The OBC could not switch to the back-up SRI 1 because that unit had already ceased to function during the previous data cycle (72 milliseconds period) for the same reason as SRI 2.
The internal SRI software exception was caused during execution of a data conversion from 64-bit floating point to 16-bit signed integer value. The floating point number which was converted had a value greater than what could be represented by a 16-bit signed integer. This resulted in an Operand Error. The data conversion instructions (in Ada code) were not protected from causing an Operand Error, although other conversions of comparable variables in the same place in the code were protected.
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The error occurred in a part of the software that only performs alignment of the strap-down inertial platform. This software module computes meaningful results only before lift-off. As soon as the launcher lifts off, this function serves no purpose.
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The error occurred in a part of the software that only performs alignment of the strap-down inertial platform. This software module computes meaningful results only before lift-off. As soon as the launcher lifts off, this function serves no purpose.

The alignment function is operative for 50 seconds after starting of the Flight Mode of the SRIs which occurs at H0 - 3 seconds for Ariane 5. Consequently, when lift-off occurs, the function continues for approx. 40 seconds of flight. This time sequence is based on a requirement of Ariane 4 and is not required for Ariane 5.
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The Operand Error occurred due to an unexpected high value of an internal alignment function result called BH, Horizontal Bias, related to the horizontal velocity sensed by the platform. This value is calculated as an indicator for alignment precision over time.
Failure event chain (cont.)

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- The Operand Error occurred due to an unexpected high value of an internal alignment function result called BH, Horizontal Bias, related to the horizontal velocity sensed by the platform. This value is calculated as an indicator for alignment precision over time.

- The value of BH was much higher than expected because the early part of the trajectory of Ariane 5 differs from that of Ariane 4 and results in considerably higher horizontal velocity values.
Achieving safety

Outline

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4 Example

5 Achieving safety
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   - Miscellaneous
How to achieve safety?

By “application of engineering and management principles, criteria, and techniques [...], throughout all phases of the system life cycle.”

[DOD MIL-STD 882D Clause 3.2.13]
Risk-based approach
Using standards

- Top level standards
  - Lower level standards/procedural standards
    - Project/management plans
      - Safety concept
        - Safety case (see later)
Generic safety process

Achieving safety → Generic safety process

Generic safety process


1. Document the system safety approach
2. Identify and document hazards
3. Assess and document risk
4. Identify and document risk mitigation measures
5. Reduce risk
6. Verify, validate and document risk reduction
7. Accept risk and document
8. Manage life-cycle risk
Eliminate the hazard if possible. When a hazard cannot be eliminated, the associated risk should be reduced to the lowest acceptable level within the constraints of cost, schedule, and performance by applying the system safety design order of precedence.

1. Eliminate hazards through design selection.
2. Reduce risk through design alteration.
3. Incorporate engineered features or devices.
4. Provide warning devices.
5. Incorporate signage, procedures, training, and personal protective equipment.
Lowest-level “standard”

- Top level standards
  - Lower level standards/procedural standards
    - Project/management plans
      - Safety concept
        - Safety case
Safety case

Definition

A safety case is an evidence-based explanation of why it is believed that a system is safe enough to be used in its intended application.

Specific for each application. This can be a Word document or a structured safety case.

Structured safety case

- Overall approach.
- Claim-Argument-Evidence (CAE) structure.
- Top-level claim supported by arguments and evidences that the arguments are correct.
- Split into sub-claims.
- Safety standards give guidance how to construct arguments.
Achieving safety → Safety case

CAE example
CAE example II.

Security-informed safety case

Source: City University London, P. Popov
Safety integrity

Safety-related systems are used to reduce the identified risks to tolerable level. Therefore, safety of our system depends on proper function of these systems.
Safety integrity

Safety-related systems are used to reduce the identified risks to tolerable level. Therefore, safety of our system depends on proper function of these systems.

Definition (Safety integrity)

The probability of a safety-related system satisfactory performing the required safety functions under all the stated conditions within a stated period of time.

- Two components:
  - Random failure integrity
  - Systematic failure integrity
- Question: How can I determine, that my safety-related system has sufficient safety integrity?
Safety integrity level

Standards (i.e. IEC 61508) gives the answer by defining “safety integrity level” and requirements for each level.

Definition (Safety Integrity Level)

Required level of protection against systematic failure in specification of the functions allocated to the safety-related systems.
Achieving safety → Safety integrity

Safety integrity level

Standards (i.e. IEC 61508) gives the answer by defining “safety integrity level” and requirements for each level.

Definition (Safety Integrity Level)

Required level of protection against systematic failure in specification of the functions allocated to the safety-related systems.

TODO: add tables with probabilities of failure
How to achieve that?

next slide->

See the tables from IEC 61508 Ed.2.

- NR – not recommended
- R – recommended
- HR – highly recommended
## Requirements for different SILs

**Table 5 – Minimum levels of independence of those carrying out functional safety assessment (overall safety lifecycle phase 9, including all phases of E/E/PES system and software safety lifecycles (see Figures 2, 3 and 4))**

<table>
<thead>
<tr>
<th>Minimum level of Independence</th>
<th>Safety integrity level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Independent person</td>
<td>HR</td>
</tr>
<tr>
<td>Independent department</td>
<td>–</td>
</tr>
<tr>
<td>Independent organization (see nNote 2 of 8.2.12)</td>
<td>–</td>
</tr>
</tbody>
</table>

**NOTE**  
See 8.2.12 (including notes), 8.2.13 and 8.2.14 for details on interpreting this table.
## Requirements for different SILs

### Table A.1 – Software safety requirements specification

(see 7.2)

