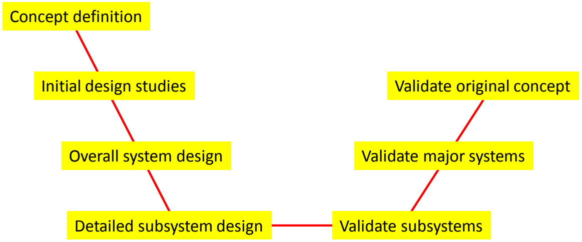
Tools and techniques for designing safe systems

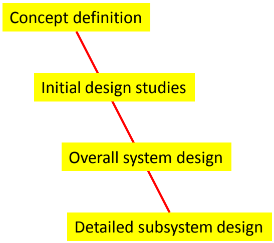
Engr 514:2014 Design of safety-critical systems

Roger Kemp, January 2014

The design process



The design process



- It is essential that safety assessment is not left until the validation process
- As the design progresses through these 4 steps, decisions must factor-in system safety

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Consider safety from the beginning

Concept definition

- Optioneering to choose best concept – intrinsic safety to be an important selection criterion.
- Confirm concept only after ensuring it is (or can be made) adequately safe.

Initial design studies

Safety to be an explicit objective, priority to be:

- Eliminate hazard
- Control hazard by technical means
- Control hazard by operational procedures
- Provide operators with PPE

Safety management tools

- Identifying hazards
  - Previous experience (including check lists)
  - Brainstorming
  - Hazard and Operability Analysis (HAZOP)
  - Fault Tree Analysis (FTA)
- Listing and classifying hazards
  - Hazard log
  - Risk matrix
- Managing risks
  - Stress analysis and other deterministic tools
  - Probabilistic risk assessment (PRA)
  - Quantified risk assessment (QRA)
  - Failure Mode, Effect and Criticality Analysis (FMECA)

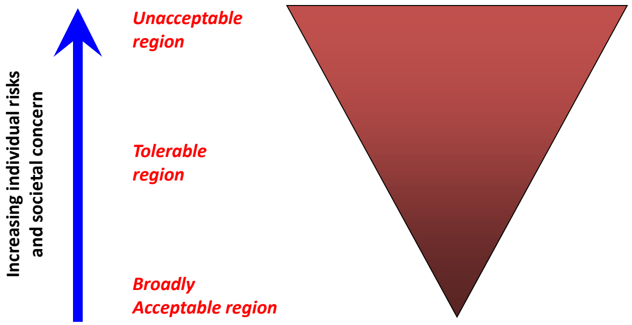
Tools

Techniques

- There is no “right” way to analyse safety or environmental impact
- The important thing is that the analysis should:
  - be clear and understandable
  - define exactly what is ***in*** and what is ***out***
  - be relevant
  - not give a false impression of accuracy or completeness

CLASSIFYING RISKS

HSE framework for tolerability of risk



Increasing individual risks and societal concern

Unacceptable region

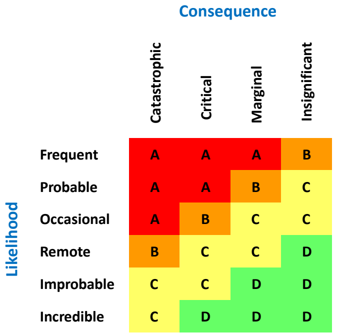
Tolerable region

Broadly Acceptable region

Environmental risks can be similarly classified

Risk matrix

from EN 50126:1999



		Consequence			
		Catastrophic	Critical	Marginal	Insignificant
Likelihood	Frequent	A	A	A	B
	Probable	A	A	B	C
	Occasional	A	B	C	C
	Remote	B	C	C	D
	Improbable	C	C	D	D
	Incredible	C	D	D	D

Risk categories:

- **A** **Intolerable**
- **B** **Undesirable**
- **C** **Tolerable**
- **D** **Negligible**

Risk = Fn (consequence, likelihood)

