Root Cause Analysis (RCA)

An essential element of Asset Integrity Management and Reliability Centered Maintenance Procedures

Dr Jens P. Tronskar

MANAGING RISK DNV

Definition of Root Cause Analysis (RCA)

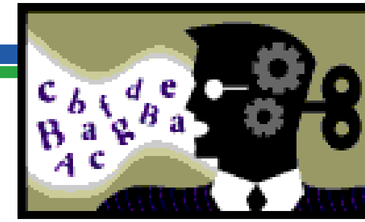
Root Cause Analysis (RCA) is a structured process that uncovers the physical, human, and latent causes of any undesirable event in the workplace.

Can be;

•Single or multidiscipline cases

•Small or large cases

Some other definitions



Failure Cause –

- The physical or chemical processes, design defects, quality defects, part misapplication, or other processes that are the basic reason for failure or that initiate the physical process by which deterioration proceeds to failure.
- The circumstances during design, manufacture, or operation that have led to a failure.

Failure Effect – The consequence(s) a failure mode has on the operation, function, or status of an item.

Failure – The termination of its ability to perform a required function

Failure Mode – The effect by which a failure is observed on the failed item

Root Cause (RCA)

- *Indispensible component of proactive and reliability centred maintenance*
- *Uses advanced investigative techniques*
- *Apply correctives*
- *Eliminates early life failures*
- *Extends equipment lifetime*
- *Minimizes maintenance*

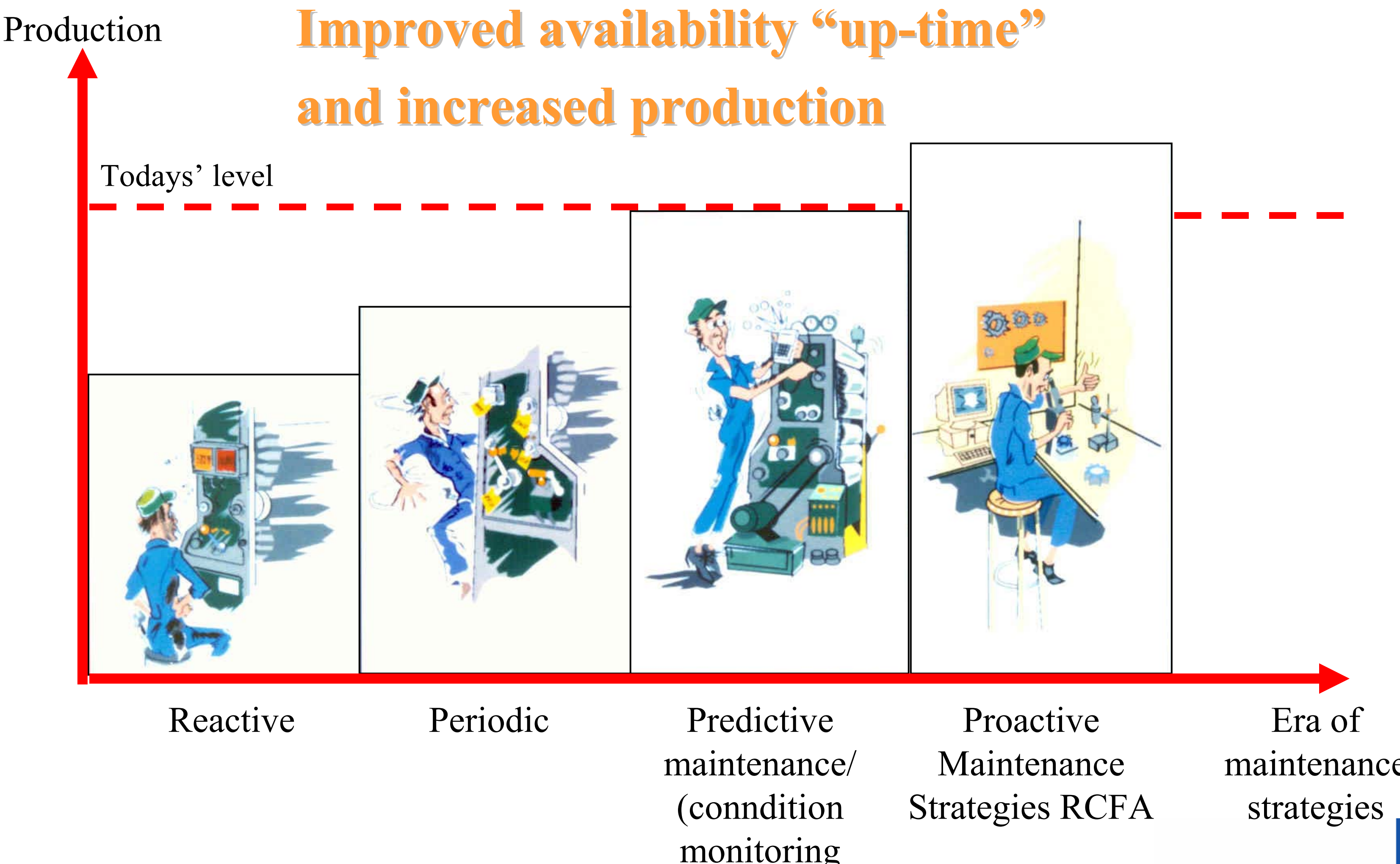
Traditional maintenance strategies tend to neglect something important:

Identification and correction of the underlying problem.

A Root Cause Analysis will disclose:

- Why the incident, failure or breakdown occurred
- How future failures can be eliminated by:
  - changes to procedures
  - changes to operation
  - training of staff
  - design modifications
  - verification that new or rebuilt equipment is free of defects which may shorten life
    - repair and reinstallation is performed to acceptance standards
    - identification of any factors adversely affecting service life and implementation of mitigating actions

Improved availability “up-time” and increased production



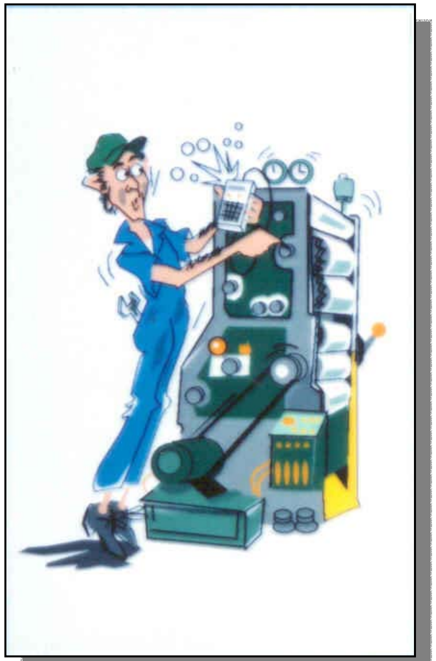
Reactive maintenance

- Run the equipment until breakdown
- Overhaul and repair
- Extensive unplanned downtime and recurrent repair

Periodic maintenance

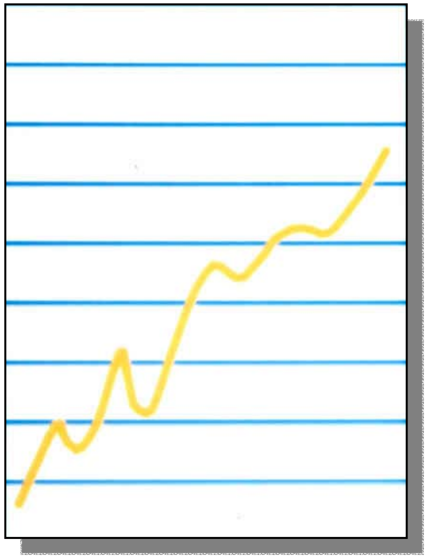
- Scheduled calendar or interval-based maintenance
- Expensive components exchanged even without signs of wear or degradation
- Unexpected failures with incorrect schedules and component change-out

Predictive maintenance by condition monitoring



- Apply technologies to measure the condition of machines
- Predict when corrective action should be performed before extensive damage to the machinery occurs

Short and long-term benefits of Proactive Maintenance Strategies involving RCFA:



Optimization of service conditions:

- Increased production
- Reduced downtime
- Reduced cost of maintenance
- Increased safety

Experience and statistical data

MMS DATABASE

- Information on equipment design and service conditions
- Failure statistics i.e. MTBF
- Description of service failures, approach and methods for failure investigation
- Consequences of failure:
  - Downtime/pollution and spillage/secondary damages
- Causes of failures
- Recommendations and remedial actions

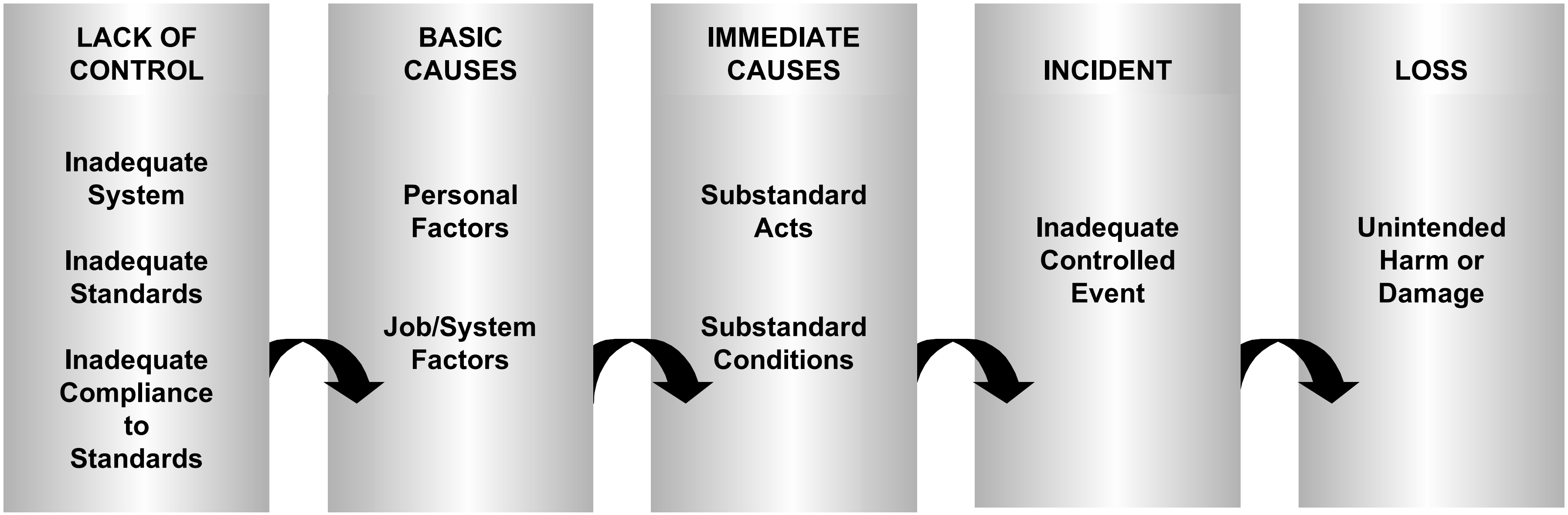
Methods and analytical tools to identify the causes of failure or breakdown

- Review background data
- Loss Causation Model and RCA methods and working process

Detailed analyses of failed parts/components:

  - Analyse service conditions
  - Utilise experience data from data bases or other sources
  - Laboratory investigation

The Loss Causation Model



The main causes…

Something
Is done wrong
or gone wrong

A failure

Here the losses occur

Data Collection

- Interviews
- Documents (paper) evidence
- Parts/component evidence

Interviewing Considerations

- Where to interview
- Who to interview
- Condition of people at the scene
- How to handle multiple witnesses
- How to handle after the incident
- How to work with teams

Investigation techniques

- A number of named techniques that are commonly used within RCA:
  - **Step-method**
  - **FMEA**
  - Bow-tie
  - Event Tree
  - **Failure Tree**
  - **Interview**
  - Fish Bone
  - Why-Why
- The techniques have strength and weaknesses depending on the situation.