<table>
<thead>
<tr>
<th>Technique/Measure*</th>
<th>Ref.</th>
<th>SIL1</th>
<th>SIL2</th>
<th>SIL3</th>
<th>SIL4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Semi-formal methods</td>
<td>Table B.7</td>
<td>R</td>
<td>R</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>1b Formal methods</td>
<td>B.2.4</td>
<td>---</td>
<td>R</td>
<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>2 Forward traceability between the system safety requirements and the software safety requirements</td>
<td>TBA</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>3 Backward traceability between the safety requirements and the perceived safety needs</td>
<td>TBA</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>4 Computer-aided specification tools to support appropriate techniques/measures above</td>
<td>B.2.4</td>
<td>R</td>
<td>R</td>
<td>HR</td>
<td>HR</td>
</tr>
</tbody>
</table>

**NOTE 1** – The software safety requirements specification will always require a description of the problem in natural language and any necessary mathematical notation that reflects the application.

**NOTE 2** – The table reflects additional requirements for specifying the software safety requirements clearly and precisely.

**NOTE 3** – See Annex C table C-A.1.

* Appropriate techniques/measures shall be selected according to the safety integrity level. Alternate or equivalent techniques/measures are indicated by a letter following the number. Only one of the alternate or equivalent techniques/measures has to be satisfied.
Achieving safety → Safety integrity

Requirements for different SILs

Table A.2 – Software design and development: software architecture design

(see 7.4.3)

NOTE - Some of these methods are about design concepts, others about how the design is represented.

<table>
<thead>
<tr>
<th>Technique/Measure*</th>
<th>Ref</th>
<th>SIL1</th>
<th>SIL2</th>
<th>SIL3</th>
<th>SIL4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture and design feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Fault detection</td>
<td>C.3.1</td>
<td>---</td>
<td>R</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>2 Error detecting codes</td>
<td>C.3.2</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>3a Failure assertion programming</td>
<td>C.3.3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>3b Safety bag techniques</td>
<td>C.3.4</td>
<td>---</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>3c Diverse redundancy</td>
<td>C.3.5</td>
<td>---</td>
<td>---</td>
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<td>HR</td>
</tr>
<tr>
<td>3d Backward recovery</td>
<td>C.3.7</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>3e Stateless design (or limited state design)</td>
<td>TBA</td>
<td>---</td>
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<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>3f Re-try fault recovery mechanisms</td>
<td>C.3.9</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>3g Memorising executed cases (e.g. in transaction systems)</td>
<td>C.3.10</td>
<td>---</td>
<td>R</td>
<td>R</td>
<td>HR</td>
</tr>
<tr>
<td>4 Graceful degradation</td>
<td>C.3.11</td>
<td>R</td>
<td>R</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>5 Artificial intelligence - fault correction</td>
<td>C.3.12</td>
<td>---</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>6 Dynamic reconfiguration</td>
<td>C.3.13</td>
<td>---</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>7 Modular approach</td>
<td>Table B.9</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>8 Use of trusted/verified software modules and components (if available)</td>
<td>C.2.10</td>
<td>R</td>
<td>HR</td>
<td>HR</td>
<td>HR</td>
</tr>
<tr>
<td>9 Forward traceability between the software safety requirements specification and software architecture</td>
<td>TBA</td>
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<td>HR</td>
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<td>HR</td>
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<tr>
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<td>HR</td>
<td>HR</td>
<td>HR</td>
</tr>
</tbody>
</table>

Design methods, notations and tools

Table B.9
1. Hazard identification (e.g. HAZOP study – next lecture)
Process of determining safety integrity level

1. Hazard identification (e.g. HAZOP study – next lecture)
2. Assign a probability of occurrence to each of the identified hazards
Process of determining safety integrity level

1. Hazard identification (e.g. HAZOP study – next lecture)
2. Assign a probability of occurrence to each of the identified hazards
3. Identify mechanisms which protect against particular hazards
Achieving safety → Safety integrity

Process of determining safety integrity level

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4. Identify effects
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6. Calculate the risk class (e.g. according to the next slide)
   - I Intolerable risk
   - II Undesirable risk
   - III Tolerable risk
   - IV Negligible risk
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Process of determining safety integrity level

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7. Identify safety integrity level
   - We want to reduce risk to class IV (negligible)
   - Systems with SIL1 capability can be used to reduce risk by one level
   - Systems with SIL4 capability can be used to reduce risk by three levels
## Risk classes

MIL-STD-882E, Table III

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>SEVERITY</th>
<th>Catastrophic (1)</th>
<th>Critical (2)</th>
<th>Marginal (3)</th>
<th>Negligible (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent (A)</td>
<td>High</td>
<td>High</td>
<td>Serious</td>
<td>Medium</td>
<td></td>
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<tr>
<td>Probable (B)</td>
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<td>High</td>
<td>Serious</td>
<td>Medium</td>
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<tr>
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<td>Serious</td>
<td>Medium</td>
<td>Low</td>
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<tr>
<td>Remote (D)</td>
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<tr>
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<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Eliminated (F)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Eliminated
Traceability

- Evidence that the low level requirements were translated to Source Code
- Evidence that no code was added that does not stem from a requirement
- Traceability means that you can answer the question "Why is this code here in this form" for every line I point at.
Safety culture

- We learn from mistakes → Traceability, consistency and completeness
- Safety culture is about ensuring that at every step you ask “what could happen”.
References

- Nicholas McGuire, Safety Manuals
- Dr. Andreas Gerstinger; Safety Engineering Course Slides, TU Wien.
- Gregor Pokorny; Safety Related Systems Slides, FH Campus Wien.
- SESAMO project