Hazard log

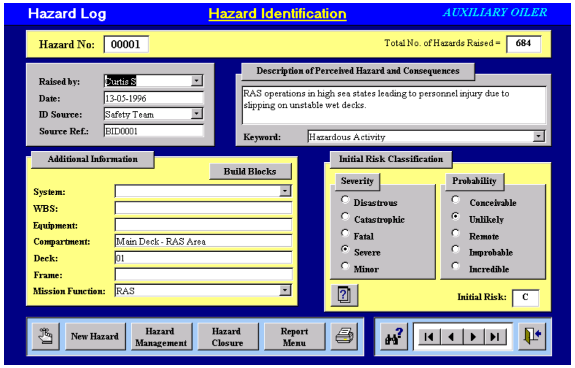
A hazard log is:

- A complete list of identified hazards
- A means of classifying risks into broad categories
- A statement of who is charged with finding a solution
- A record of the action taken to resolve the hazard

A hazard log is not:

- A way of identifying hazards
- A detailed calculation of risk
- A safety justification for a project
- A calculation of reliability
- A means for demonstrating contractual targets are met

"Hazard Identification" Screen



Hazard No: 00001

Total No. of Hazards Raised = 684

Raised by: Curtis S

Date: 13-05-1996

ID Source: Safety Team

Source Ref.: BID0001

RAS operations in high sea states leading to personnel injury due to slipping on unstable wet decks.

Keyword: Hazardous Activity

System:

WBS:

Equipment:

Compartment: Main Deck - RAS Area

Deck: 01

Frame:

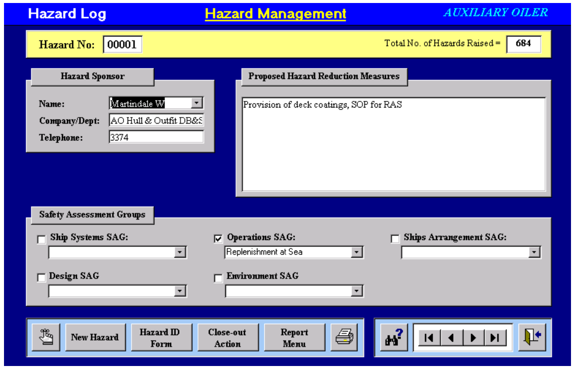
Mission Function: RAS

Severity: ○ Disastrous ○ Catastrophic ○ Fatal ● Severe ○ Minor

Probability: ○ Conceivable ● Unlikely ○ Remote ○ Improbable ○ Incredible

Initial Risk: C

“Hazard Management” Screen



Hazard No: 00001

Total No. of Hazards Raised = 684

Name: Martindale W

Company/Dept: AO Hull & Outfit DB&S

Telephone: 3374

Provision of deck coatings, SOP for RAS

☐ Ship Systems SAG:

☑ Operations SAG: Replenishment at Sea

☐ Ships Arrangement SAG:

☐ Design SAG

☐ Environment SAG

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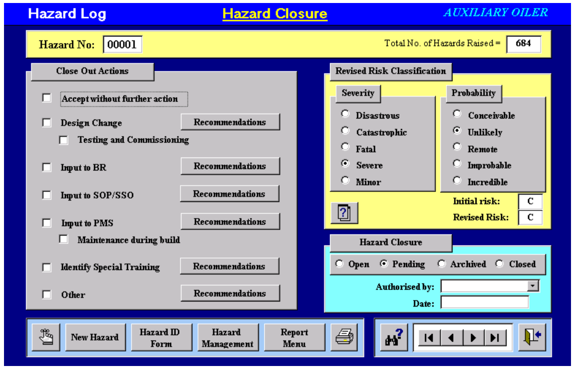
“Hazard Closure” Screen



Hazard No: 00001

Total No. of Hazards Raised = 684

☐ Accept without further action

☐ Design Change

☐ Testing and Commissioning

☐ Input to BR

☐ Input to SOP/SSO

☐ Input to PMS

☐ Maintenance during build

☐ Identify Special Training

☐ Other

Severity:
○ Disastrous
○ Catastrophic
○ Fatal
● Severe
○ Minor

Probability:
○ Conceivable
● Unlikely
○ Remote
○ Improbable
○ Incredible

Initial risk: C

Revised Risk: C

○ Open ● Pending ○ Archived ○ Closed

Authorised by:

Date:

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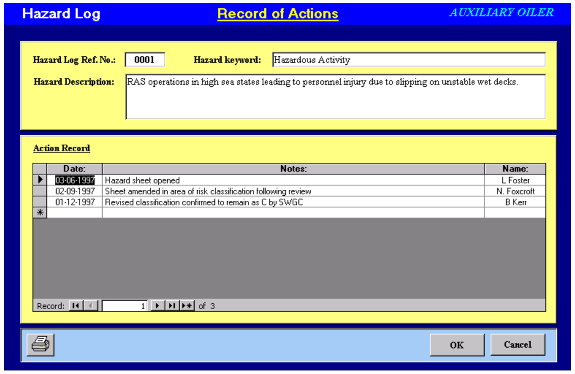
“Record of Actions” Screen



Hazard Log Ref. No.: 0001

Hazard keyword: Hazardous Activity

Hazard Description: RAS operations in high sea states leading to personnel injury due to slipping on unstable wet decks.

Action Record

Date:	Notes:	Name:
03-06-1997	Hazard sheet opened	L Foster
02-09-1997	Sheet amended in area of risk classification following review	N. Foxcroft
01-12-1997	Revised classification confirmed to remain as C by SWGC	B Kerr

Record: 1 of 3

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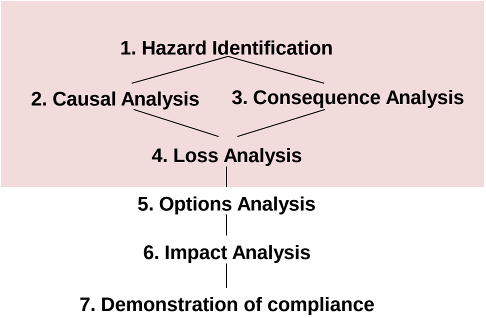
IDENTIFYING HAZARDS

Hazard identification

- Previous experience
  - What went wrong last time?
  - Service and maintenance records
  - Information on competitors' failures
- Brainstorming
- Hazard and Operability Analysis (HAZOP)
- Fault Tree Analysis (FTA)

Where does HAZOP fit?



1. Hazard Identification

2. Causal Analysis 3. Consequence Analysis

4. Loss Analysis

5. Options Analysis

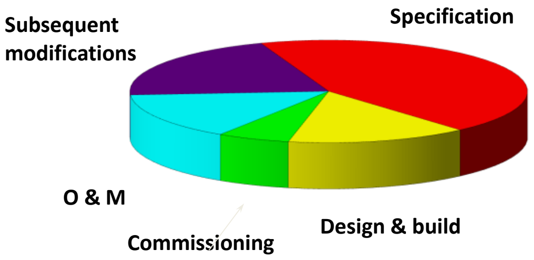
6. Impact Analysis

7. Demonstration of compliance

NB: Not everyone would agree with this definition – Trevor Kletz uses HAZOP for stages 1 to 5 – risk management, not just hazard identification

Why use a HAZOP?

Reasons for unsafe failures of electronic systems



Source: S. Brown HSE

Why use a HAZOP?

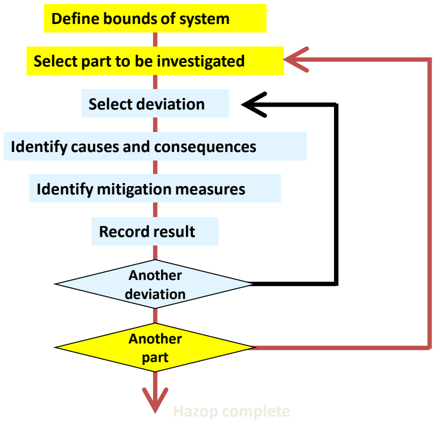
- Most accidents are caused by people doing the wrong thing, not technical failures
- HAZOP allows interactions of people and equipment to be investigated
- HAZOP identifies possible failures that "technical" analysis cannot see

What is a HAZOP?