Methods for RCA; Content

- Data Collection
  - Interviews
  - Paper and technical evidence
- Methods for RCA
  - STEP
  - FMEA
  - FTA

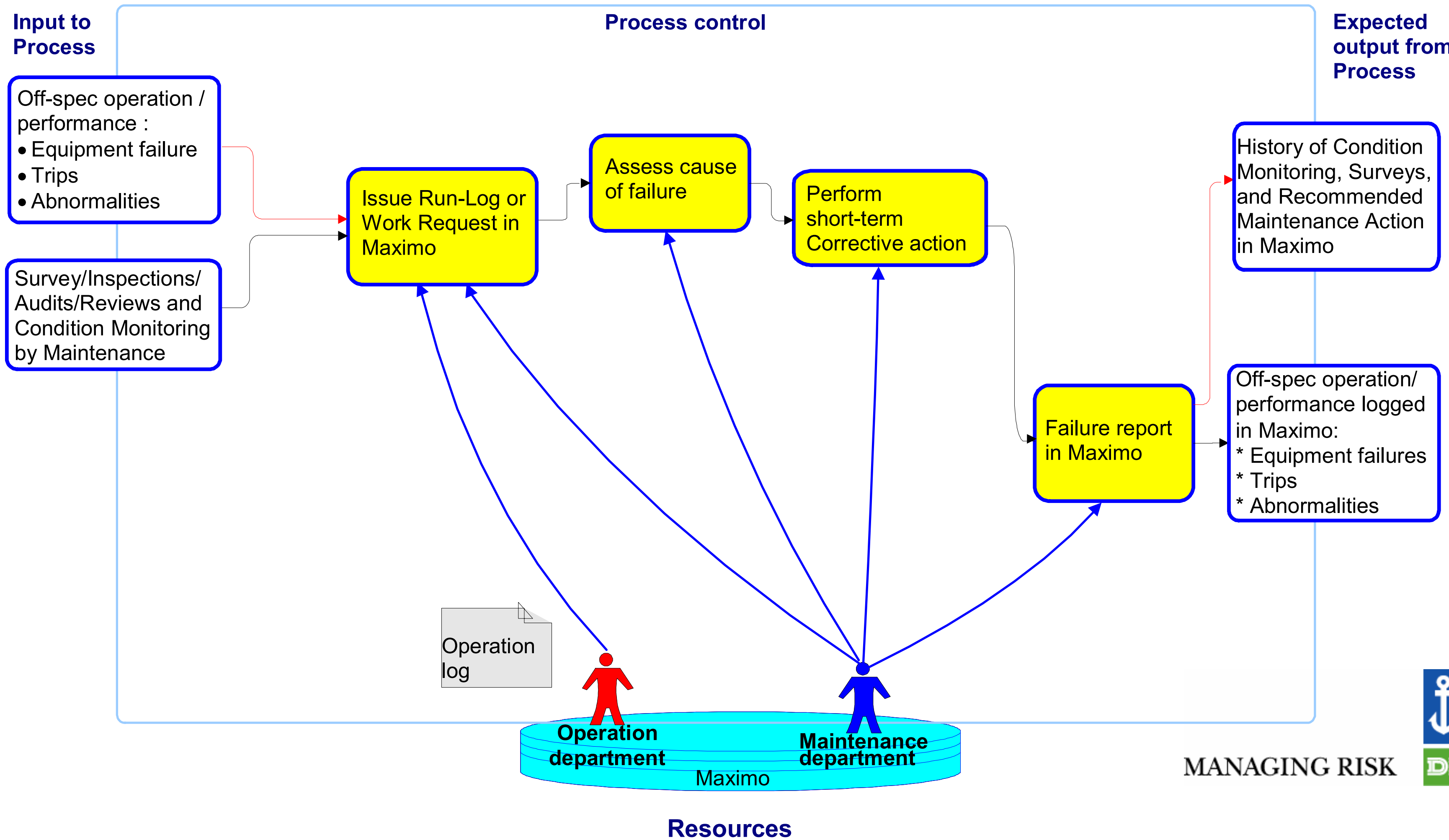
STEP 1: Register Equipment Incidents

1 Register Equipment Incidents

Purpose : Register Off-spec. Operation / performance, Survey & Condition Monitoring data

Start: Trigged by off-spec. operation/performance, Survey & Condition Monitoring data

Stop: Incident logged in Maximo

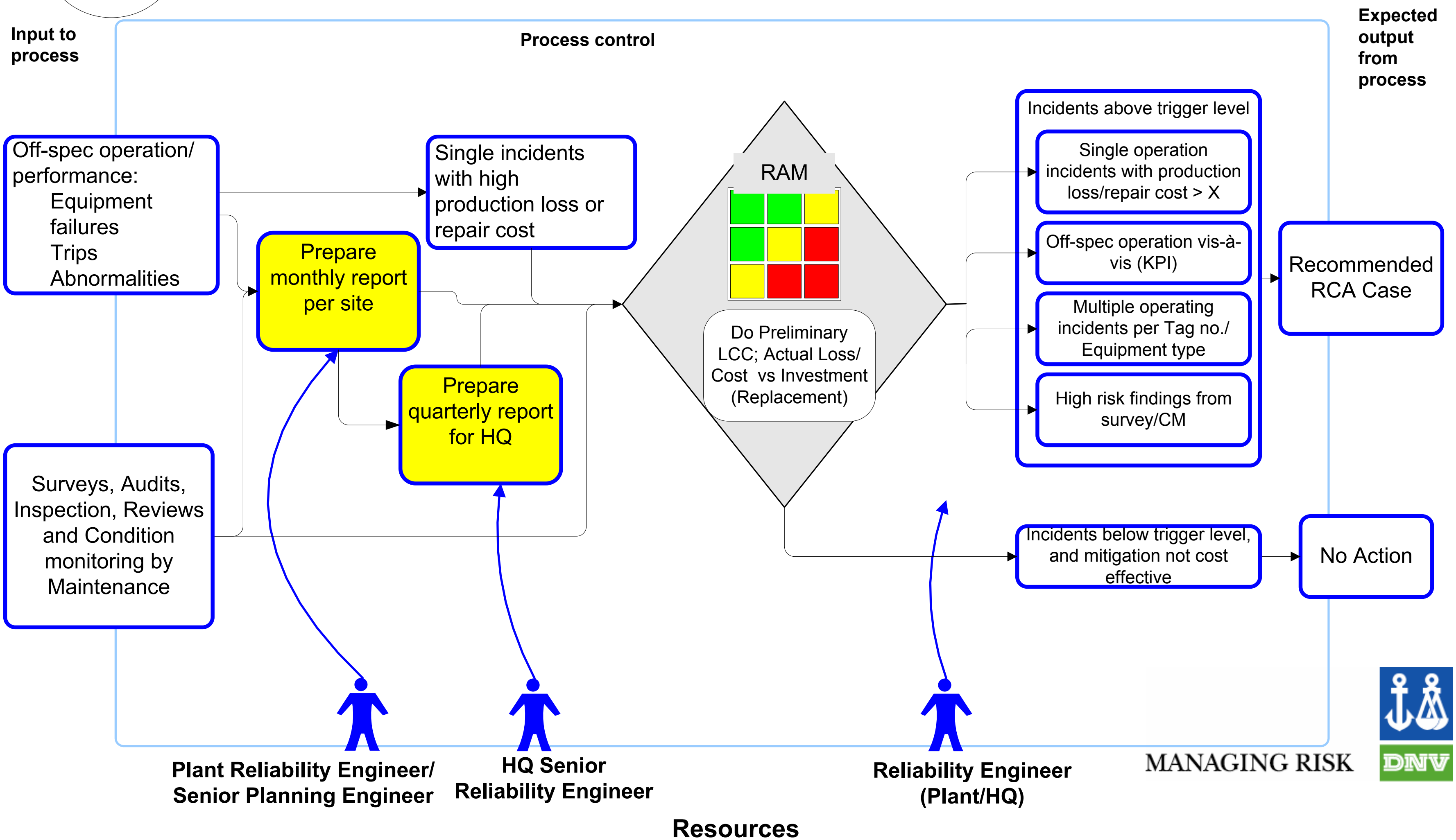


STEP 2: Trigger Mechanism for RCA

2 Trigger mechanism for RCA

Purpose: Evaluate need for RCA

Start: Registered HSE issues or off-spec operation/ performance incidents
Stop: Start RCA



MANAGING RISK DNV

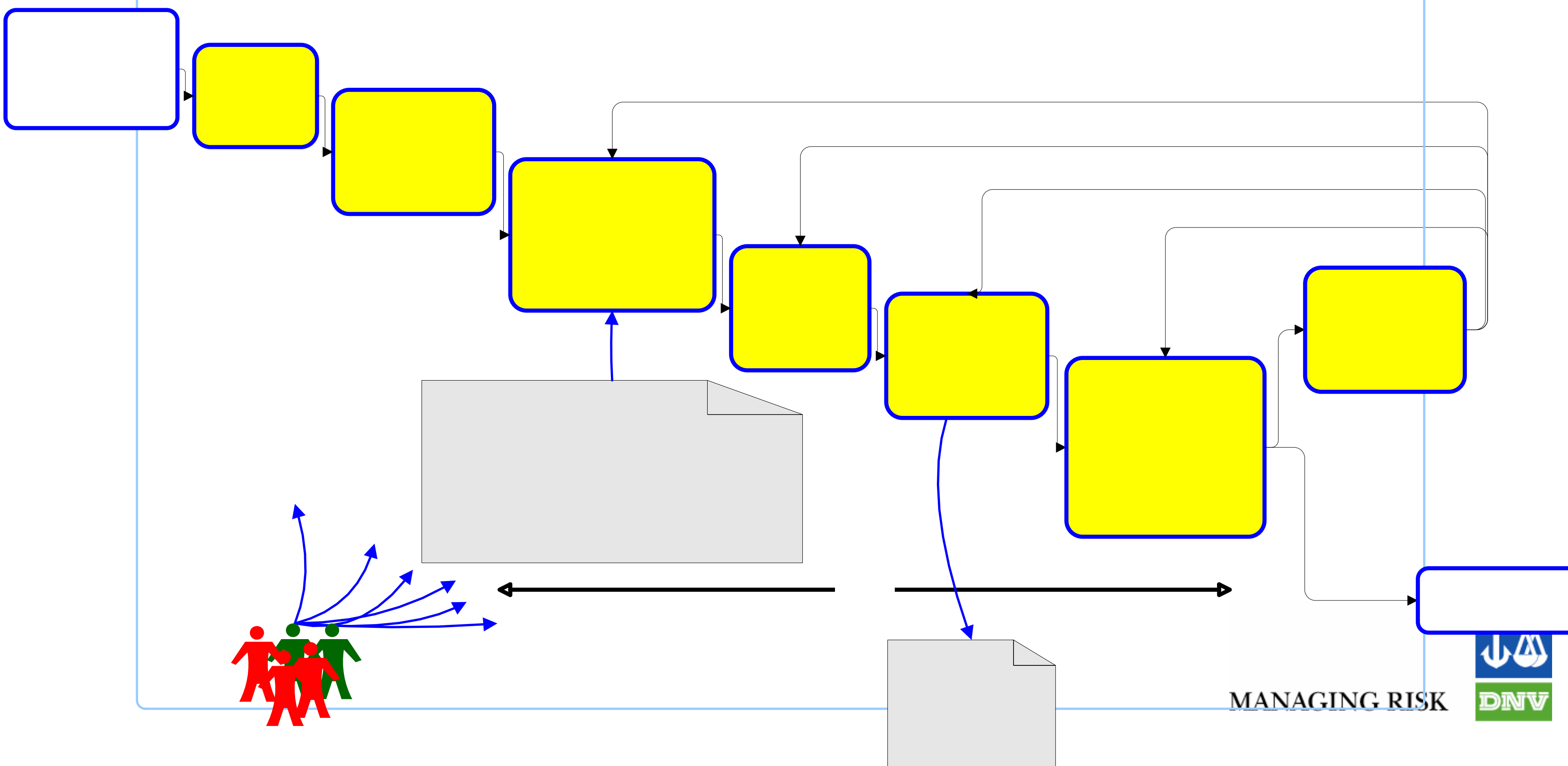
STEP 3: Appoint the RCA Team

- Minor RCAs:
  - Run within a department, using the procedure
- Larger RCAs:
  - Leader – appointed by the Plant manager
  - Facilitator – reliability engineer.
  - Discipline(s) or specialists at specific plant

- Optional to involve:
  - Disciplines from other sister plants
  - HQ-Engineering support and technical staff
  - Vendor
  - Failure laboratories
  - Other 3rd parties
  - Specialist

STEP 4: The Root Cause Analysis

4 RCA method steps



The main RCA report

1 Description of the Incident(s)

An incident is the event that precedes the loss or potential loss. This section should include a description of what happened. Include all aspects related to the incidents, like outage time, cost of repair, people involved, tools in use, operational status, weather conditions etc.

2 Immediate Cause(s)

The immediate causes of an incident are the circumstances that immediately preceded the contact and can usually be seen or sensed. For example if the incident is an oil spill, the immediate cause could be a broken sealing. The Immediate Causes often are the same as the failure codes registered in Maximo.

3 Basic Cause(s)

Basic Causes are the real causes behind the immediate causes: the reasons why the substandard acts and conditions occurred, the factors that, when identified, permit meaningful management control. In case of an oil spill caused by a broken sealing, the Basic Causes could be that the sealing used was of wrong type, it had a design failure or it might be installed wrong.

4 Lack of Control

Lack of Control means insufficient oversight of the activities from design to planning and operation. Control is achieved through standards and procedures for operation, maintenance and acquisition, and follow-up of these. If an oil spill has occurred because of wrong installation of a sealing, the Lack of Control could be related to inadequate procedures for checking after maintenance.