> "HAZOP is a technique which provides opportunities for people to let their imaginations go free and think of all possible ways in which hazards or operating problems might arise, but – to reduce the chance that something is missed – it is done in a systematic way. . . The study is carried out by a team so that members can stimulate each other and build upon each other's ideas."

Trevor Kletz

Structure of a HAZOP



Define bounds of system

Select part to be investigated

Select deviation

Identify causes and consequences

Identify mitigation measures

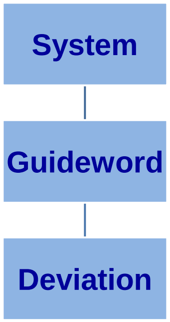
Record result

Another deviation

Another part

Hazop complete

How to define a deviation ?



System

Guideword

Deviation

- Typical guidewords
- None
- More of
- Less of
- Part of
- More than
- Other than

Example from chemical industry

Guideword	Deviation	Possible causes
None	No flow	No hydrocarbon available from previous stage
		Pump fails
		Line blockage, valve closed in error
		Line fracture
More of	More flow	Valve fails open
	More pressure	Valve closes with pump running
		Thermal expansion due to solar gain with valves closed

From Trevor Kletz, *Hazop and Hazan*, 1999

Other possible guidewords / deviations

- Speed
  - Too fast
  - Too slow
  - Does not move
- Position
  - Too low
  - Too high
  - Wrong bearing
  - Off course laterally
- Weight
  - Too heavy
  - Too light
  - Unbalanced L-R
  - Unbalanced fore-aft
  - CG too high

Who should be involved ?

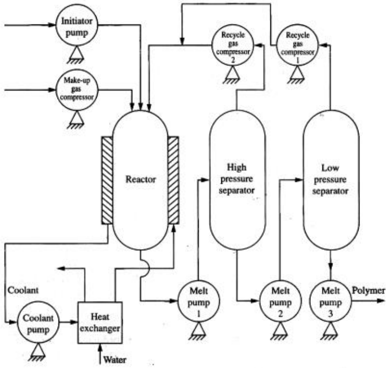
- Independent team leader
  - Understands HAZOP process
- Customer's chief engineer
  - Understands what was intended
- Operator
  - Can predict how operators might respond to system
- Supplier's project engineer
  - Understands what has been built
- Experts – if relevant *(see next slide)*
- Independent person who understands the technology

Experts

- For process plant, do you need a chemist to predict what could happen when the reaction chamber is too hot, too cold, contaminated, etc.?
- For a power station control room, do you need an HF expert who could give a view on how the operators might respond to particular crises?
- For a process involving plasma or arcing, do you need a health physicist to identify hazards such as the emission of soft X-rays by a plasma or toxic decomposition products?

A HAZOP is only as good as the people involved

Example of coarse scale Hazop: Polythene plant



Source NIOSH

Part of coarse-scale HAZOP

- Guide word:
  - HIGHER
- Deviation:
  - Higher reactor temperature
- Consequences:
  - Runaway reaction in reactor
- Causes:
  - Coolant pump to reactor fails
  - Coolant temperature too high
- Recommended actions:
  - Reactor temperature control
  - Reactor high temp. alarm
  - Pressure relief valve
  - Spare coolant pump
  - Alarm on coolant temp.

Source NIOSH

When to programme a HAZOP

- Coarse scale
  - When an outline design exists and can be discussed
  - When it is reasonably clear what staffing / management processes will exist
  - When changes are possible without prohibitive cost
    - *"Design-stage gate review" ?*
- Detailed HAZOP
  - When the design is largely complete
  - Before "design freeze"
  - When drafts of the operating instructions are available

Running a HAZOP

- There is no cast-iron rule on how to prepare a HAZOP
  - Choose suitable guidewords for the application
  - Decide on a coarse-scale or normal analysis
  - The important thing is "to provide opportunities for people to let their imaginations go free and think of all possible ways in which hazards or operating problems might arise - in a systematic way"*
- Make sure the team is competent but not overcommitted to the design (or intrinsically hostile!)
- Decide whether the HAZOP is to identify hazards or to come up with recommendations on how to resolve them
- Decide how HAZOP fits in to the other risk identification and management processes