RCA TEMPLATE

STATUS OF THE STUDY:
- ☐ In-progress
- ☐ Completed
- ☐ Pending

MANAGING RISK DNV

TITLE: Root Cause Reporting Form   RCA #:

Incident Date: System/Component/Tag:

Loss / Incident

Loss: Description of the Incident

Loss/Incident

Failure Code from Maximo
Group: Problem Code:
Failure Class: Cause Code:

Risk Assessment Matrix – RAM
Potential Consequence (1-5)   Assets: Production Loss:

Immediate Cause

Immediate Causes

Sub-Standard Condition (A):
- ☐ 1. Detect Equipment & Tools
- ☐ 2. Working Environment
- ☐ 3. External Weather
- ☐ 4. Control / Operation
- ☐ 5. Production Profile
- ☐ 6. Mobilization of equipment
- ☐ 7. Modification of equipment
- ☐ 8. Deterioration / Corrosion

Sub Category:

Sub-Standard Acts (A):
- ☐ 10. Maintenance
- ☐ 11. Operation of equipment outside design parameters
- ☐ 12. Wrong use of equipment
- ☐ 13. Violation of procedures
- ☐ 14. Process Control
- ☐ 15. Ineffectiveness / Inadequate protection

Sub Category:

Basic Cause

Basic Causes

Personal Factors(B):
- ☐ 1. Inadequate knowledge of the working process
- ☐ 2. Inadequate Competence
- ☐ 3. Motivation
- ☐ 4. Physical and psychological load during work

Sub Category:

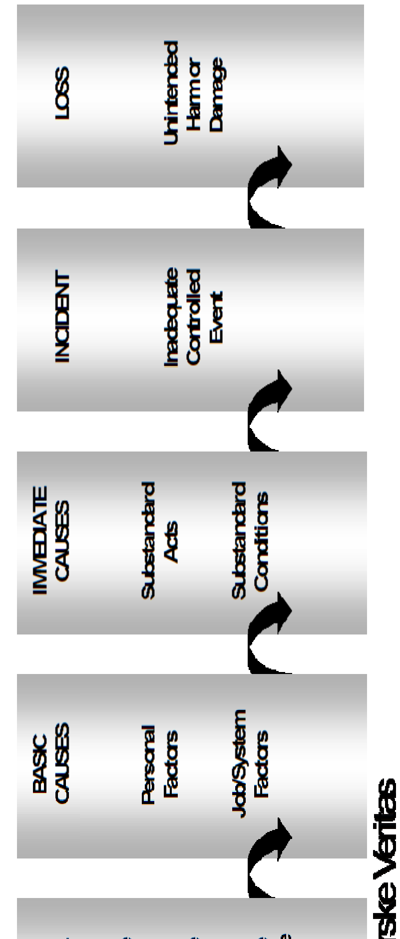
Causes related to the work (B)
- ☐ 10. Inadequate management and control of work
- ☐ 11. Design Failure (or lack of design)
- ☐ 12. Purchasing
- ☐ 13. Maintenance
- ☐ 14. Ageing / Obsolescence

Sub Category:

Lack of Control

Lack of Control

Lack of Control (C):
- ☐ 1. Inadequate Management System
- ☐ 2. Inadequate system standards
- ☐ 3. Inadequate compliance with routines
- ☐ 4. Inadequate Maintenance Procedures
- ☐ 5. Inadequate Operational Procedures
- ☐ 6. Inadequate Design Procedures



MANAGING RISK DNV

RCA reporting system

RCA TEMPLATE

STATUS OF THE STUDY:
- ☐ In-progress
- ☐ Completed
- ☐ Pending

TITLE: Root Cause Reporting Form RCA #:

Loss / Incident

Incident Date: System/Component/Tag:

Loss: Description of the Incident

Failure Code from Maximo
Group: Problem Code:
Failure Class: Cause Code:

Risk Assessment Matrix – RAM
Potential Consequence (1-5) Assets: Production Loss:

Immediate Cause

Sub-Standard Condition (A):
- ☐ 1. Detect Equipment & Tools
- ☐ 2. Working Environment
- ☐ 3. External Weather
- ☐ 4. Control / Operation
- ☐ 5. Production Profile
- ☐ 6. Mobilization of equipment
- ☐ 7. Modification of equipment
- ☐ 8. Deterioration / Corrosion

Sub Category:

Sub-Standard Acts (A):
- ☐ 10. Maintenance
- ☐ 11. Operation of equipment outside design boundaries
- ☐ 12. Wrong use of equipment
- ☐ 13. Violation of procedures
- ☐ 14. Process Control
- ☐ 15. Ineffectiveness / Inadequate protection

Sub Category:

Basic Cause

Personal Factors(B):
- ☐ 1. Inadequate knowledge of the working process
- ☐ 2. Inadequate Competence
- ☐ 3. Motivation
- ☐ 4. Physical and psychological load during work

Sub Category:

Causes related to the work (B)
- ☐ 10. Inadequate management and control of work
- ☐ 11. Design Failure (or lack of design)
- ☐ 12. Purchasing
- ☐ 13. Maintenance
- ☐ 14. Ageing / Obsolescence

Sub Category:

Lack of Control

Lack of Control (C):
- ☐ 1. Inadequate Management System
- ☐ 2. Inadequate system standards
- ☐ 3. Inadequate compliance with routines
- ☐ 4. Inadequate Maintenance Procedures
- ☐ 5. Inadequate Operational Procedures
- ☐ 6. Inadequate Design Procedures

IMMEDIATE CAUSES		
A	Substandard conditions	
A1	Defect equipment and tools:	A1.1: Defect fabrication or use of the equipment for this service
		A1.2: Defect material used in tool and equipment
		A1.3: Equipment failure during operation
A2	Working environment	A2.1: Excessive noise level
		A2.2: Too little space to do work
		A2.3: Fire and explosion risk in the area
		A2.4: Bad general household
A3	External weather	A3.1: Failure caused by bad weather conditions
A4	Control/ operation	A4.1: Wrong set point (pressure, temperature, vibration, ...)
		A4.2: Lack of instrumentation
		A4.3: Lack of logic in the instrument function
		A4.4: Defect controller devices
A5	Production profiles	A5.1: Chang in production not communicated in the organisation
A6	Change of operation conditions	A6.1: Change in operation conditions not verified
A7	Modification of equipment	A7.1: Modification of equipment not verified against the system.
A8	Deterioration / Corrosion	A8.1: Deterioration of the equipment due to corrosion, erosion, fatigue
	Substandard acts	
A10	Maintenance	A10.1: Cleaning, lubrication, adjustment or replacement of components during operation
		A10.2: Welding and hot work without proper preparation
		A10.3: Defect initiated by maintenance or inspection
		A10.3: Wrong replacement kit installed.
A11	Operation of equipment outside design boundaries	A11.1: Operation outside rated capacity
		A11.2: Operated outside pressure limits
		A11.3: Operation outside temperature limits
A12	Wrong use of equipment	A12.1: Operation with defect equipment
		A12.2: Equipment/tools used for a purpose not designed for
		A12.3: Equipment/tools overloaded during operation
A13	Violation of Procedure	A13.1: Operational procedures
		A13.2: Safety procedures
		A14.3: Procedures for maintenance
		A14.4: Work permit
A14	Process control	A14.1: Defect/error in overall operation control initiated by operator
		A14.2: --initiated automatically by system
A15	Ineffective/ Inadequate protection	A15.1: Ineffective/Inadequate protection system for the equipment/ system/machinery

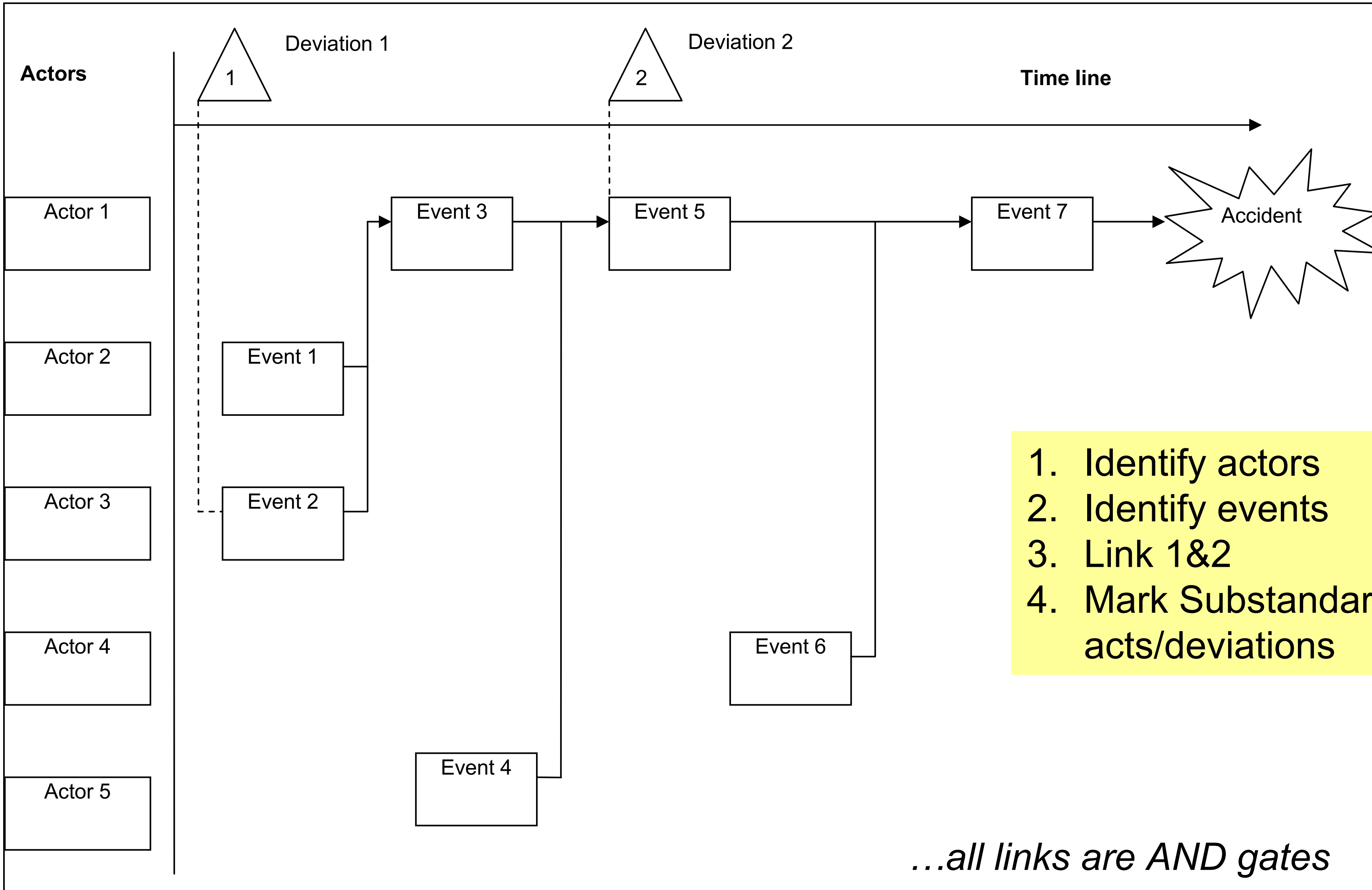
BASIC CAUSES		
B	Personal Factors	
B1	Inadequate knowledge of the working process	B1.1: Lack of experience
		B1.2: Lack of information
		B1.3: Lack of training for new employee
		B1.4: Lack of training related to modification/change in process conditions
		B1.5: Misunderstanding
B2	Inadequate competence	B2.1: Lack of basic training
		B2.2: Long period between each time the knowledge is used/required
		B2.3: Lack of instruction/Missing instruction
B3	Motivation	B3.1: Lack of feedback (positive/negative) for conducted work
		B3.2: Lack of feedback related to quality when that is required
		B3.3: Lack of follow-up during work execution
		B3.4: General frustration of working conditions
B4	Physical and psycho-logical load during work	B4.1: Stress due to psychological pressure
		B4.2: High physical demand
	Causes related to the work	
B10	Inadequate management and control of work	B10.1: Unclear communication lines
		B10.2: Unclear guidance for responsibility
		B10.3: Unclear goals for executed work
		B10.4: Lack of instructions, procedures, reference documentation
		B10.5: Lack of identification/focus on possible loses/damages
		B10.6: Managers lack knowledge about execution of work
		B10.7: Unqualified personnel used for the work
		B10.8: Lack of overall goals for the work
		B10.9: Lack of experience feedback
B11	Design failure (or lack of design)	B11.1: Missing/not complete design requirement and specification
		B11.2: Lack of operational response
		B11.3: Lack of start-up procedures
		B11.4: Change in design not verified against the rest of the process
B12	Purchasing	B12.1: Lack of needs analysis and specification of system/equipment requirement
		B12.2: Inadequate specification to vendor
		B12.3: Inadequate handling of equipment
		B12.4: Inadequate storage of equipment
		B12.5: Inadequate transport of equipment
		B12.6: Inadequate quality control/testing of equipment
B13	Maintenance	B13.1: Lack/not sufficient maintenance
		B13.2: Inadequate planning of maintenance
B14	Ageing/ Obsolescent	B14.1: Equipment in use is obsolescent

Methods for RCA

- STEP; Sequential Time Event Plotting
- FMEA; Failure Mode Effect Analysis
- FTA; Fault Tree