* T Kletz

Exercise – making a cup of tea

Instructions (from packet)

- Use only fresh water (do not reboil water)
- Use one teabag per cup
- Pour water onto tea as soon as it has boiled
- Stir immediately
- Leave for 3 – 5 minutes depending on preference
- Press bag against side of cup and remove

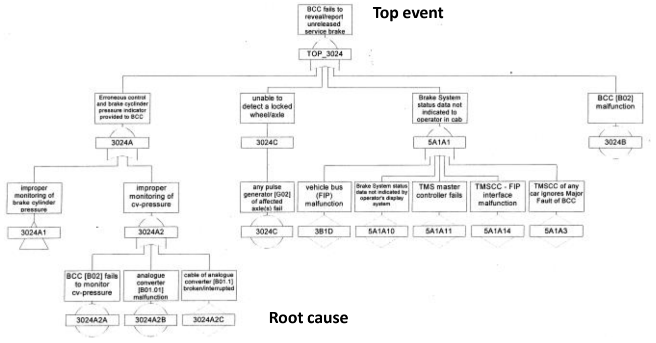
From Trevor Kletz, Hazop and Hazan, 1999

Hazop results

Step	Guide word	Deviation	Possible causes	Result	Action required
1	Non[illegible]	No water [illegible] kettle	No water supply	No tea	Keep bottle of water
			[illegible] fails [illegible]		

Please work in groups for 10 minutes to complete table

Fault tree



If probabilities are associated with the root causes, combinational maths can be used to analyse the probability of a "top event"

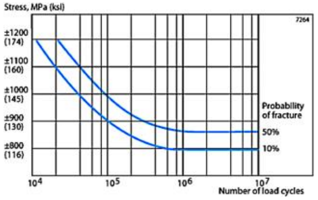
When to use a fault tree

- Top down – only analyses what is important
- Reasonably easy to understand
- Identifies single-point failures
- Identifies possibility of double failures
  - and thus identifies maintenance requirements
- Can be used either for identification of hazardous failures or for quantitative analysis of failure modes

NB: Fault tree concentrates on technical failures, not human factors

MANAGING RISKS

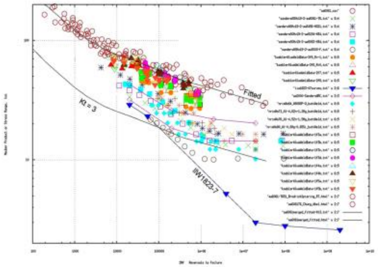
Deterministic tools – fatigue stress



- Calculate fatigue stresses in components
- Select materials so that probability of fracture is acceptably low

The diagram shows a Wöhler S-N curve for Sandvik Chromflex (strip steel) type 7C27Mo2 under reverse bending stress

Weld fatigue calculations for aluminium alloy



Aluminium Weld Fatigue Calculation Curve, F A Conle, University of Waterloo, January 2012

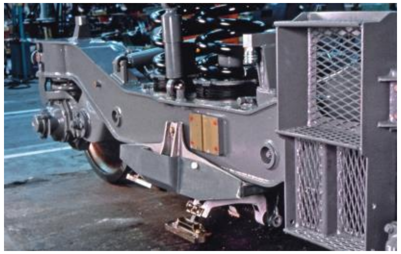
"In the ground vehicle industry much of the local stress analysis is done using elastic finite element (or simple stress*Kt) type calculations.

These elastic stresses are then transformed into local stresses and strains using some form of plasticity correction tool which requires a definition of the cyclic stress-strain curve along with the fatigue life curve.

The analysis method proposed here allows this type of correction to be made for aluminium weld data sets, and thus will conform to the standard methods presently applied in the ground vehicle industry."