- + *common sense, engineering/operational experience*

STEP; Sequentially Time Event Plotting



1. Identify actors
2. Identify events
3. Link 1&2
4. Mark Substandard acts/deviations

…all links are AND gates

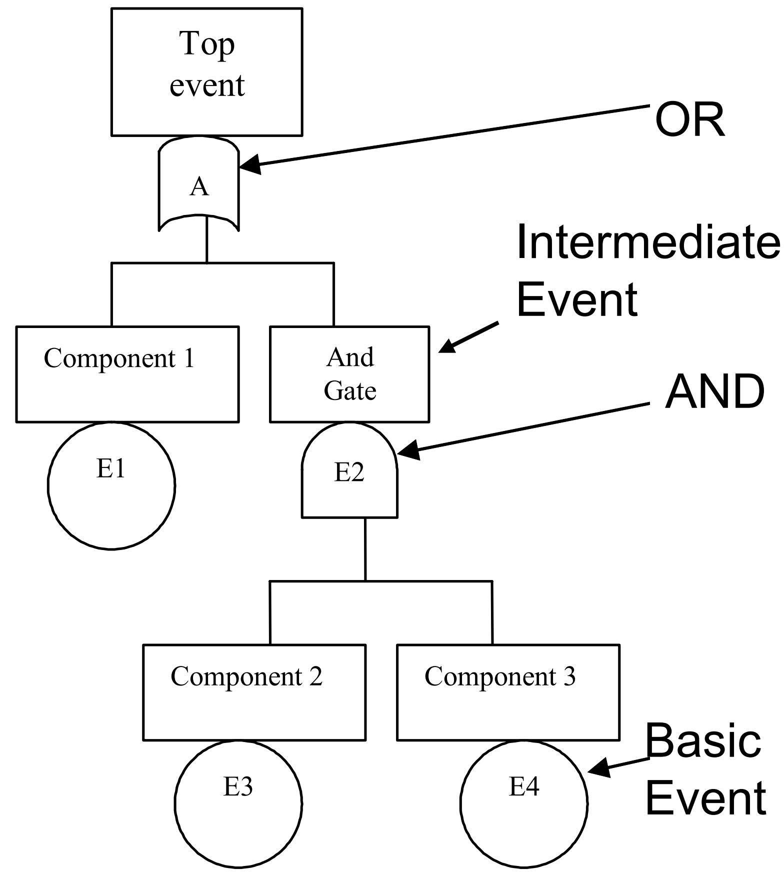
FMEA; Failure Mode and Effect Analysis

Loss/Consequence: Pump not started						
Function/ Object	**Failure Mode**	**Failure Cause**	**Consequence System/ Component**	**Detection**	**Likelihood** (low – possible- high)	**Comment**
Pump	Broken axel	Fatigue		None		
	Impeller	Corrosion /Wear	Loss of Pressure	Pressure Indicator		
El. Motor	Winding			None		
Soft-starter	Fail to Operate	Unknown		None		
Switch	In off position			None		
Signal				Alarm		
Sensor	Fail to operate		Wrong signal to control unit	None		
High Temp. Protection	Fail to operate		No detection of failure and larger damage			

Fault Tree

What is a Fault Tree?

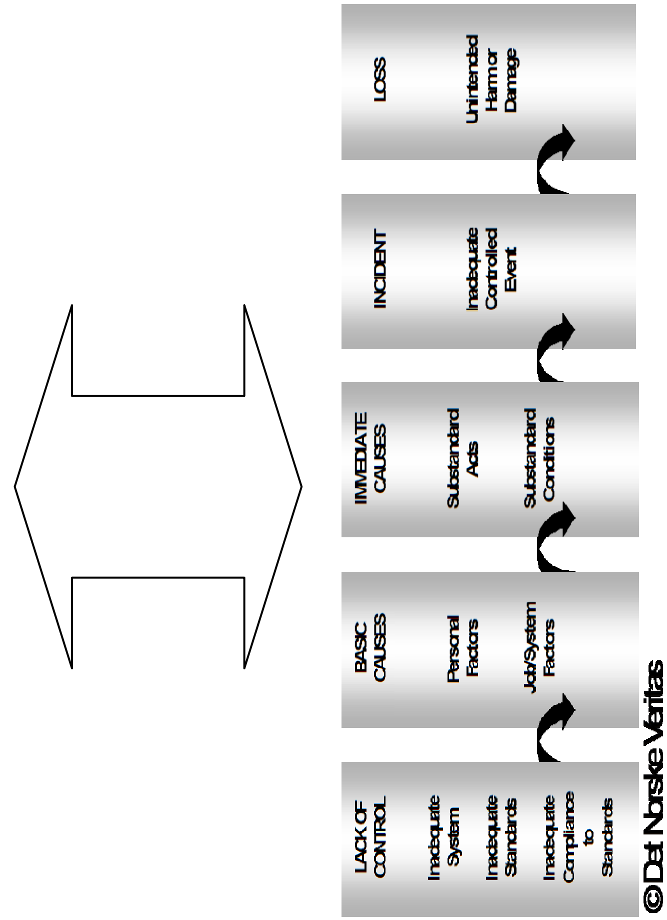
- Identifies causes for an assumed failure (top event)
- A logical structure linking causes and effects
- *Deductive* method
- Suitable for potential risks
- Suitable for failure events



MANAGING RISK

Which one to use?

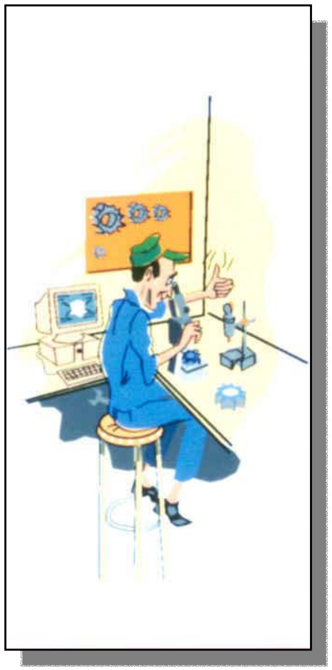
- STEP:
  - For complex events with many actors
  - When time sequence is important
- FMEA:
  - Getting overview of all potential failure
  - Easy to use
- FTA:
  - Identifies structure between many different failure causes
  - Non-homogenous case (different disciplines)



Detailed analyzes of failed parts/components

Typical examples of systems/equipment that can be analyzed:

- Electrical generators
- Heat exchangers
- Subsea equipment
- Valves
- Control systems
- Pumps
- Fire and gas-detectors
- Sensors and measuring devices
- Components of gasturbines
- Compressors
- Cranes and lifting equipment
- Well and down hole drilling equipment

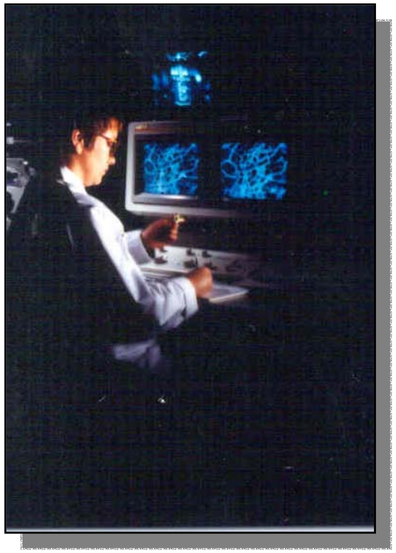


Proactive maintenance through Root Cause Failure Analysis (RCFA)

Maintenance strategy based on systematic and detailed knowledge of the causes of failure and breakdown

- Systematic removal of failure sources
- Prevent repetitive problems
- Minimise maintenance down-time
- Extend equipment life

RCFA evaluates factors affecting service performance such as:

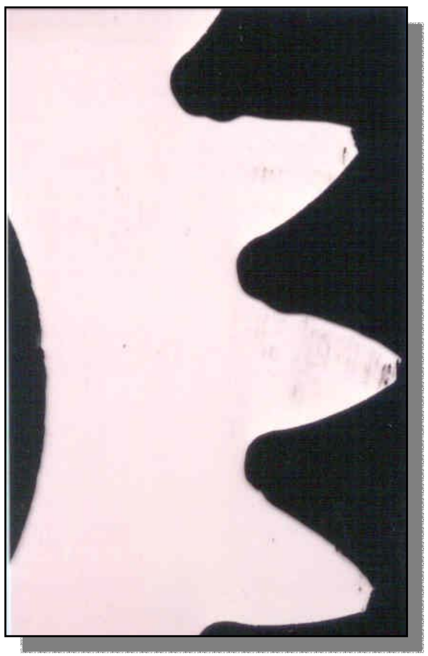


- Materials/corrosion/environment
- Changes in operational conditions
- Stresses and strains
- Presence of defects and their origin, nature and consequences
- Design
- Welding procedures and material weldability

The most common causes of service failures or breakdown:

- Incorrect operation
- Poorly performed or inadequate maintenance
- Incorrect installation and bad workmanship
- Incorrect repair introducing new defects
- Poor quality manufacture leading to sub-standard components
- Poor design

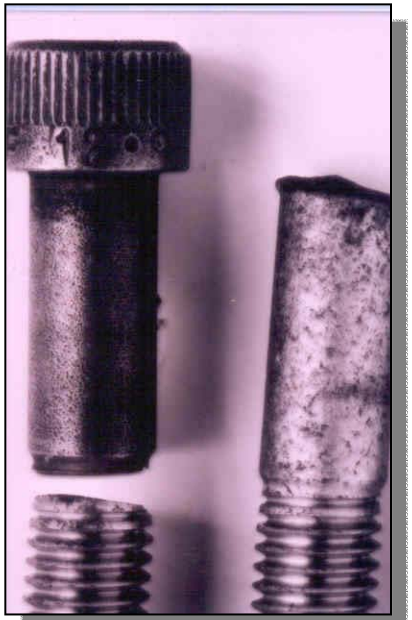
Examples of problems disclosed by the laboratory investigation as part of the RCFA:



GEARS

- Incorrect material
- Incorrect heat treatment
- Incorrect design
- Incorrect assembly
- Corrosion
- Lubricating problems
- Vibration
- Incorrect surface treatment
- Geometric imperfections
- Incorrect operation
- Fatigue or overloading

Examples of problems disclosed by the laboratory investigation as part of the RCFA:



BOLTS

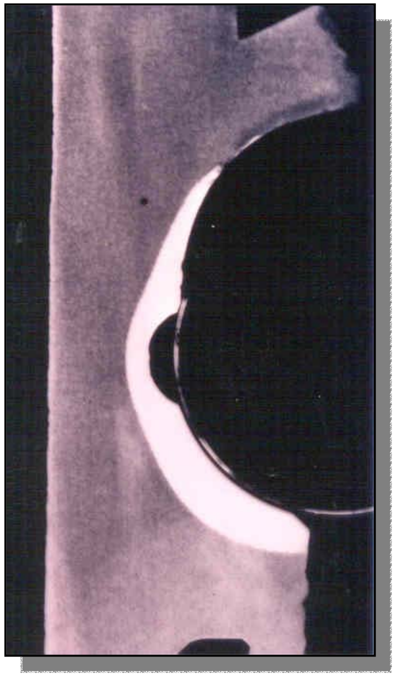
- Indoor material
- Poor design
- Manufacturing defects
- Incorrect assembly
- Corrosion
- Vibration
- Poor or incorrect surface treatment
- Geometric imperfections
- Incorrect application
- Incorrect torque or overloading

Examples of problems disclosed by the laboratory investigation as part of the RCFA:

BALL-/ROLLER BEARING

- Poor design
- Manufacturing defects
- Poor alignment and balance
- Seal failure
- Electrical discharge (arcing)
- Overload
- Inadequate lubrication
- Vibration
- Contamination
- Fretting
- Corrosion

Root Cause Failure Analysis Disclosed Failure of:



MAIN BEARING

- Heavily worn raceway, cracking of casehardened surface, plastic deformation of sealing groove
- The main cause of failure was overloading of the bearing.