Stress calculations on Eurostar power bogie

- Calculated accelerations at axlebox up to 30g
- Computer modelling used to predict stresses in bogie frame
- Pessimistic weld fatigue characteristics assumed
- Designed for infinite fatigue life



Example of FMECA (Pendolino auxiliary system)

ID1	Dwg. No	Ref	Item	Component	SFAS	Car type
11676	ZM5.IC1.Iss 6.		BZ-SSK	Bell/buzzer	No	A

Function	Failure Mode	Fail rate fpmh	Fail mode ratio
Smoke siren kitchen	Buzzer O/C	9.90E-02	1

Fail mode fpmh	No off	Total fpmh	System effect	Train level effect
1.00E+00	1	1.00E+00	Smoke siren in kitchen permanently disabled	Siren will not sound in kitchen. Reduced diagnostic facility

Railway effect	HSC	Detection	Mitigating effects?	Dormant failure?	Remarks
Minor	2	Operator	None	Yes	Audible alarm on detector may provide some back up

When to use FMECA (or FEMA)

- Use other tools to identify critical subsystems or components, then use FMECA to analyse these areas in detail
- Typical areas where FMECA could be used:
  - Track circuit receiver
  - Ejector seat firing circuit
  - Control rod lowering system
- Do not attempt to do a FMECA on a whole project as you risk drowning in paper!

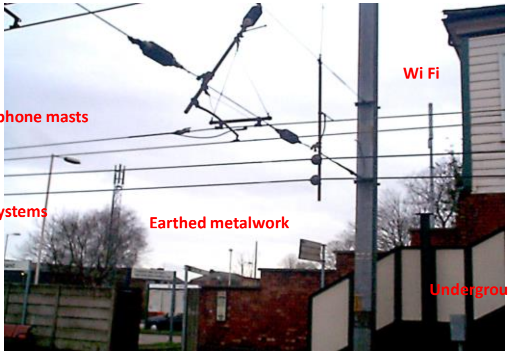
Track circuits – part of the railway system

- Electric trains are part of a railway system
- The system consists of the major sub-systems:
  - A power supply – the energy source
  - A distribution and return current network
  - An electric train – the energy consumer
  - A safety system – “signalling”
  - A communication system – “command & control”
- Outside the railway system – neighbours
- In or out? – passengers

The ideal railway environment

- Track not near other electrical systems
- Stone bridges (not steel)
- No near neighbours
- Clean ballast on consistent soil

What normally happens



Interference & susceptibility

- Each of these sub-systems contributes to the overall tendency to interference
- “Interference” is defined as “unwanted effects due to one system acting on another, causing malfunctions”
- Interference can affect safety and/or functionality
- The most desirable situation is that system components neither emit interference, nor are susceptible to it!
- Reality means interference is inevitable!

Signalling Interference

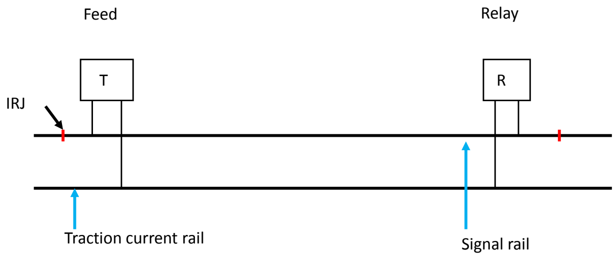
- Signalling is obviously a safety-critical system
- The “**Train detection**” function is probably the most important part of it
- In UK generally we are concerned with the block system of signalling, where the track is divided into sections and only one train is allowed to be in each section at any one time, under the control of lineside colour-light signals
- A failure to detect that a train is on the track section is a **wrong-side safety failure** as it may lead to a second train being allowed into the section
- A failure to detect that a track section is clear is a **right-side failure** – a reliability problem – as it will normally prevent a train from being allowed to enter a section
- Signalling is often referred to as a “**fail-safe**” system