  Actions/recommendation:
- Reanalysis by FEM and redesign

Root Cause Failure Analysis Disclosed Failure of:

O-RING

- Four gas leaks on TLP platform equipment in HP & IP service
- Caused by explosive decompression (ED) of O-Ring
- Actions/recommendation:

  Change to another O-Ring type with other elastomer

MANAGING RISK DNV

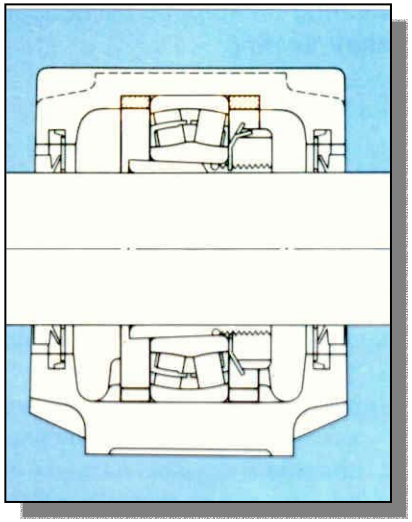
Examples of problems disclosed by the laboratory investigation as part of the RCFA:

DRIVE SHAFTS

- Incorrect material quality
- Incorrect design
- Poor quality manufacture
- Geometric imperfections
- Incorrect operation

- Surface defects
- Corrosion
- Incorrect balance and alignment
- Incorrect assembly
- Fatigue or overloading

ROOT CAUSE FAILURE ANALYSIS DISCLOSED:



Bearing Breakdown

- Axial overloading
- Thrust washers fitted in both bearing housings
- Incorrect assembly

Actions/recommendation:

Remove thrust washers from one bearing housings

ROOT CAUSE FAILURE ANALYSIS DISCLOSED:

Gear Breakdown

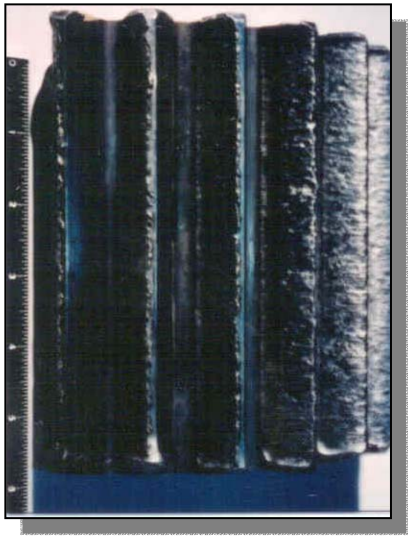
- Broken gear tooth. Fatigue initiated from quench cracks.
- Fabrication induced defects (Basis for discussion of liability and subsequent claims against manufacturer)

Actions/recommendation:

Fitting of new gears where heat treatment and case hardening procedure had been verified to be correct

ROOT CAUSE FAILURE ANALYSIS DISCLOSED:

Damaged pinion and gear wheel



- Severe surface deformation on one side of teeth
- No surface hardening
- Incorrect lubrication

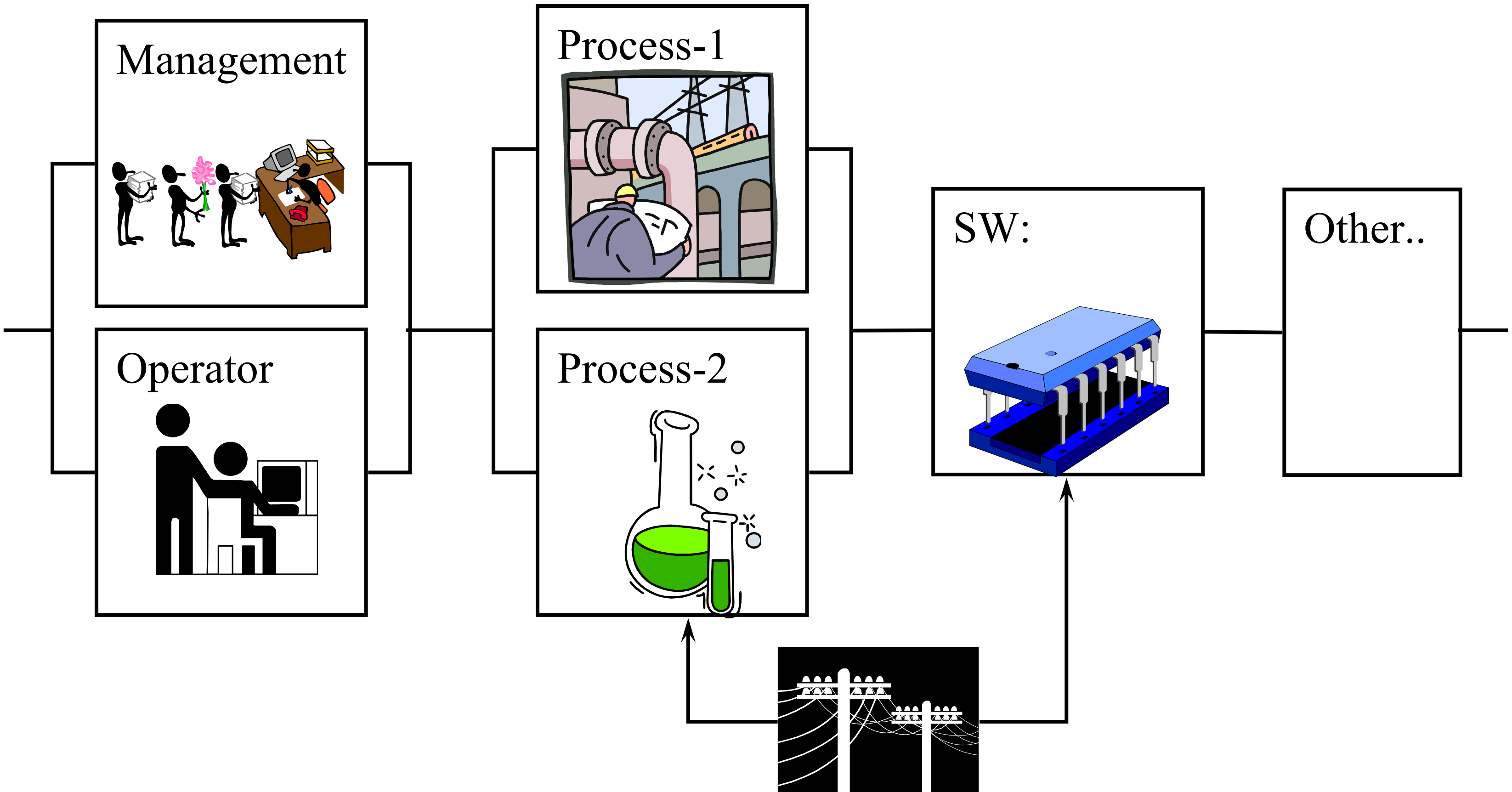
Actions/recommendations:

Renew gear wheel and pinion with components that have been verified to have correct surface hardening. Change lubricant and revise lubrication procedure.

Typical components that can be analysed

- Gears
- Bearings
- Bolted connections
- Shafts
- Impellers
- Pistons/cylinders
- Motor rotors/stators
- Pressurized components and pressure vessels
- Steel wire ropes
- Hydraulic components
- Welded joints

Reliability assessment



… considering total system reliability!

STEP

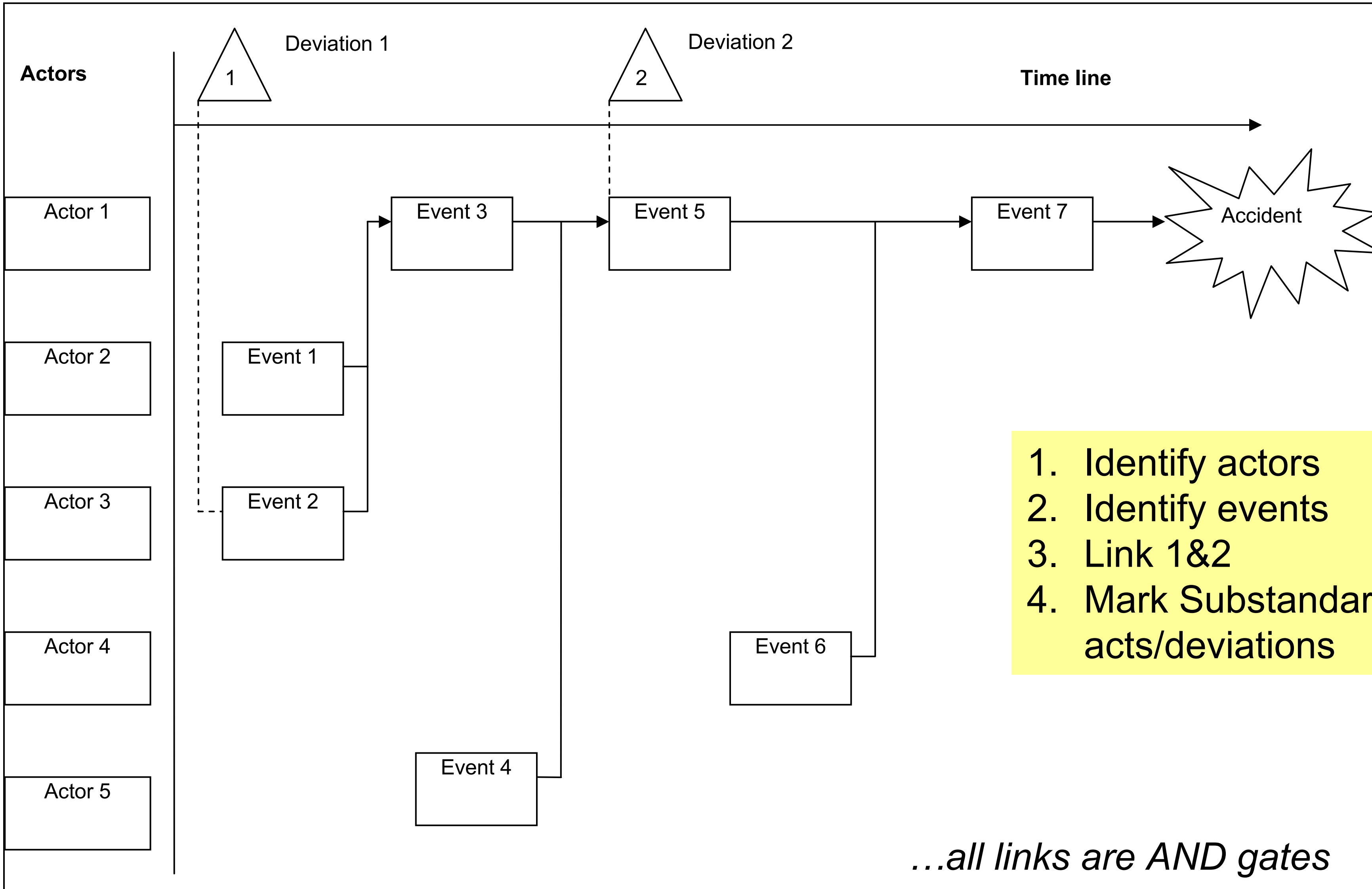
(Sequentially Time Event Plotting)

STEP Method

(Sequentially Time Event Plotting)

- Capturing of the sequential events leading up to an accident.
- Can be a simple timeline
- Investigation of larger incidents/accidents where the time sequence is important
- Handles complex events with:
  - several actors
  - several events in parallel
  - a longer time horizon
- Should include both equipment, control and human actions

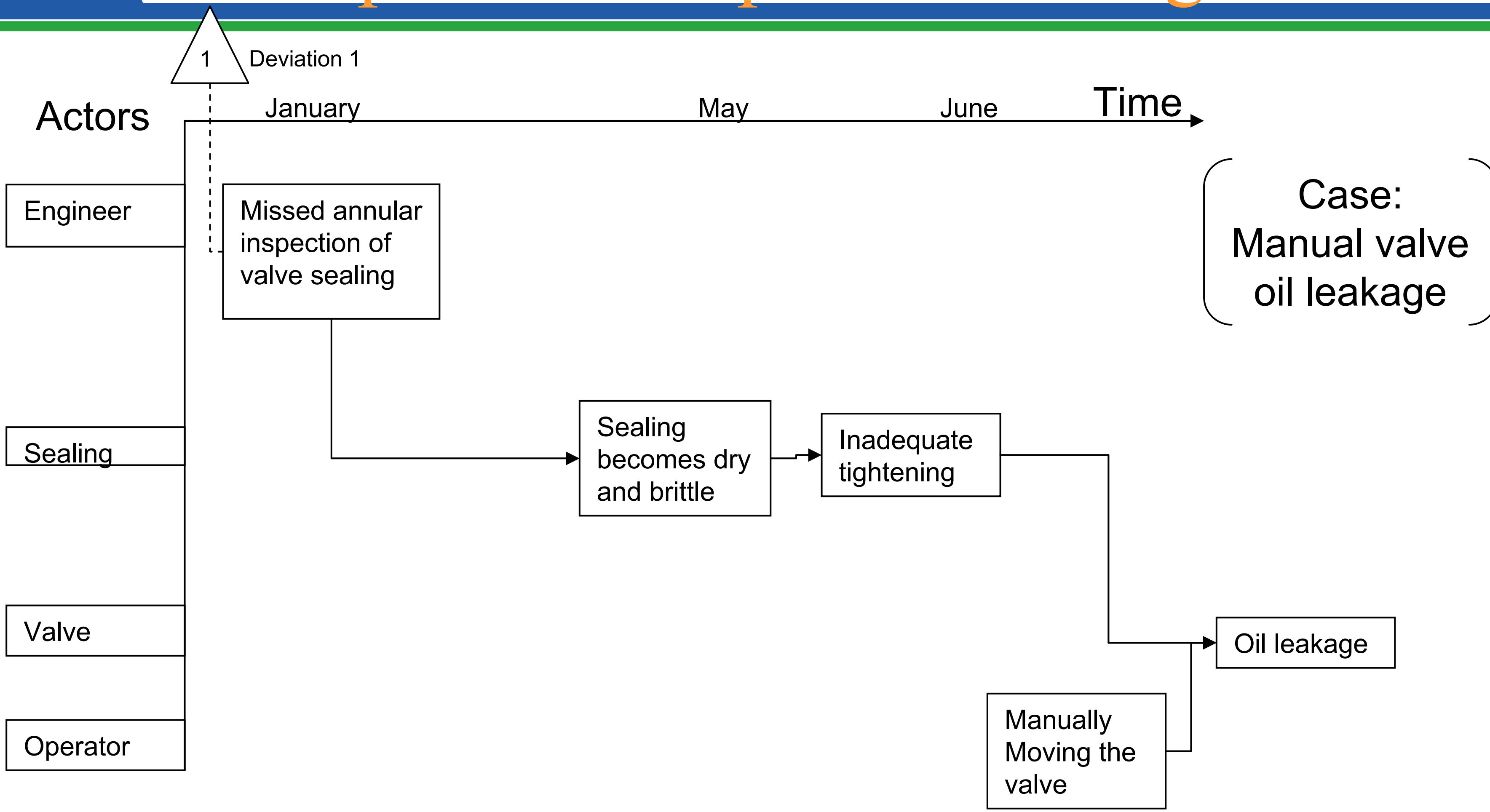
STEP; Sequentially Time Event Plotting



1. Identify actors
2. Identify events
3. Link 1&2
4. Mark Substandard acts/deviations

…all links are AND gates

Example of a simple STEP diagram



FMEA
Failure Mode and Effect Analysis

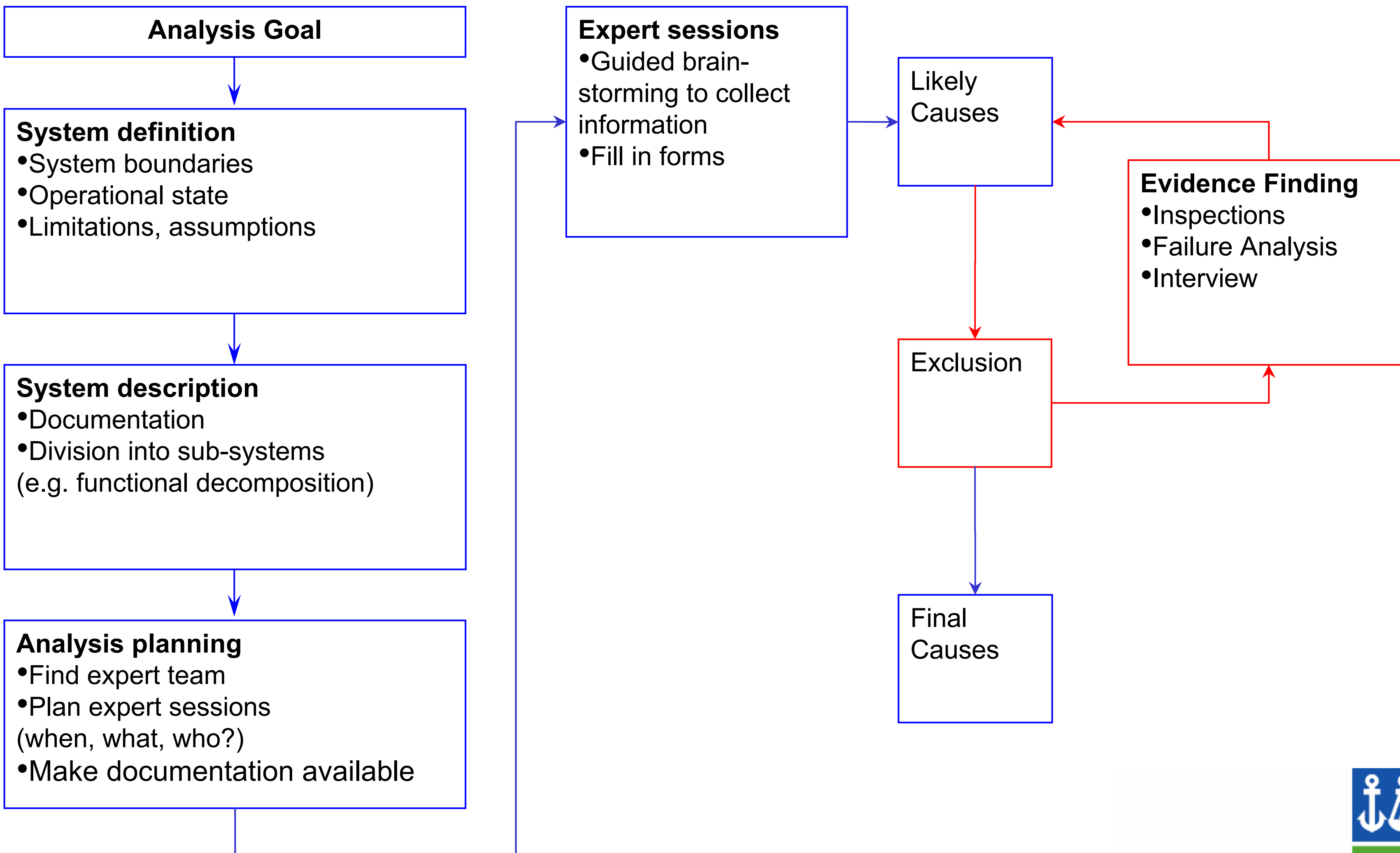
FMECA
Failure Mode and Effect Criticality Analysis

FMEA (Cause-Consequence)

(Failure Mode and Effects Analysis)

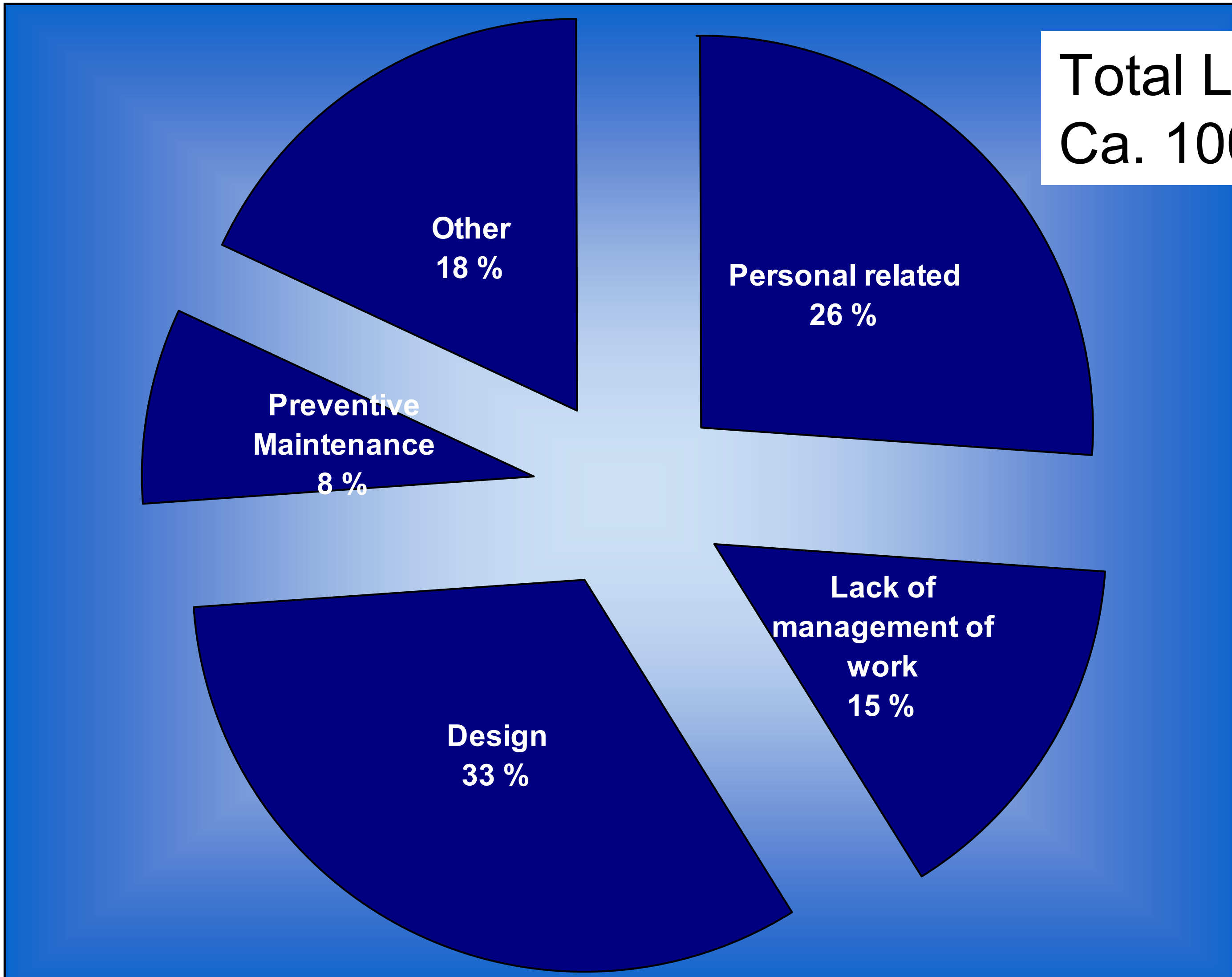
- Overview of failure mode and effect for a complex machinery/operation
- Getting an overview of all potential failure causes and effects at an initial stage of an investigation
- Requires detailed knowledge of the problem in question
- Easy to use for both events and for potential losses where risk is included
- Not good at handling time series

Technique/Working Process



Cases/Examples

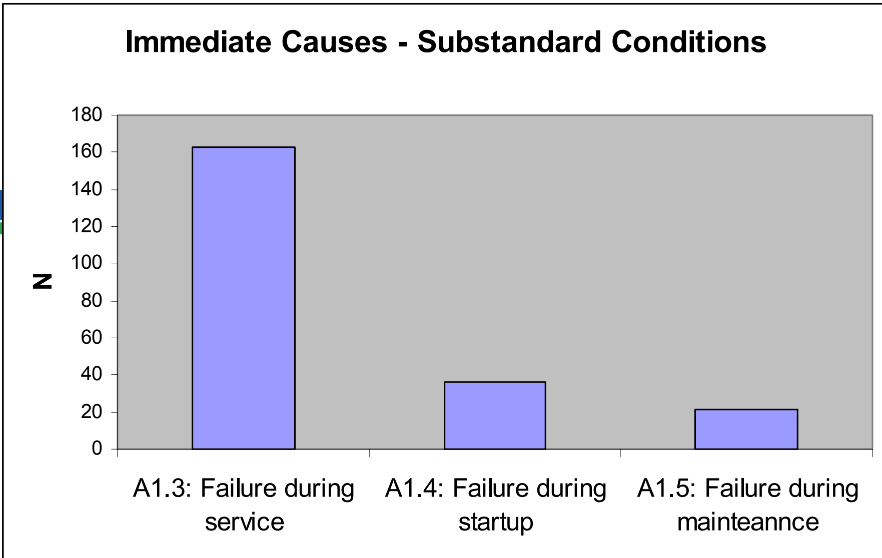
Offshore Gas production
Statistics from 320 incidents/ "RCA" cases