Track Circuits & traction

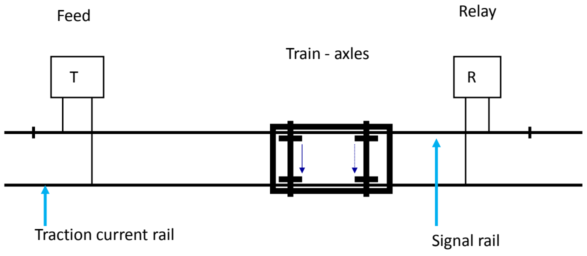
- “Track circuits” use the track, either 1 or 2 rails with IRJs (insulated rail joints), as their circuit conductors to detect trains
- The voltage and current levels of a TC are typically a few volts and amps in the DC to low AF band
- The return traction current in the rails from a train can be up to 300A at 50Hz or 6800A at DC with high harmonic levels
- Modern TCs use modulated currents – an anti-mimicking technique – but there are plenty of old ones in service!

Track Circuit Operation

Discussed in more detail in Engr 529



Track circuit operation



Longitudinal voltage

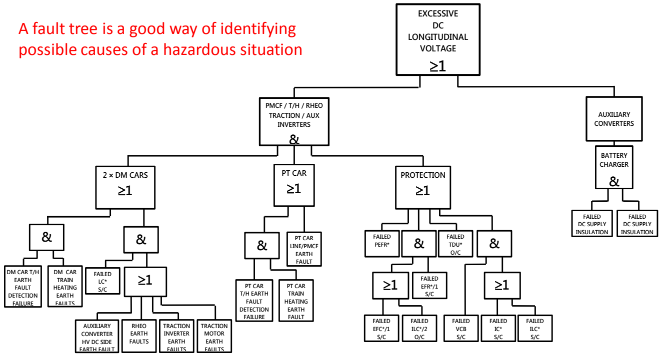
Apart from traction currents, there are other sources of track voltages:

  - Primarily from “earth faults” giving longitudinal currents in the vehicle body shell
  - Protection against interference therefore involves prevention of such currents, by design, and detection of such currents in the event of a fault
  - The reliability of the design is required to be high to give a low probability of interference

- The LV problem also occurs with non-electric trains & vehicles

Class 334 DC Longitudinal Voltage Fault Tree

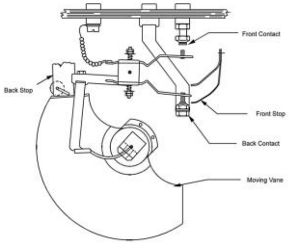
A fault tree is a good way of identifying possible causes of a hazardous situation



Vane relay

A frequency and phase-sensitive detector for track circuit currents

Use FTA to identify potential hazards – FMECA to drill-down into the design



IGBT drive on Pendolino

FMECA is a suitable tool for determining what faults are likely to cause interference

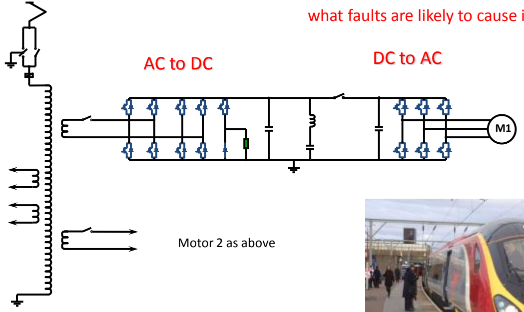


Photo: Alstom

Risk assessment - dealing with "defences"

- A traction converter could, theoretically, create currents that cause a signal to show a more permissive aspect.
- But, what is the probability of the fault occurring:
  - over a susceptible track circuit?
  - at the worst point on that track circuit?
  - on more than one motor?
  - at exactly the "right" train speed?
  - with the fault current exactly in-phase with the reference?

Use **quantitative risk assessment** – e.g. Monte Carlo technique – to assess likelihood of risk (see Engr 529)

What assumptions do you make?

New impedance bond

As found on track

Using the right tools

- **Hazard Log** – classifies hazards
- **Risk matrix** – assesses risk caused by hazards
- **Fault trees** – link components to hazards
- **Deterministic tools** – to ensure design can cope with stresses to which it will be subjected
- **FMECA** – drills down into critical components
- **HAZOP** – investigates human interaction