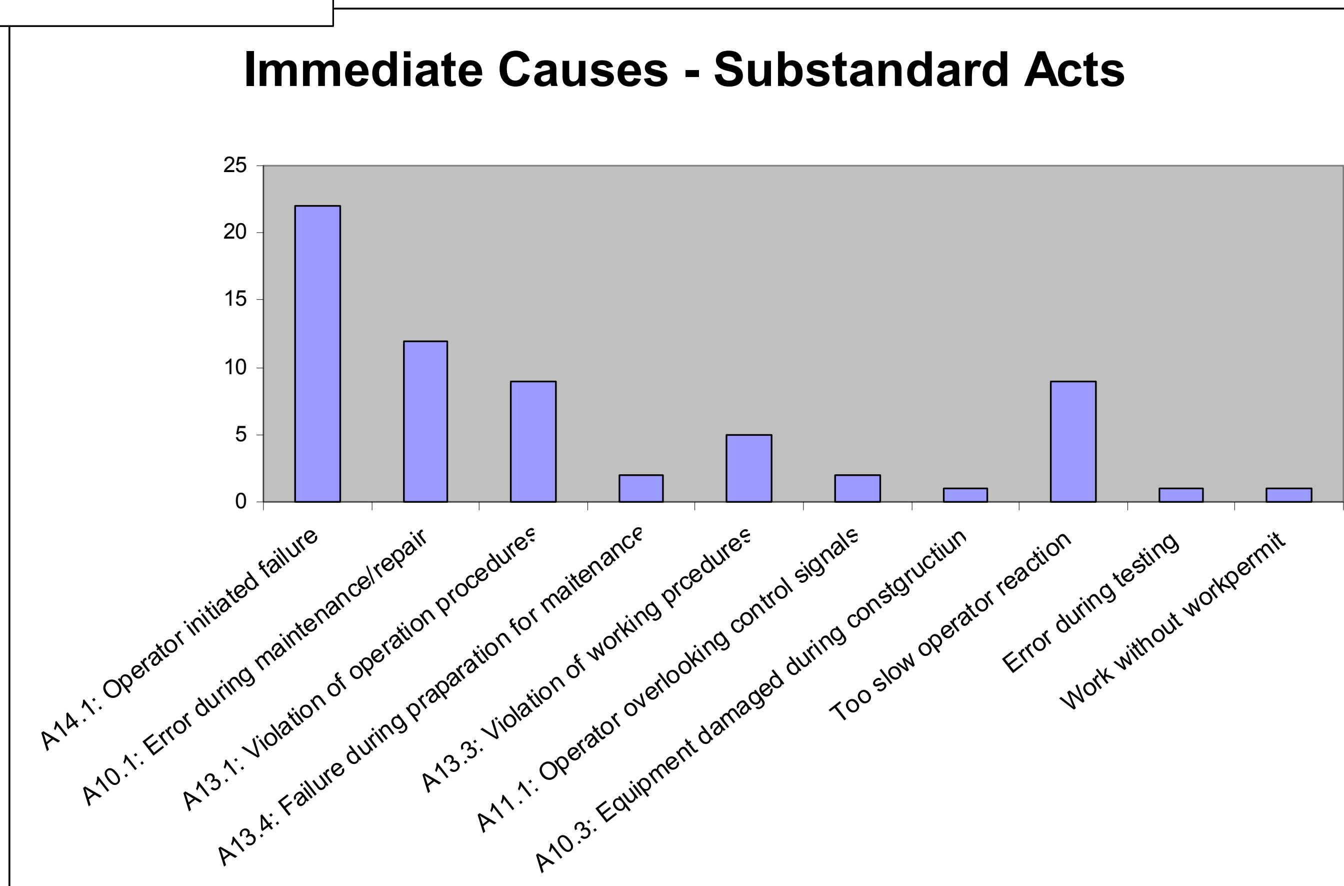


Total Losses;
Ca. 100 mill$/yr

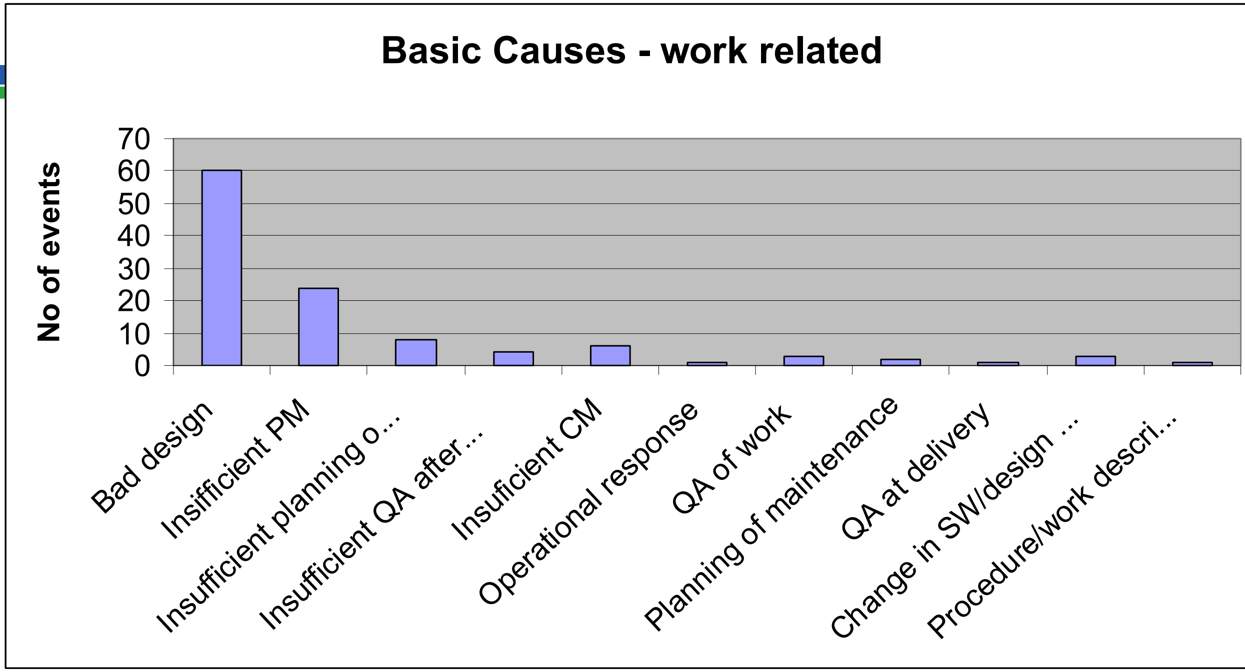
MANAGING RISK DNV

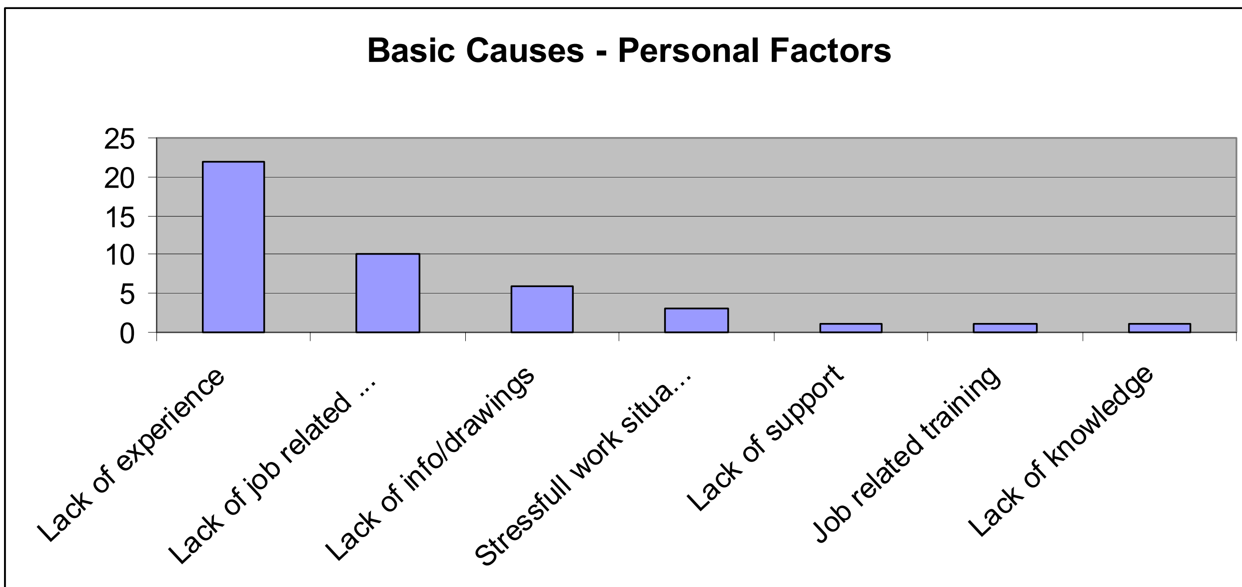
Immediate causes





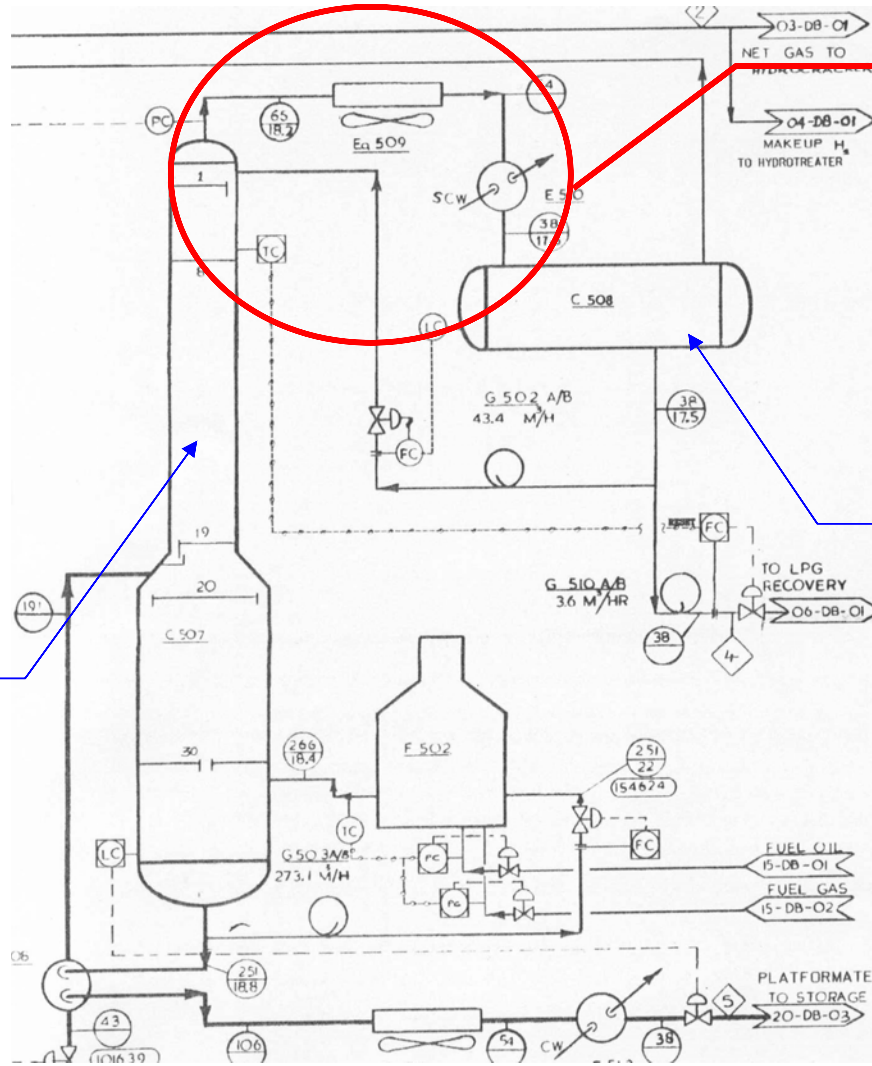
Basic Causes





Explosion and fire at refinery

Refinery Explosion & Fire



Localised Corrosion in overhead Piping

Debutanizer Overhead Receiver

Debutanizer Column

Longford Gasplant

MANAGING RISK

Rich oil de-ethanizer reboiler

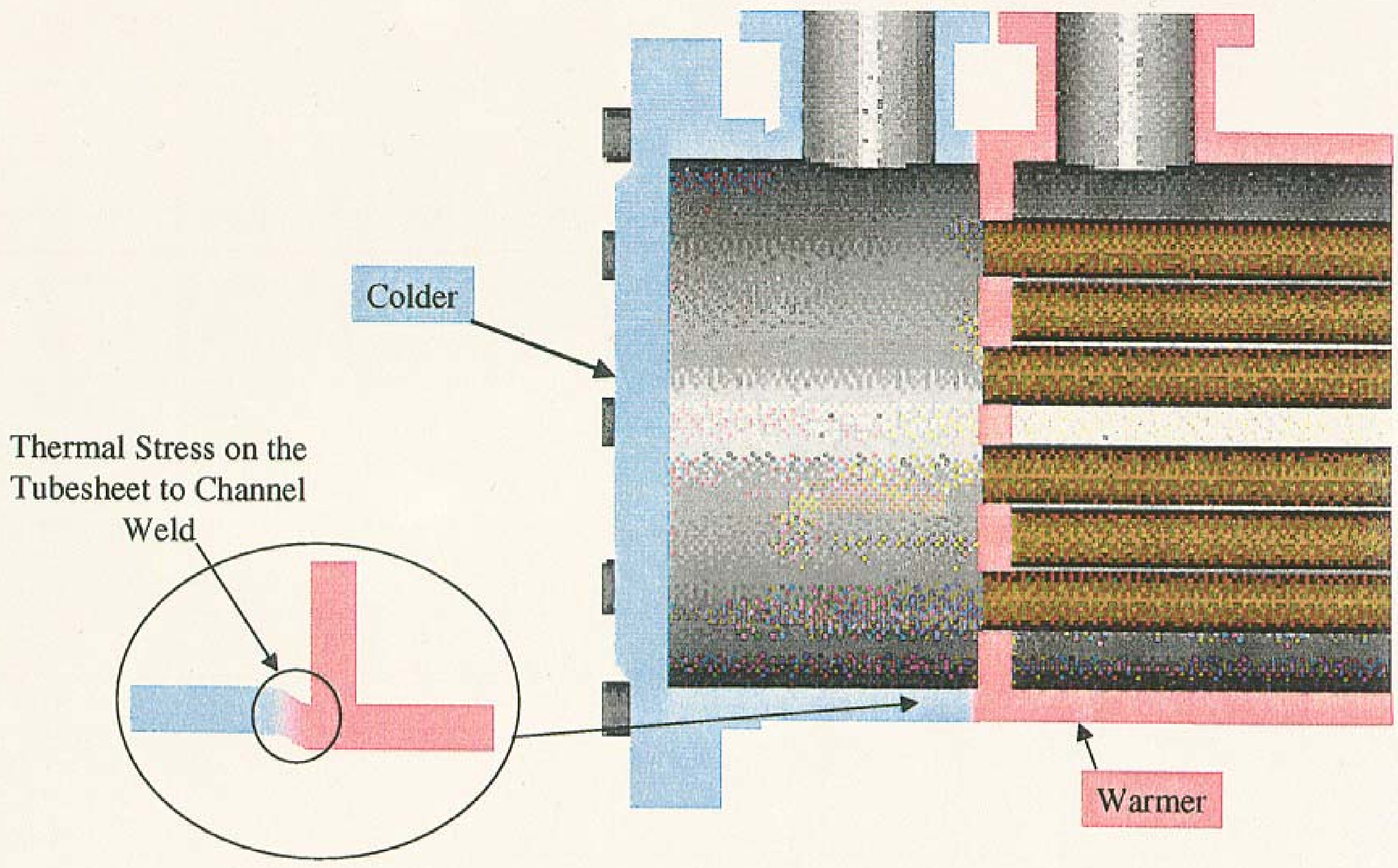
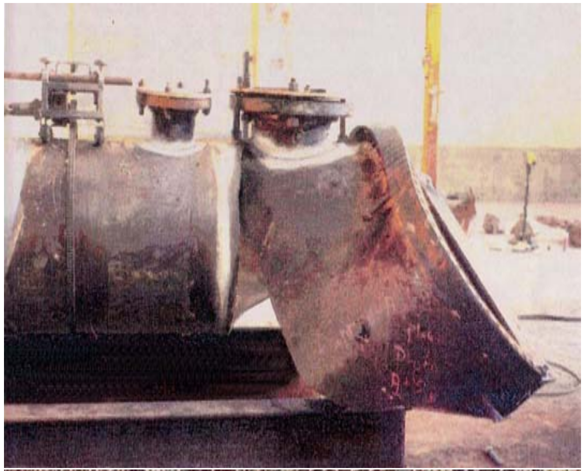


Figure 6.18 Finite element model for GP905 thermal stress calculations

Root Cause Failure Analysis



Damage mechanism: Brittle fracture

DISCLOSED:

BRITTLE FRACTURE IN CHANNEL TO TUBESHEET WELD

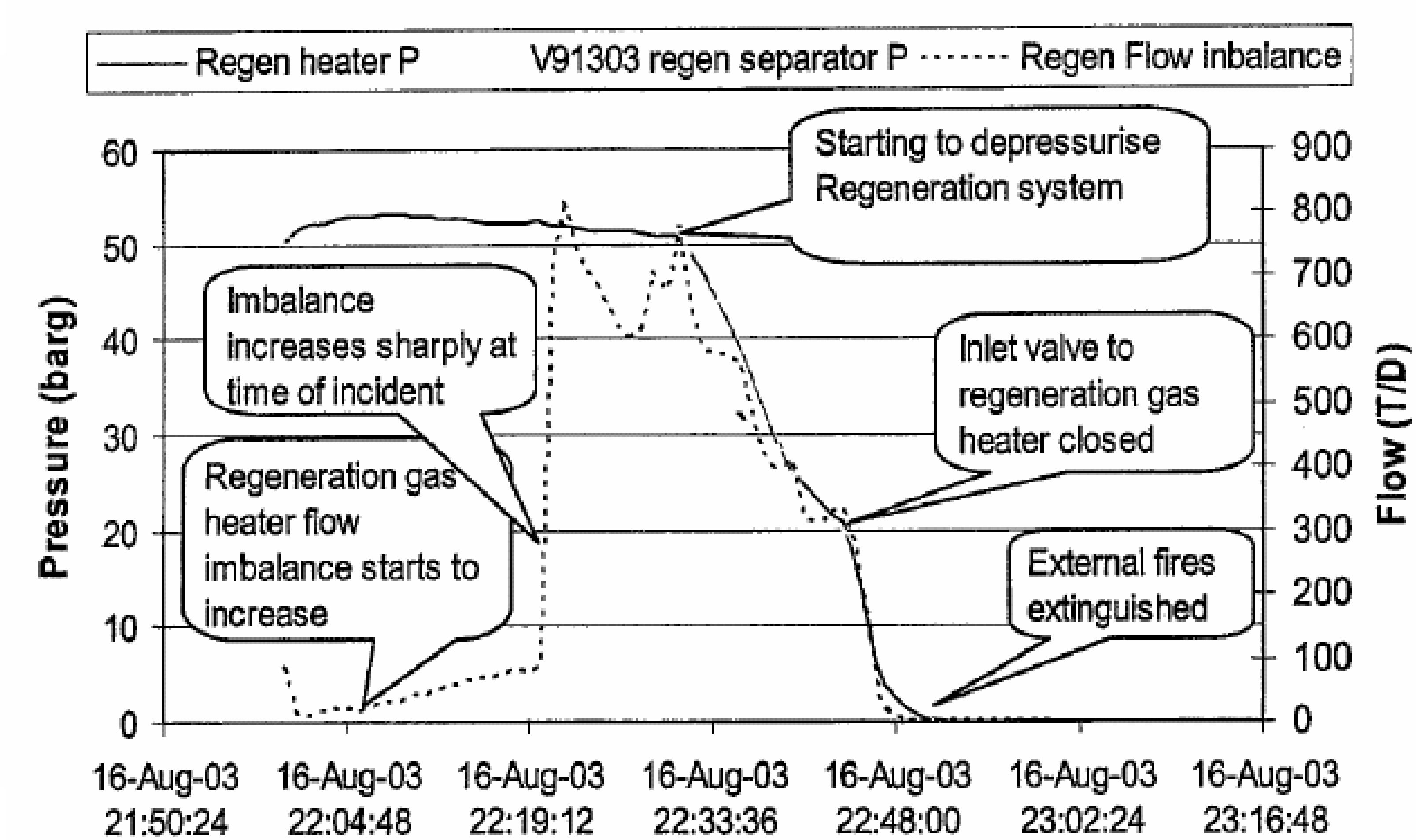
- Low temperature due to process upset
- caused brittle fracture initiation from root
- of weld containing lack of fusion defect

- **Actions/recommendations:**
- Reconstruct using low temperature steel
- grade, carry out proper UT. Modify operation
- procedure and controls to prevent
- future process upsets.

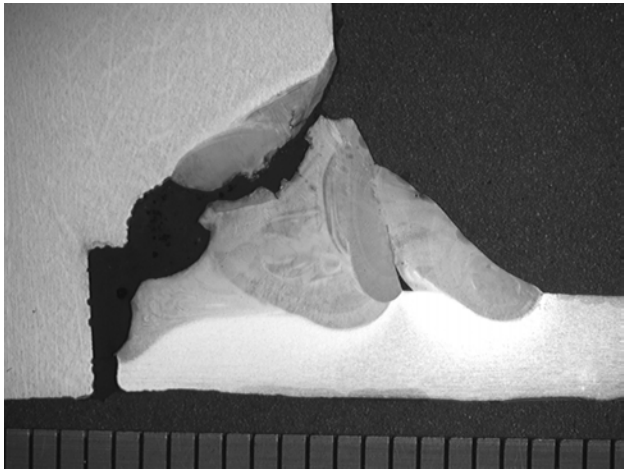
RCFA of LNG Plant Failure

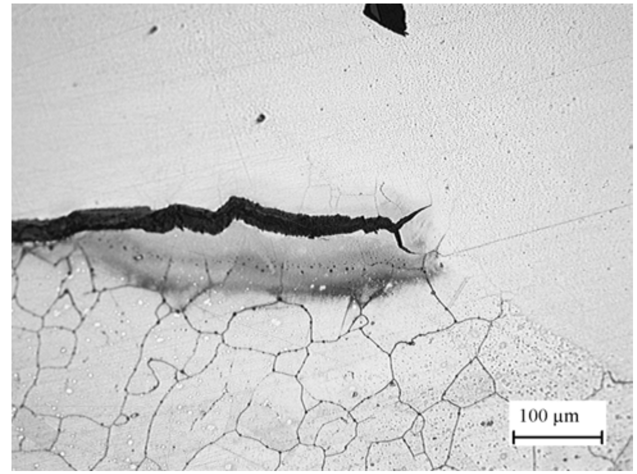
RCFA of LNG Plant Failure

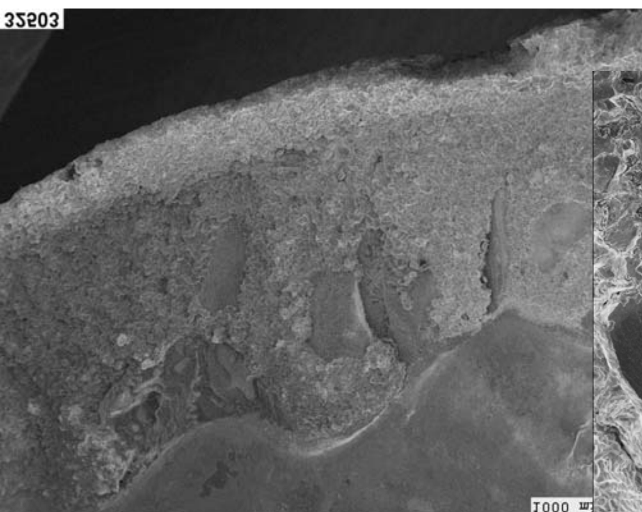
RCFA of WHRU

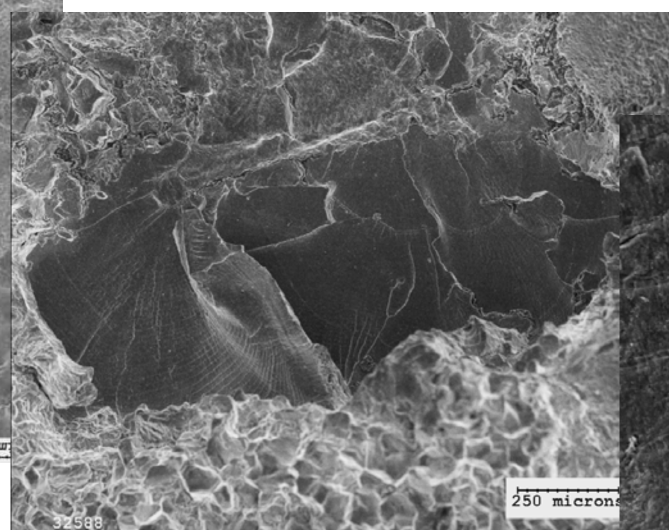

Regen heater P
V91303 regen separator P
Regen Flow inbalance
Pressure (barg)
Flow (T/D)
60
50
40
30
20
10
0
900
800
700
600
500
400
300
200
100
0
16-Aug-03 21:50:24
16-Aug-03 22:04:48
16-Aug-03 22:19:12
16-Aug-03 22:33:36
16-Aug-03 22:48:00
16-Aug-03 23:02:24
16-Aug-03 23:16:48
Starting to depressurise Regeneration system
Imbalance increases sharply at time of incident
Regeneration gas heater flow imbalance starts to increase
Inlet valve to regeneration gas heater closed
External fires extinguished

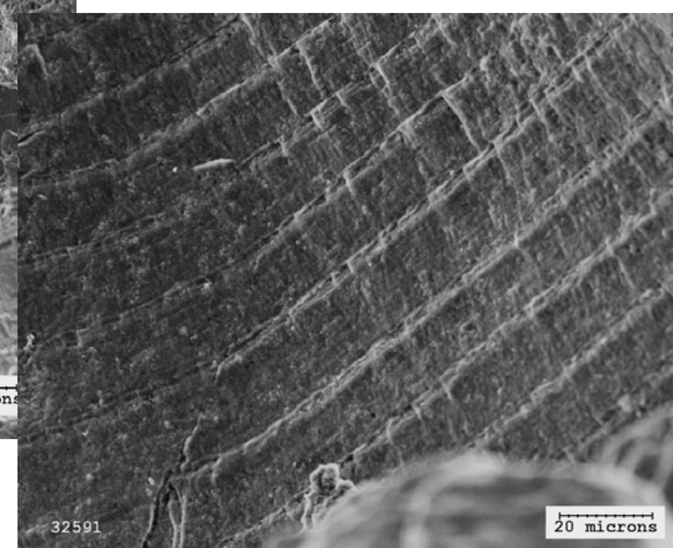
Metallurgical investigation











Findings

- Explosion caused by trip of turbine and leak from WHRU gas coil to header weld
- Following gas leak, auto-ignition of air/gas mixture occurred. The auto-ignition temperature was equal to the surface temperature of the equipment based on instrument readings
- Weld failure due to creep/fatigue and time dependent embrittlement of weld HAZ
- Damage was caused by air/gas mixture explosion equivalent to 68 kg TNT

Failure of 24" OD subsea clad pipeline

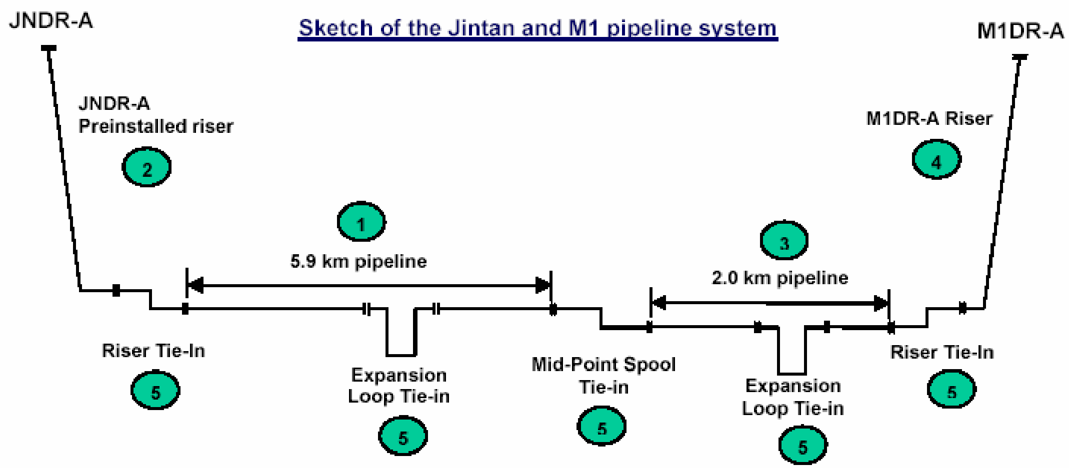


Figure 1: Schematic representation of the pipeline and riser system

Corrosion in 24" OD clad pipeline